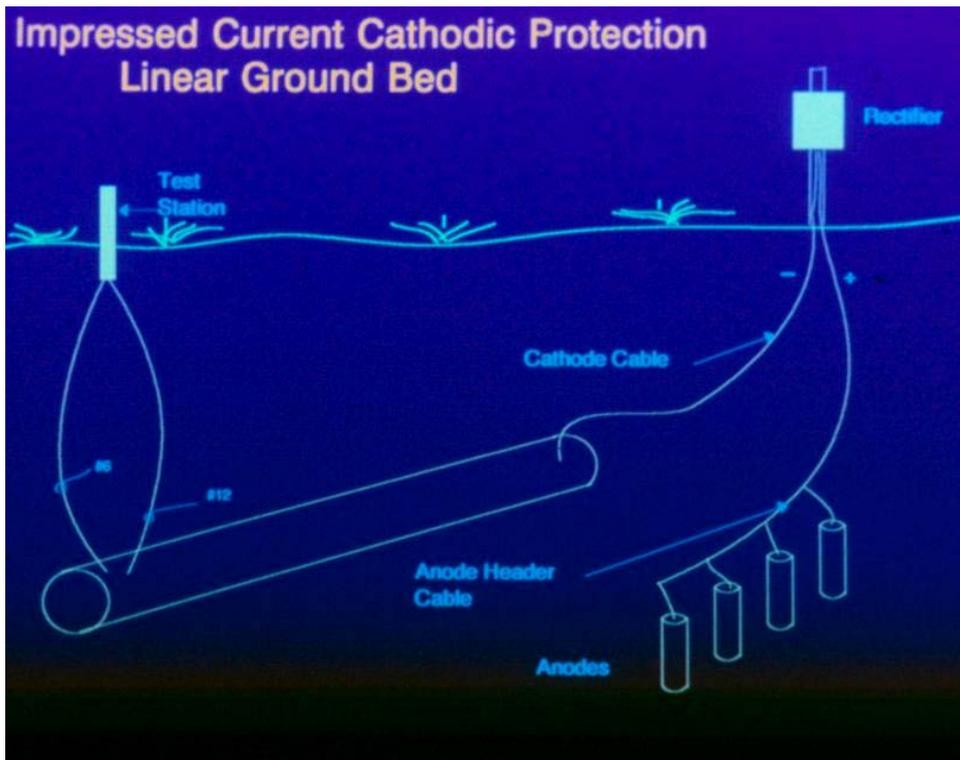# RECLAMATION
Managing Water in the West

Facilities Instructions, Standards, and Techniques Volume 4-5

Corrosion and Cathodic Protection

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)*.	2. REPORT TYPE.	3. DATES COVERED *(From - To)*.
09-16-2013	Draft	Implementation Date: 01-01-2014

4. TITLE AND SUBTITLE
FIST 4-5, Corrosion and Cathodic Protection

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Bureau of Reclamation
Materials Engineering Research Laboratory
Mail Code 86-68180
Denver, Colorado

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Materials Engineering Research Laboratory, Bureau of Reclamation
Denver Federal Center
P.O. Box 25007
Denver CO 80225-0007

8. PERFORMING ORGANIZATION REPORT NUMBER
FIST 4-5

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Power Resources Office
Bureau of Reclamation
Mail Code 86-61600
PO Box 25007
Denver CO 80225-0007

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Available from the National Technical Information Service, Operations Division,
5285 Port Royal Road, Springfield, Virginia 22161

13. SUPPLEMENTARY NOTES.

14. ABSTRACT

This document provides field personnel the principles they need for a clearer understanding of basic corrosion processes and methods to deal with them. It further describes some simple situations in which they might design and install a cathodic protection system using site forces. The document also describes general cathodic protection monitoring procedures. In most circumstances, however, field personnel should seek some level of participation and assistance from corrosion professionals.

15. SUBJECT TERMS
Corrosion, corrosion mitigation, corrosion principles and concepts, oxidizer, oxidation, reduction, polarization, depolarization, passive, corrosion cell, galvanic series, concentration cell, pH cell, stray current corrosion, attenuation, cathodic protection, coatings, galvanic anode cathodic protection, impressed current cathodic protection, anodes, rectifier, test station, junction box, bond box, service life.

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON. Power Resources Office
a. REPORT UL	**b. ABSTRACT** UL	**c. THIS PAGE** UL	UL	88	19b. TELEPHONE NUMBER *(include area code)* 303-445-2922

Facilities Instructions, Standards, and Techniques Volume 4-5

Corrosion and Cathodic Protection

Materials Engineering and Research Laboratory
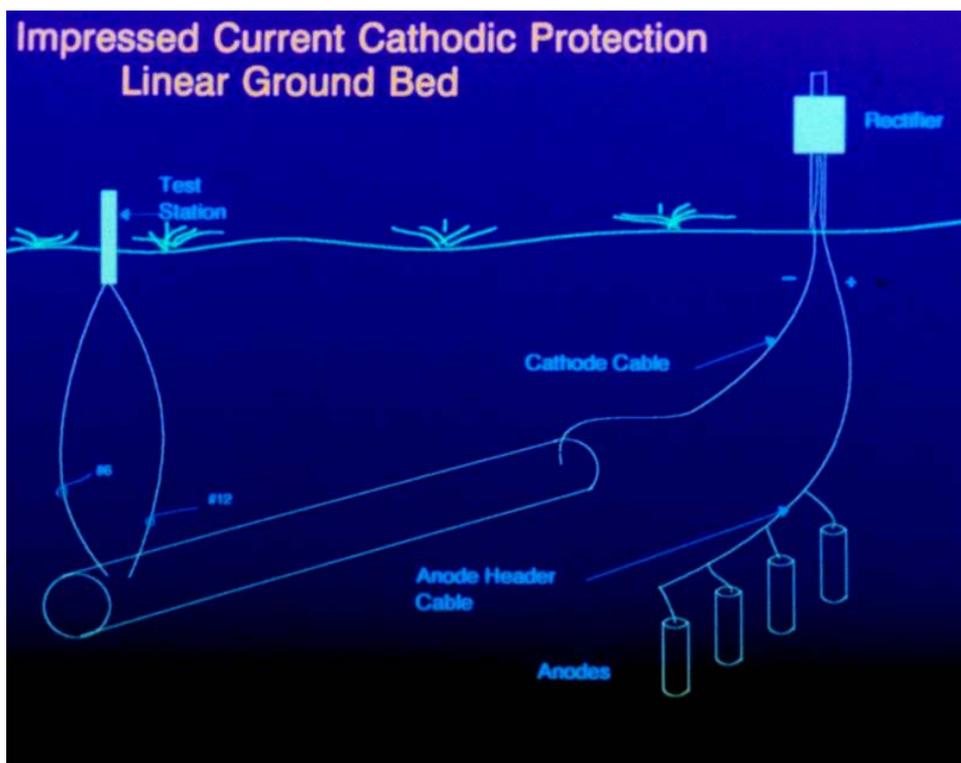
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Acronyms and Abbreviations

AC	Alternating current
CP	Cathodic protection
CSE	Copper sulfate electrode
DC	Direct current
D&S	Directive and Standard
ERI	Electrical resisting imaging
FIST	Facilities Instruction, Standards, and Techniques
HMWPE	High molecular weight polyethylene
HSCI	High-silicon cast iron
ICCP	Impressed current cathodic protection
IR	Infrared
PPM	Parts per million
SOP	Standard Operating Procedures
TSC	Technical Service Center
UV	Ultraviolet

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1.0 Introduction

The Bureau of Reclamation operates and maintains multiple hydroelectric power plants, switchyards, pumping plants, and associated facilities in the 17 Western United States. These facilities are critical to the electric power and water delivery systems on which many rely. Operating and maintaining the complex electrical and mechanical equipment which these facilities house is essential to ensure reliability. In fulfilling this responsibility, Power Operation Managers must ensure the safe and sound operation of all structures and equipment.

1.1 Purpose

This volume provides basic information concerning:

- Corrosion of submerged and buried metals encountered in various installations, including electric power.
- The application of corrosion mitigation methods, particularly cathodic protection (CP).

Mitigating corrosion is important from both an operational 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 also quite important. Measures such as cathodic protection help diminish such losses.

1.2 Scope

This document provides field personnel the principles they need for a clearer understanding of basic corrosion processes and methods to deal with them. It further describes some simple situations in which they might design and install a cathodic protection system using site forces. The document also describes general cathodic protection monitoring procedures. In most circumstances, however, field personnel should seek some level of participation and assistance from corrosion professionals.

1.3 Reclamation Standard Practices

Refer to the Reclamation Manual Directive and Standard (D&S) FAC 04-14, *Power Facilities Technical Documents*, for more details concerning Reclamation Standard Practices.

1.4　Effect of Section Headings

Section headings or titles appearing in this document are inserted for convenience only and must not be construed as interpretations of text or a standard practice.

2.0 General

2.1　Corrosion Terms

For the convenience of the reader, Appendix D at the end of this document defines corrosion along with a number of corrosion-related terms frequently used in this Facilities Instructions, Standards, and Techniques (FIST) document and in corrosion work. Several are described more in terms of practical corrosion concepts rather than as formal definitions. NACE/ASTM G193 contains additional definition.[1]

2.2　Forms of Corrosion

Corrosion, though commonly associated with metals, can affect any material of construction and takes many forms. Corrosion of metals occurs as the result of their tendency to revert to their natural state – an ore. Commonly identified forms associated with corrosion of a metal in an electrolyte include:

- General corrosion – in which metal loss is more or less even.
- Galvanic corrosion – in which electrically connecting dissimilar metals causes accelerated corrosion of one while reducing corrosion of the other.
- Crevice corrosion – such as corrosion at mating surfaces or under deposits.
- Pitting corrosion – which leaves pinholes in a surface.
- Intergranular corrosion – in which the borders of metal crystal grain boundaries are attacked, causing grains of metal to drop out, and leaving a sugary appearance.
- Selective leaching – wherein a component of an alloy selectively corrodes, leaving a mechanically weak structure with essentially original dimensions.
- Erosion corrosion – wherein velocity combines with corrosion to produce synergistic damage.
- Stress corrosion – in which corrosion and stress combine to crack a metal.
- Hydrogen damage – in which hydrogen, such as produced by corrosion in an acid, may embrittle or blister a metal.

The reader may also see other classifications such as microbial-induced corrosion or stray current corrosion. In addition, many of the types described above have

sub-categories for specific forms of corrosion or for a specific metal. For instance, cavitation corrosion is a special form of erosion corrosion, and dezincification of brass and graphitic corrosion of gray cast iron are both forms of selective leaching.

A full treatment of each type of corrosion and its intricacies is beyond the scope of this document.

2.3   Taking Action and Getting Help

This document will restrict itself to some of the more common forms and mechanisms of corrosion that the reader is likely to encounter with ferrous metals in soil and water environments and which they might address using cathodic protection. However, cathodic protection is not the best approach to every corrosion problem. For instance, seal welding a crevice may be the best solution to crevice corrosion. It is not possible to adequately access such areas to prepare the surface and apply a coating, and cathodic protection currents do not penetrate crevices very well. Different corrosion problems have different solutions; hence the importance of understanding corrosion mechanisms in order to take proper actions. **[When faced with an unfamiliar corrosion issue, the reader must seek aid from a Technical Service Center (TSC) or similar corrosion professional.]** While this document may not allow the reader to handle all corrosion problems on their own, it will allow them to discuss corrosion more effectively when contacting that professional.

Incorporating corrosion mitigation measures into the design of a structure at construction is the best and most economical strategy. This approach may require advanced notice to permit corrosivity testing and evaluation of data as well as some added construction expense, however, if this is not done and significant structural corrosion occurs after construction, the labor and expense can be significantly greater. After construction, repairing corrosion damage can necessitate re-mobilizing and sometimes re-excavating to reach the problem area, equipment downtime, and other corollary expenses. After repairs, a retrofit method of controlling the corrosion still needs to be developed in order to prevent recurring repair costs. Involve a corrosion professional as early in the project as possible.

When faced with corrosion damage, one should perform a preliminary examination to define the extent, severity, and characteristics of corrosion in the environment in question. This information can provide a clue as to what corrosion mechanism is at work or what further testing may be needed. Personnel should expose enough of the corroding surface to permit adequate examination at various locations. When reporting suspected corrosion damage, provide such information as:

- The specific alloy involved (e.g., 304 or 316 stainless steel).
- As much information as possible regarding the environment surrounds the damaged part, including temperature, pH, 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, if possible.

[Report pipe corrosion damage using the form at the end of Technical Memorandum No. MERL-2011-35, *Guidelines for Reporting Corroded Pipe*.[2] A copy of this form is reproduced at the end of this document in Appendix B.]

3.0 Corrosion Principles and Concepts

3.1 Soil and Water Corrosivity Factors

The corrosion of a metal, whether immersed or in soil, involves a wet environment. Soil is like a wet sponge holding moisture against a buried structure. This moisture in corrosion nomenclature is known as the electrolyte, and it has several important components, including:

- Water
- Oxidizers
- Ionizable chemicals

These components of the electrolyte can have a strong influence on corrosion rate. However, temperature and the chemical that corrosion itself causes are also important. These factors will be explored further in the following paragraphs.

3.1.1 Water

Bare ferrous pipe kept in a dry storage area will suffer little or no significant corrosion, but will show rust shortly after immersion or exposure to rain or dew. This is because a significant amount of dissolved oxygen in the water has rapidly reacted with the metal. Even though there is plenty of oxygen in the air around a pipe, it generally reacts with the metal at a very slow or even negligible rate under ambient dry conditions. The water allows oxygen and other corrosives to readily interact with the metal in ways they cannot otherwise.

3.1.2 Oxidizers

The component of an electrolyte that does the actual corrosion damage is called an oxidizer. Among this class of dissolved chemical, oxygen is very commonly encountered. Oxidizers like oxygen in solution steal electrons away from the metal atom, and having done so, the oxidizer acquires a negative charge and is said to be reduced. A reduced oxidizer is spent and will not react with additional metal. The attacked metal atom, having lost one or more electrons, acquires a positive charge and is said to become oxidized, and it is thereby freed from its position in a rigid metal structure. Because of this mechanism, the corrosion reaction in an electrolyte is described as an oxidation-reduction, or a redox reaction. In this manner, a buried or immersed structure corrodes atom by atom.

The corrosion reaction products of iron or steel with oxygen accumulate as rust. Since the reacted oxidizer, like oxygen that has formed rust, is no longer available to do further damage, fresh oxidizer must constantly be replenished at the metal surface to keep corrosion going. Hence, anything that blocks or makes the migration of an oxidizer to the metal surface more difficult, such as certain corrosion products, will slow down corrosion. Whatever brings oxidizers to the surface, such as a flowing electrolyte, will accelerate corrosion.

Oxygen is not the only oxidizer dispersed in water. Carbon dioxide in the air forms carbonic acid when it enters water, and acids can also oxidize iron and steel. Likewise, dissolved air pollutants such as oxides of sulfur and nitrogen will also form corrosive acids, as can decomposing organic matter. Fortunately, naturally occurring dissolved acids are often too dilute to significantly corrode ferrous metal. The corrosion products formed when acid attacks ferrous metals are hydrogen gas and a metal salt, such as iron carbonate which forms when carbonic acid attacks ferrous pipe. Dissolved oxygen in combination with an acid can be particularly corrosive. There are many other soluble materials in soil, and some may also be oxidizers that can cause corrosion. Dissolved chemicals will tend to be at equilibrium concentrations in rain, lakes, streams, ground water, and the like and will tend to return to equilibrium as those components are consumed. Hence, there should always be a ready supply of some level of oxidizers in the electrolyte.

Charge balance is central to redox reactions. For every electron given up by the corroding metal, an oxidizer must take in an electron. Furthermore, nature requires that charge balance must be maintained at every point in the electrolyte; positive charges and negative charges cannot accumulate at separate locations. Ionizable chemicals are important in maintaining this charge balance.

3.1.3 Ionizable Chemicals

Salts, acids, and bases break apart to some extent in water. When they do, the atomic electrons that these compounds shared and that held them together are not divided evenly between the atoms or groups of atoms. The dissociated particles therefore acquire a positive or negative charge, with the sum of positive and

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negative charges canceling out. Even pure water itself dissociates to a small extent. The fact that water has a pH of 7 reflects this dissociation. These charged particles are called ions or radicals, and the materials from which they came are said to be ionizable. Ions and radicals that carry a positive charge are called cations while those carrying a negative charge are called anions.

Ionizable materials play an important role in both corrosion and in cathodic protection. Oxidation and reduction portions of an overall corrosion reaction can take place in separate locations because intervening ions and radicals will migrate to maintain charge balance. Some ionizable materials, such as acids, are oxidizers. Since rocks, pebbles, and grains of soil have very high electrical resistance, current in soil is through the interstitial soil electrolyte.[3] Ions and radicals reduce the electrical resistance of moisture and carry the current of a cathodic protection system through the electrolyte.

The more ionizable chemicals in soil moisture or water, the more conductive it is (i.e., the lower its resistivity) and often the more corrosive it may be. A good comparison is sea water versus fresh water. The former is highly conductive and typically much more corrosive than the latter. However, there are exceptions to the resistivity/corrosivity correlation, as in the case of concrete and similar cementitious materials.

Of the ionizable chemicals, chloride salts in particular strongly and adversely impact corrosion. They increase the conductivity of electrolytes, and also affect how corrosion products perform. The chloride ion is a very small, penetrating anion associated with passive film breakdown (described below), pitting, and crevice corrosion. Even small amounts of chloride ion can be quite detrimental.

3.1.4 Temperature

Temperature can have a significant impact on corrosion. Elevating the temperature generally accelerates corrosion, everything else being constant. It can even determine whether particular forms of corrosion will develop. However, raising the temperature sufficiently can reduce the solubility of gasses such as oxygen in an electrolyte and may even dry out a metallic surface in extreme situations. If this occurs, corrosion may actually slow down or halt. Temperatures on buried or immersed Reclamation structures are typically not elevated or too variable.

3.1.5 Chemical Changes Due to Corrosion

During corrosion, oxidation and reduction reactions cause chemical changes at their respective sites. Reduction reactions consume oxidizers, tending to decrease their concentration at cathodic locations. At the same time, oxidation products accumulate and may deposit on anodic sites, making it more difficult for additional oxidation to take place. These effects are called polarization. In some instances, early stage corrosion may even cause the metal to form a passive film

that resists further corrosion, as explained further below. Hence, corrosion rates are typically greatest at the onset.

Anything that reduces these chemical changes at anodic or cathodic sites is said to depolarize that site. A simple way of depolarizing a surface is by agitating a solution, which will sweep reaction products away and refresh the reactants. Increasing the temperature or introducing certain chemicals can have a similar impact.

3.2 Metal/Alloy Susceptibility Factors

The environment alone does not determine how rapidly metallic materials will corrode. The specific metal or alloy and the corrosion products formed in a specific environment have a big influence.

3.2.1 The Metal or Alloy

Metals and alloys differ in how readily they cede electrons to an oxidizer – hence, in how easily they corrode. The ones that hold on more tightly are said to be more noble or cathodic, while the ones that easily give up electrons are said to be more active or anodic.

If a more noble metal and a more active one are electrically connected together (e.g., through a wire or by direct contact) in an electrolyte:

- The more active metal will tend to provide at least some of the electron oxidizer demand at the surface of the noble metal.
- The more active metal will supply some additional electrons to oxidizers at its own surface.

As a result, the anodic metal corrodes more rapidly while protecting the noble metal. This is typical of galvanic corrosion and, as will be seen, is the basis for galvanic anode cathodic protection. This differing tendency to lose electrons demonstrates itself as a voltage difference between the two metals.

3.2.2 Passive Films

Some corrosion products can form an effective barrier that prevents additional oxidizers from reaching a metallic surface, stifling corrosion. Such protective corrosion products are called passive films, and the metal surface is said to be passivated. Passivation is the mechanism whereby stainless steel and a number of other alloys resist corrosion. However, not all corrosion products in all environments form effective passive films. The metal and environment need to be correctly matched. Rust, even if thick, is not an effective passive film in most instances; further corrosion often takes place even under a thick rust layer. Steel rebar in a high pH concrete environment can passivate. However, chloride ion in

sufficient quantity will induce passive film breakdown of iron or steel in concrete, as will carbonation of the concrete by dissolved carbon dioxide.

3.2.3 Ferrous Corrosion Products

Oxides of iron or steel are collectively termed rust, which actually consists of a number of ferrous mineral forms. Depending on its precise make-up, rust can take up to an order of magnitude more volume than the original metal from which it formed. The outsized thickness of rust formed on steel often causes alarm and concern for excessive metal loss that, when actually measured, turns out to be tolerable. However, this voluminous corrosion product can have deleterious results, as when steel encased in concrete corrodes. For instance, when rebar in concrete corrodes, the steel corrosion products cause cracking and spalling of the concrete. This damage then allows corrosives to more readily reach the rebar, causing accelerated corrosion until the reinforced concrete is extensively damaged and weakened.

Gray cast iron and ductile cast iron corrosion products behave somewhat differently from the rust on steel. Gray cast iron composed of iron in an interconnected network of graphite flakes. As a result, when a gray cast iron pipe buried in soil corrodes, it often suffers selective leaching; the iron corrodes while the graphite flake network remains intact. This is called graphitic corrosion. The corroded iron may dissolve away, but rust will more often remain in the voids of the graphite flake network. Little or no corrosion product expansion results. The corroded pipe has essentially the same dimensions as the original metal, but with very little strength. A screw driver or shovel can easily break through graphitic corrosion products. Ductile iron is also composed of iron and graphite, but the graphite is in discrete nodules. Unlike gray cast iron, the graphite network is not interconnected and continuous; the corrosion products are essentially graphite spheres floating in a continuous network of rust. Nonetheless, a corroded ductile iron pipe will also often suffer severe corrosion while retaining the looks of an uncorroded pipe, until one cleans out the pockets of corrosion.

3.3   Corrosion Cell Concept

The corrosion cell is a way of visualizing the various processes taking place during corrosion and described above. It is especially relevant when talking about galvanic or concentration cell corrosion, but it can be applied even to general corrosion of a single metal. The elements of a corrosion cell are shown in Figure 1. Its basic components include:

- Anode
- Cathode
- An electrolyte for ion flow between these electrodes
- An external metal path for current flow between these electrodes

The following discussion will refer to these components. The principles of this simple model are also useful when considering cathodic protection.
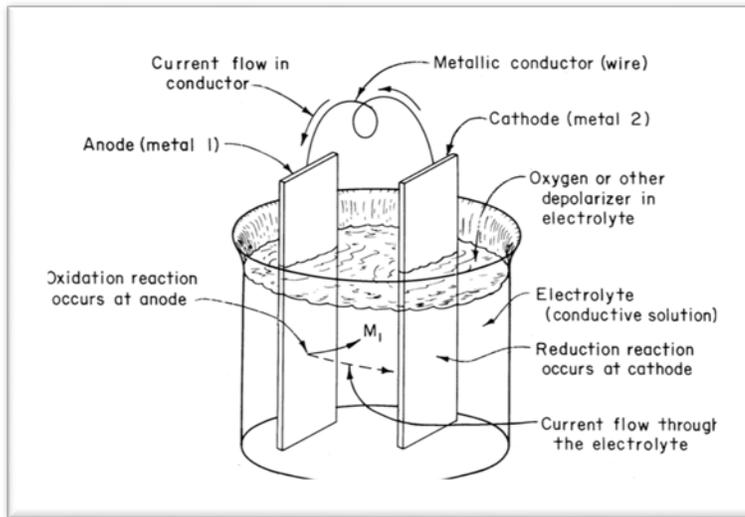
Figure 1. The corrosion cell.

3.3.1 Microcells and Macrocells

The corrosion cell envisions oxidation and reduction as occurring simultaneously, but at separate locations. The anodic locations where mainly oxidation takes place are called anodes while the cathodic locations where mainly reduction takes place are called cathodes. As a result of the different reactions taking place at these separate locations, the anodes and the cathodes create a potential or voltage difference between them. Since these electrodes are in the same electrolyte, this model creates a battery out of the corrosion process. Current can pass when anodes and cathodes are connected by an electron carrying path. This electron path may consist of the anodes and cathodes being in direct contact or being spaced but connected by an external wire or the like.

Even general corrosion of a single metal has been described using this model. 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.

Corrosion cells in which tiny anodes and cathodes are in close proximity to each other are termed microcells. In addition to general corrosion of a metal, pitting corrosion and intergranular corrosion are other examples of microcells.

Similarly, larger discrete cells can exist and develop a voltage difference. These are often referred to as macrocells. Examples of macrocells include:

- Two distinct metals connected together and in the same soil or water – a galvanic cell.
- A large metallic structure in different electrolytes or soil conditions – a concentration cell.

As discussed previously, the reactions at anodic and cathodic sites change the surrounding chemistry and can affect corrosion. These changes are also reflected in the voltage difference between anodes and cathodes. The voltage difference between anodic sites and cathodic sites becomes less as the result of anodic sites becoming less anodic and cathodic sites becoming less cathodic.

3.3.2 Common Corrosion Cells

Corrosion cells are quite common. Different metals used to construct a structure can serve as anode, cathode, and the necessary metallic conductor between the two. The immersed environment or soil moisture constitutes the electrolyte required to complete the cell circuit. The following are a few examples in which buried or immersed structures satisfy the essential requirements for a complete corrosion cell:

a) Buried iron or steel will be anodic to copper ground mats or to brass bolts or other copper alloy parts.
b) An immersed or buried steel plate with mill scale may suffer accelerated corrosion at metal exposed through the scale because the steel anodic to mill scale.
c) Weld areas of a welded pipe may suffer accelerated corrosion because the weld metal is of slightly different composition or may contain impurities that make them anodic to nearby base metal.
d) The bottom of a pipeline may corrode while the top remains largely undamaged because higher oxygen concentration in the soil moisture (electrolyte) at the top of the pipe creates an oxygen concentration cell with the bottom of the pipe being the anode.
e) A pipe passing through different types of soil develops voltage differences, suffering areas of greater and lesser corrosion.
f) The soil side of buried iron steal areas passing through concrete may suffer accelerated corrosion because the ferrous metal in concrete is at a more noble potential than the ferrous metal in the soil.

4.0 Specific Corrosion Issues

Reclamation personnel observe some types of corrosion more frequently than others. These deserve additional mention.

4.1 Galvanic Series and Coupling Metals/Alloys

Metals and alloys have different tendencies to corrode in any given environment. An experimental list called a galvanic series shows this tendency by placing the metals and alloys in order of susceptibility. The potential of a metal or alloy with respects to a standard reference cell determines its position in the order. Some galvanic series are simple lists, like Table 1, while others may be in graphical form, with boxes indicating a range of potentials observed for an alloy. ASTM G82-98 (*Standard Guide for Development and Use of a Galvanic Series for Predicting Galvanic Corrosion Performance*) details the development and use of a galvanic series.[4] A galvanic series also suggests the consequences of joining two metals or alloys.

Note that in Table 1, graphite, a form of carbon and non-metal, will also develop a potential in an electrolyte. It is quite noble and can induce galvanic corrosion of a number of metals or alloys.

A galvanic series must not be confused with the electromotive series. The latter provides potentials for pure metals and other materials referenced to standard reversible conditions. While the electromotive series can be valuable research tool, its use in engineering applications is somewhat limited.

4.1.1 Acceptable and Unacceptable Couples

A considerable voltage difference results from electrically coupling two metals widely separated in a galvanic series. This voltage produces a relatively large amount of what is called galvanic current, 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 together; 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 damaging effects, 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 useful in all instances.

Galvanic Series of Metals Exposed to Seawater	
Active or Corroding End	
(-)	Magnesium
↑	Magnesium Alloys
|	Zinc
|	Galvanized Steel
|	Aluminum 1100
|	Aluminum 6053
|	Alclad
|	Cadmium
|	Aluminum 2024
|	Mild Steel
|	Wrought Iron
|	Cast Iron
|	410 SS (Active)
|	304 SS (Active)
|	316 SS (Active)
|	Lead-Tin Solders
|	Lead
|	Tin
|	Muntz Metal
|	Manganese Bronze
|	Naval Brass
|	Nickel (Active)
|	Yellow Brass
|	Admiralty Brass
|	Red Brass
|	Copper
|	Silicon Brass
|	70-30 Cupro Nickel
|	G-Bronze
|	M-Bronze
|	Silver Solder
|	Nickel (Passive)
|	67Ni-33Cu (Monel)
|	410 SS (Passive)
|	Titanium
|	304 SS (Passive)
|	316 SS (Passive)
|	Silver
|	Graphite
↓	Gold
(+)	Platinum
Noble or Passive End	

Table 1. Extracted from NACE Corrosion Engineer's Reference Book, 3rd Ed.;
R. Baboian (Editor).

4.1.2 Specificity of Galvanic Series

There is an important caveat to note when referring to a galvanic series. A given galvanic series is *not* totally valid for every environment and temperature. Sea water 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 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 case example for this warning. This metal is considerably more active than steel in the galvanic series of Table 1 and should sacrificially protect steel. However, elevating the temperature about 180°F, such as in a domestic hot water tank, or introducing nitrates, bicarbonates, or carbonates can cause the potential of zinc to become nobler than that of steel.[5] When this happens, the steel will sacrificially protect zinc.

Table 1 is a typical galvanic series tabulation. Like most galvanic series, it was experimentally developed for typical sea water at a given temperature, flow rate, and other specific conditions.

4.1.3 Why Some Alloys Are Listed Twice

Another peculiarity in this galvanic series is that some alloys that form a passive film are shown in two locations with "passive" and "active" indicated next to the alloy. As long as the alloy has not begun to corrode, it will have a more noble potential; if corrosion initiates (e.g., pitting), a more anodic potential will develop. Thus a stainless steel that may resist corrosion in moving sea water will display a passive potential under that condition and will be in a more noble position in the galvanic series. However, if flow stops and that stainless steel begins to pit, it will demonstrate an active potential and its position in the galvanic series above will change. Once the alloy has become active, it *may not* repassivate and regain its more noble potential.

4.1.4 Reference Electrodes

To place the members of a galvanic series in order, researchers need a stable reference point. A standard reference electrode or cell provides this baseline. The standard hydrogen electrode is the primary reference cell to which all others are compared, however, it can be difficult to use, not very rugged, and is strictly a laboratory device. Reference cells for field work 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 still 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 most commonly used for soil or fresh water testing. When salt water is involved, a silver/silver chloride reference cell may be employed instead. In addition, zinc, normally in a chemical backfill, is sometimes used as a reference particularly when there is a need for a permanent, in-place reference. The voltage difference between a reference electrode and a metal or alloy is termed the metal potential, or sometimes the structure-to-electrolyte potential (e.g., pipe-to-soil potential).

Figure 2. A steel fastener holding a stainless steel ladder demonstrates undesirable anode (fastener) to cathode (ladder) area ratio.

4.1.5 Minimizing Galvanic Corrosion

One can eliminate or minimize galvanic corrosion in the design process. The following design principles will help accomplish this:

a) Avoid immersing or burying metals and alloys that are electrically continuous if they are widely separated galvanically. Note, however, that galvanic corrosion will not occur in a dry condition.

b) For buried or immersed applications, select metal and allow combinations from groups as close together as possible in the galvanic series if they must be connected (e.g., stainless steels with stainless steels; copper alloys with copper alloys, etc.). A minimal voltage driving force will produce minimal corrosion.

c) Electrically isolate different metals or alloys from one another in an electrolyte, especially if they are far apart in the galvanic series. Without electrical contact, current will not flow and galvanic corrosion will not occur.

d) Avoid combinations where the area of the more anodic metal is relatively small compared with the area of the more anodic metal (e.g., steel bolts fastening a stainless steel ladder in a sump – rapid corrosion of the bolts). A large anode to cathode area ratio will tend to spread corrosion over a wide area, minimizing the depth of corrosion penetration. A small anode to cathode area ratio will remove much more metal from a small area, intensifying the depth of penetration. Figure 2 demonstrates this principle.

e) Apply a dielectric coating to the more cathodic or noble metal, not just the active one that you expect to corrode. Since coating tend to 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.

f) 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.

g) Consider using cathodic protection to control galvanic attack.

Note that dissimilar metal corrosion can only occur if:

- Both metals are in 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 the like.

4.1.6 Electrical Isolation

There are basically two ways to electrically isolate parts. First, do not connect them together, either directly or through a separate device (e.g., wire). Secondly, if they must be mechanically connected together, install electrical isolating materials at their juncture to prevent current flow. Electrical isolation can prevent a portion of a structure from sacrificing itself in a galvanic couple. It can also isolate a structure being cathodically protected from others that one does not intend to protect; additional metal to protect means an added drain on a cathodic protection system.

NACE SP 0286 describes the equipment and principles for electrical isolation of cathodically-protected pipelines.[6] This specialized equipment includes flange isolation kits (incorporate an isolating gasket, isolating washers, and bolt sleeve isolators), monolithic isolation units for weld applications, and isolating unions for threaded applications. Isolation materials, especially buried or immersed, can absorb moisture, which will reduce their electrical resistance. As a minimum, coatings must be applied to resist moisture absorption. Thick coating systems such as wax tapes have been used in some Reclamation buried applications. 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.

A typical example of a situation where isolation would be useful is shown in Figure 3. Figures 3A and 3B show an installation subject to severe soil corrosion. In Figure 3A, which shows the conceptual arrangement, the direct connection of dissimilar metals provides an ideal path for the flow of current from the iron to the copper through the soil (electrolyte). The iron in this case is the anodic or sacrificial metal. In Figure 3B, which shows the practical situation that demonstrates the concept, a copper grounding mat is connected directly to the steel pipe, both being in a common electrolyte, the soil. The flow of current in this case is from the steel pipe to the copper grounding mat through the soil. The steel pipe is the anodic, or the sacrificial metal. The condition depicted in Figures 3C and 3D is identical to that shown in Figures 3A and 3B with the exception that the wire connection in Figure 3D has been isolated from the copper grounding mat by the installation of electrical isolation material at a joint. Under this condition, the galvanic component of corrosion has been eliminated, and only corrosion due to the aggressive soil around the pipe takes place. The examples in Figures 3E and 3F are identical to the examples in Figures 3C and 3D except that a sacrificial anode of magnesium has been added to protect the steel pipe from

soil corrosion. Since the magnesium anode is the least noble of the three metals (magnesium, steel, and copper) in the ground (electrolyte), it could have been used even without the electrical isolation. However, without isolation, the copper would have demanded current from the anode in addition to the steel pipe. As a result of using isolation, less anode material is required for this application.
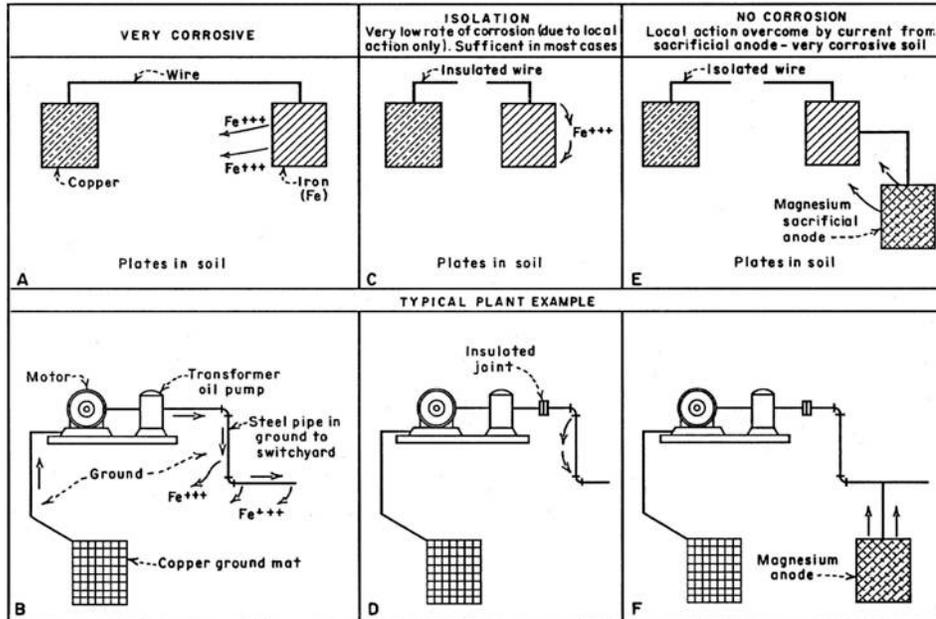
Figure 3. The use of isolating joints to prevent galvanic corrosion.

In some instances, there may be a need for alternating current (AC) grounding that conflicts with the need for electrical isolation. For instance, if in Figure 3 had there been some AC-induced current on the pipeline or some requirement that the pipe be grounded against AC or fault currents, then an isolation device would have prevented this safety feature. Direct current (DC) decoupling devices provide an alternate solution in such cases. These devices block the flow of DC current while allowing the flow of AC. In this instance, placing a DC decoupling device between the motor and the ground mat instead of a flange isolation kit, or across the isolated flange, would block the draining of cathodic protection current while allowing any AC pick up by the pipeline to drain to the grounding mat. DC decouplers can allow the passage of steady-state AC, AC fault currents, and even lightning currents. Solid state DC decouplers are more popular these days, displacing polarization cells that were formerly used for a similar purpose.

4.2   Concentration Cell Corrosion

Connecting different metals or alloys is not the only way to develop an electrochemical voltage difference. The same metal in two different environments will develop differing potentials. Thus, if an immersed steel structure extends from a quiet region of water into a region that is being aerated, a

potential or voltage difference will develop between the two regions. A similar effect occurs when buried pipe passes through different soils; potential differences develop at different points on the pipe. These differing potentials can accelerate corrosion at the more anodic points. A common concentration cell effect involves iron or steel partially encased in cementitious material like concrete or mortar and partially in soil.

4.2.1 Corrosion in Cementitious Materials and the pH Cell

Concrete, mortar, and other cementitious materials, though rigid, are porous and will retain moisture. As it would in soil, this moisture will have dissolved materials in it and constitutes and electrolyte. The chemistry of cementitious electrolytes, however, can be quite different from the typical soil environment. In particular, the type and quantity of alkalies in cementitious materials often produce an elevated pH that would be quite unusual for a soil. The excess of calcium hydroxide in the cement is largely responsible for this. Calcium hydroxide has a saturated pH of 12.5 at 77°F (25°C).[7]

The alkalinity of cementitious materials has two major impacts on iron and steel corrosion. First, embedded iron and steel can undergo passivation at high pH, stifling the corrosion process. This is commonly observed in concrete, which has a typical pH around 12.5. Secondly, carbonic acid or other environmental acids dissolved in groundwater will react with the alkalies in the cementitious material. This reaction neutralizes their acidity so that they are no longer corrosive. Unfortunately, this neutralization can slowly consume the alkalinity of the cementitious material, eventually destroying the passivity of encased iron and steel, especially if the cementitious covering is shallow.

Carbon dioxide, which forms carbonic acid in water, can react with the calcium hydroxide to form calcium carbonate, which has an equilibrium pH of 9.4 at 77°F (25°C).[7] This process is called carbonation, and the resulting pH is too low to develop and maintain passivation on iron or steel. The thicker and less porous the layer of cementitious material over the iron or steel, and the more buffering capability it contains, the longer it is able to neutralize acids and maintain a low corrosion rate.

The electrochemical potential developed by steel or iron encased in high pH concrete or mortar can be similar to that typically developed by copper in soil.[8] Since Table 1 above shows that a galvanic couple of copper and steel should corrode the steel, a similar effect might be expected from coupling steel in concrete to steel in water or soil. This is in fact observed when encased ferrous metal leaves concrete and enters soil or water; the metal outside the concrete suffers accelerated corrosion. This particular type of concentration cell has been termed a pH cell. Exposed metal immediately outside the concrete encasement is especially vulnerable since the electrolyte resistance path between that area and encased metal is least.

4.2.2 Minimizing pH Cell Corrosion

A concentration cell such as a pH cell resembles a galvanic couple in a number of ways, and one can also deal with either in a similar fashion. As in the case of galvanic corrosion, the more exposed cathodic metal there is in a concentration cell (metal in the cementitious material in this case), the worse the concentration cell effect is expected to be. Hence coatings can be helpful. Isolating anodic areas from cathodic areas can eliminate a concentration cell or a galvanic couple. Cathodic protection can also control pH cell and other concentration cell corrosion.

While cathodic protection can be employed without isolating the encased metal from that in the soil, the encased metal may needlessly drain a considerable amount or current. Coating the encased metal will minimize the cathode to anode area ration and reduce cathodic protection current requirements. Isolation joints and measures previously described to control galvanic couples are also often useful in dealing with concentration cells like pH cells. Isolating within the cementitious material can minimize the amount of coupled metal within the concrete that will draw CP current; but subsequent testing and repair of the isolation joint will be difficult. Isolating at or just outside the encasement eliminates these problems, but may leave a stub projecting from the concrete to the point of isolation. This stub may still suffer pH cell corrosion at any holidays in the coating, and the isolating material may absorb moisture and deteriorate. A thick coating system such as a wax filler and wax tape has sometimes been used to eliminate such holidays and protect the isolating material. Isolating within a vault has the benefit of minimizing the amount of encased metal needing to be cathodically protected while helping to keep the isolating materials dry and readily available for testing or replacement if needed.

pH cell corrosion may also occur where a structure rises from concrete into the air. This is particularly a concern when there is puddling at that location due to condensation, precipitation, etc. Sloping concrete or mortar up to a vertical ferrous structure may help prevent such puddling. Coating the concrete as well as the metal around the area where the metal emerges may be helpful, especially if a layer of carbonated concrete is not yet present. Carbonation of concrete at the air interface can eliminate the passivating ability of that concrete. As a result, bare metal just below the surface may start to rust. Coating the metal for a distance into the concrete when that metal is first installed may able be helpful.

4.3   Stray Current Corrosion

If current flowing through an electrolyte encounters a ferrous structure not electrically connected to its source, it may still flow onto that structure. This is because metals are low resistance paths as compared to electrolytes, and current prefers paths of low resistance. This current has to flow onto a structure by drawing electrons from the metal; current, by convention is the flow of positive

charge and is opposite from the flow of electrons or negative charge. To draw electrons out of the metal, the current must produce a reduction reaction in the electrolyte at the point of entry. The reduction reaction is normally hydrogen evolution or oxygen reduction in aqueous electrolytes. Because the metallic structure in question is not connected to the original source of the current, the current has to re-enter the electrolyte in order to complete its path. To re-enter the electrolyte, the current must produce an oxidation reaction at the point. This oxidation reaction will be corrosion of the ferrous structure, which releases positive metal ions into the electrolyte and the electrons needed by the reduction reaction where the current enters. This type of corrosion is called stray current corrosion. Note that stray current corrosion is not a function of the corrosivity of the environment. A metal can be made to corrode by this method even in a benign environment.

Cathodic protection systems on foreign structures are a common source of DC stray current corrosion. However, DC stray currents may also emanate from high-voltage DC systems (when operating in an emergency monopolar mode for maintenance – may impact at a great distance), from electrical substations or from street railway systems.

High-voltage AC may also cause stray current corrosion. This sometimes occurs when a three-phase overhead transmission system parallels a buried metallic pipeline. Corrosion, if it is to occur, is normally in the area where the transmission line and the pipeline paths eventually diverge. Because of canceling effects, a buried high-voltage cable containing the three conductors is very unlikely to cause high-voltage AC stray current corrosion. Fault currents, as from lightning strikes, are also considered under the topic of stray AC currents.

Telluric currents resulting from sun spot activity are a special case of stray current corrosion. These currents cause problems especially nearer northern and southern regions of the globe and near the equator. Solar activity associated with telluric currents is approximately on an 11-year cycle.[9]

4.3.1 Detection of Stray Currents

Reclamation usually determines the presence of stray current corrosion during potential surveys on structures. Where current gets onto a pipeline, the potential is typically more protective (i.e., more negative potential). Where current jumps off the pipeline, there is usually a potential shift in the positive direction. When uncovering a structure such as a pipe that has been damaged due to stray current effects, the damage will typically be localized – a large, deep pit, for example.

DC stray current corrosion will more likely be a problem if:

- The structure passes near the anode bed of a foreign structure, placing it in the anode voltage gradient field.

- The structure crosses or approaches a cathodically protected foreign structure.
- The foreign structure is under impressed current cathodic protection.

Intermittent DC stray current, as from a rail system, may require recording instruments operating over many hours or days to detect an occurrence.

High-voltage AC stray current corrosion will usually occur where either an pipeline or the overhead line diverge from their parallel paths.

Request the services of a corrosion specialist when stray current corrosion is suspected.

5.0 Indicators of Corrosive Environments

After the fact, determining that one has a corrosion problem is relatively simple. The challenge is to determine ahead of time that there is an issue in order to take timely measures. The most reliable method is to perform site corrosion testing to determine the corrosion susceptibility of a metal in the environment; this may include field corrosion coupon testing, chemical analysis of the environment, and resistivity testing. However, project requirements may not allow sufficient time for an exhaustive study.

5.1   Soil Corrosivity

High soil corrosivity and low soil resistivity, an electrical property of materials expressed in ohm-cm, generally coincide. This is because low soil resistivity typically results from high levels of dissolved salts in the electrolyte. When an electrolyte contains much dissolved salt, its low resistivity and resistance allow corrosion cells to readily express themselves, even at long distances. However, environments that have a low resistivity because of other chemical constituents may not be as corrosive. Concrete, for instance, can have a very low resistivity due to its high alkalinity; however, this high alkalinity allows embedded steel to passivate in concrete. Hence, steel rebar in a low resistivity concrete usually suffers very little corrosion.

When experience with corrosion in a specific soil location is not available, Reclamation routinely relies on a soil resistivity assessment. The specific method that Reclamation uses is described in Technical Memorandum No. MERL-05-19 (*The 10% Soil Resistivity Method*).[10] This technique is specific to Reclamation and is intended to be used along with Technical Memorandum No.8140-CC-

2004-1 (*Corrosion Considerations for Buried Metallic Water Pipe*).[11] The first document uses raw field resistance data that has been computer processed using an electrical resistivity imaging (ERI) inversion routine; this provides the geo-electric structure along the pipeline alignment. A statistical treatment is then applied to the layer resistivity readings along the run of pipe; the end result is termed the 10 percent probability. Resistivities along a pipeline will typically vary randomly by 3 or 4 orders of magnitude from location to location along the alignment. **[Do not use the Barnes Layer Method of determining layer soil resistivities unless a TSC geophysicist or corrosion professional recommends doing so in a particular situation.]** The second document recommends minimum corrosion mitigation measures based on the 10 percent probabilities determined in the first document. A corrosion specialist may also employ experience with similar materials in the same or similar soil, if available. At times, additional data (e.g., chloride or sulfate concentration, etc.) may be useful.

Soil resistivity readings along the structure and at anode locations are also essential in designing cathodic protection systems. These resistivities are determined separate from the 10 percent probability value.

[To avoid data acquisition methods unacceptable to Reclamation (e.g., Barnes Layer) and arrive at suitable soil resistivity numbers, coordinate with a TSC corrosion professional or geophysicist when such data is needed.]

5.2   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. For instance, deep waters may be less aerated than those near the surface; variations may also be present if a location in the water is being aerated or if there is an outfall nearby.

Indicators such as the Langelier Index have sometimes been used to help assess water corrosivity. The belief was that the tendency of water to form scale on the surface of a metal indicated that it would not be corrosive. However, this is not always true, and the use of such indices for natural waters in not reliable.

Analysis of pH, chloride content, and resistivity (conductivity) provide an idea as to the corrosivity of waters. Corrosion significantly accelerates at low pH. While pH 4 and below may be considered quite corrosive, even somewhat less acidic pH can be of concern. Chloride levels in the 10s of parts per million (ppm) raise alarm, and 100 ppm chlorides and higher can be expected to be significantly damaging. Conductivity readings are usually more readily obtained than resistivity readings in the case of water. Conductivity is mathematically the inverse of resistivity and is usually measured in micro-siemens per meter or per centimeter ($1\mu S/cm = 1/1,000,000$ Ω-cm). Technical Memorandums Nos. MERL-05-19 and 8140-CC-2004-1 are not intended for use in immersed

applications, and no similar documents are available at this writing. However, corrosivity in waters generally parallels conductivity. The more conductive waters are generally more corrosive.

Due to the geometric variety of anodes that might be used for protecting immersed structures, this document will not provide basic design algorithms for that situation. **[Seek the assistance of a TSC corrosion specialist or similar when assessing water corrosivity and designing cathodic protection systems for immersed structures.]** As in soil, reliable resistivity (conductivity) readings are essential when designing a cathodic protection system for water.

6.0 Protective Coatings

6.1 Coating Variety

Protective coatings are a common corrosion mitigation measure. They are often one of the few effective and economical protection measures against atmospheric corrosion. They include galvanizing, mortar, and organic coating systems.

Galvanizing, a zinc coating, isolates the ferrous metal beneath from exposure to atmospheric corrosives. Furthermore, during periods of wetness (e.g., rain or dew) it can act galvanically (see galvanic table above) to protect substrate metal at scratches and nicks in the galvanizing. Galvanizing used in atmospheric exposures can often provide 30 to 50 years of service life. Performance in immersion or buried service often does not provide nearly as much service life and is quite variable. Galvanizing may even passivate in some waters, causing it to accelerate corrosion of exposed ferrous metal.

Mortar coatings can help the ferrous metal beneath to passivate. However, such coatings are somewhat fragile and thin. Damage at a mortar coating can lead to pH cell corrosion at the metal exposed to soil. Problem areas for mortar-coated pipe are often found at girth weld seams. Such welds are performed in the field after installation, and the mortar coating is repaired at that time. Field repairs may not be as effective as shop mortar coatings.

Organic coatings isolate the ferrous metal from a corrosive environment. Unlike galvanizing and mortar coatings, organic coatings are commonly electrically isolating barriers and are often called bonded dielectric coatings. If the barrier is intact, corrosion cannot progress since the metal does not see the corrosive electrolyte. However, bonded dielectric coatings, especially thin coatings (e.g., less than 0.040 in.), are usually not perfect. They typically have pores and defects as applied and may be damaged during installation or in service; stray currents

such as lightning arc strikes can create major defects in them. They also deteriorate at varying rates with time. Defects in a coating are called holidays.

Buried or immersed structures are often protected with a combination of a bonded dielectric coating and cathodic protection.

6.2   Selection and Application of Coatings

Coating technology is a specialized field and is ever evolving. Not only are manufacturers constantly researching and developing coatings with improved characteristics, but state and federal environmental regulations have outlawed or severely restricted the use of some older coating systems. As a result, coatings that were formerly popular have in many cases been replaced with newer coatings that are more environmentally friendly. Among coatings generally no longer in use within Reclamation are red lead and chromate primers, vinyl paint, and a number of high-VOC coating systems. Some coatings allowed in one jurisdiction may not be allowed in others.

Factors critical to coating performance include:

- Surface cleaning and preparation prior to coating.
- The environmental conditions (e.g., temperature and humidity) when applying the coating.
- The blending and curing of a specific coating.

Short-cuts have ruined many a coating that otherwise would have provided many years of service. Coating manufacturers are well aware of this and usually provide detailed instructions for coating applications. Employing trained and experienced personnel helps ensure good coating performance. Having an inspector separate from the application vendor helps as well.

Given the importance of a good coating system, the significance associated with the details of its application, and the developments that are ongoing, site personnel are strongly advised to work with a TSC coatings specialist for proper selection and application.

6.3   Coatings in Conjunction with Cathodic Protection

Coatings and cathodic protection complement each other. Where possible, one can use them in combination to achieve the optimal economy and protection. The coating protects everywhere but at holidays. This minimizes the amount of current a cathodic protection system must provide and distributes that current further and more evenly. With undercutting of the coating by corrosion mitigated, a coating can last longer.

However, the coating system must be compatible with cathodic protection and the level of cathodic protection must not be excessive. For instance, the normal elevated pH produced on a structure by cathodic protection can damage zinc-rich primers, and these primers may also lead to inaccurate corrosion monitoring readings. **[Zinc-rich primers must therefore be avoided on cathodically protected structures.]** However, even normally compatible coatings may disband due to excessive levels of cathodic protection. Corrosion can then take place at the disbondments where cathodic protection currents may not reach. As described later, Reclamation employs protection criteria that limit the polarized potential of a protected structure to prevent cathodic disbondment.

7.0 Cathodic Protection Design Considerations

Cathodic protection uses direct current to mitigate metal corrosion in an electrolyte. Cathodic protection makes the protected metal surface the cathode of a galvanic or electrolytic cell. The passage of current then causes the electrolyte surrounding a protected structure to become more basic (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 an economic consideration. Cathodic protection usually in conjunction with protective coatings, can allow a long service life equivalent to that from using more expensive alloys. Cathodic protection, however, may not be practical for some structures, such as the interior surfaces of small diameter pipelines. There may be instances when other corrosion mitigation measures are preferable.

Cathodic protection designs are customized for each application. Furthermore, they require specialized knowledge and training. Although this document will describe methods for using cathodic protection to protect the exterior of buried structures, **[site personnel are strongly advised to get a corrosion professional experienced in cathodic protection involved before attempting even simple installations.]** Such personnel include Cathodic Protection Specialists certified by NACE International and are available at the Materials Engineering Research Laboratory (MERL) of the Reclamation TSC.

7.1   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.
- Shunt resistors used for measuring current by application of Ohm's Law.
- Variable resistors used to adjust current throughout.
- A high-impedance (10 megohm minimum) portable voltmeter.
- A reference cell – usually a copper/copper sulfate electrode (CSE).
- Wire leads.

This document will explain how to properly use this equipment to accomplish common cathodic protection tasks.

7.2   Cathodic Protection Criteria

NACE International is recognized worldwide as a premier professional society and standards setting organization concerned with corrosion control. NACE has a number of industry standards dealing with cathodic protection. These include:

- SP 0100, *Cathodic Protection to Control External Corrosion of Concrete Pressure Pipelines and Mortar-Coated Steel Pipelines for Water and Wastewater Service.*[12]
- SP 0169, *Control of External Corrosion on Underground or Submerged Metallic Piping Systems.*[13]
- RP 0193, *External Cathodic Protection of On-Grade Carbon Steel Storage Tank Bottoms.*[14]
- RP 0196, *Galvanic Anode Cathodic Protection of Internal Submerged Surfaces of Steel Water Storage Tanks.*[15]
- RP 0285, *Corrosion Control of Underground Storage Tank Systems by Cathodic Protection.*[16]
- RP 0290, *Impressed Current Cathodic Protection of Reinforcing Steel in Atmospherically Exposed Concrete Structures.*[17]
- RP 0388, *Impressed Current Cathodic Protection of Internal Submerbged Surfaces of Carbon Steel Water Storage Tanks.*[18]

These standards generally include either of two main criteria for protection of ferrous metal that Reclamation usually employs for ensuring effective cathodic protection, especially when the protected structure cannot be observed:

- A *polarized* potential equal to or more negative than -0.850V with respect to a standard saturated copper/copper sulfate reference cell.
- 0.100V of polarization more negative than the native potential of the protected structure.

These criteria were derived semi-empirically and have served the industry well for many years. Note that these values involve determining polarized electrochemical potential values (i.e., with extraneous voltage drop errors eliminated). IR drop, a major voltage drop error, results when measuring voltage in a resistive soil or water medium with current flowing.

Special instances may require adjustments to the usual criteria. For instance, microbial-induced corrosion calls for a minimum -0.950V$_{(CSE)}$ *polarized* potential criterion instead of the usual -0.850V$_{(CSE)}$. With some higher strength steels, the 0.100V of polarization may not be usable as it may subject a structure to stress corrosion cracking. Too negative a potential may also cause either hydrogen embrittlement or high pH corrosion of some metals.

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

An effective cathodic protection design proved sufficient current per area of exposed metal to induce the stated range of electrochemical potential values. These current densities may be based on experience or actual testing.

7.3   Structure Current Requirements

By supplying electrons to a corroding structure, one can induce reduction reactions to take place, stifling corrosion, an oxidation reaction. The polarized potential of the structure will then reflect this corrosion mitigation. How much current is needed to supply the correct amount of electrons and how to supply it become the issues.

7.3.1   Current Requirements per Exposed Area

The amount of current needed to protect a structure depends on two main factors:

- The amount of exposed surface area of the metal.
- The depolarizing capabilities of the environment.

This is fairly intuitive. The more exposed metal in an environment, the more corrosion (oxidation) will be taking place. The more readily oxidizers can reach the surface of a metal and reaction products can be removed, the more rapidly exposed metal corrodes. Therefore, current requirements for cathodic protection are normally stated in units of current per area (e.g., mA/ft^2), and they can vary significantly with conditions. Table 2 is a partial list of typical current requirement values for exposed steel.[19]

For most soils, a current density between 1 and 3 mA/ft^2 of bare steel is usually effective. Water tends to require more current, in part due to the depolarizing action of eddies and flow. Obviously, if a structure is already in the soil, performing a current requirement test will provide a more accurate estimate of the current needed at that time. One can then augment this amount to compensate for additional coating deterioration in the future. It is a relatively simple matter to reduce the current on a cathodic protection system that has some excess capacity; it is often not possible to increase the current on an undersized system.

Pipe is usually considered a smooth cylinder. Determining its surface area in that instance is then a simple exercise in geometry. However, in some instances a surface may be textured, uneven, or otherwise rough. Centrifugally cast ductile iron pipe is a good example; it has a bumpy textured surface, unlike smooth sand cast ductile iron fittings. A 1 foot by 1 foot textured surface may effectively expose more than a square foot of metal. A rough or textured surface may also be more difficult to coat as compared to a smooth surface. When faced with such surfaces, a cathodic protection designer may need to make more conservative assumptions than those suggested in this document. Examples in this document assume a smooth surface condition unless otherwise noted.

Environment	Current Requirement (mA/ft^2)
Dry, well aerated soil	0.4 – 1.5
Well-aerated neutral soil	2 – 3
Wet soil, moderate/severe conditions	2.5 – 6
Highly acidic soil	5 – 15
Soil supporting active sulfate reducing bacteria	Up to 42
Dry concrete	0.5 – 1.5
Stationary fresh water	5
Moving fresh water	5 – 6
Highly turbulent fresh water containing dissolved oxygen	5 – 15

Table 2. Typical current requirements for bare steel.

7.3.2 Exposed Metal

On a cathodically protected coated structure, most of the current flows to the metal exposed at pinholes, scratches, and other defects in the coating. There will be some minor current flow through the coating itself. However, since dielectric

coatings normally have very high resistivities, the electrical current path through the coating can usually be ignored, unless there is extensive coated surface area.

A newly installed structure with an excellent coating needs very little current for cathodic protection. However, coatings deteriorate over time due to soil stresses and other such factors. In order to supply sufficient current over the long term, Reclamation cathodic protection designs anticipate this deterioration. A design that assumes 2 percent exposed metal is typical; however, in some instances as little as a 1 percent exposure and as much as 5 percent exposure have been assumed. The exact number depends upon how conservative the designer wants to be. The amount of effectively coated surface is termed the coating efficiency – 2 percent exposed metal is equivalent to a 98 percent efficiency.

To provide an example, assume a designer wanted to protect 100 feet (l) of newly coated 2-foot diameter (d) standard wall pipe being buried in a wet, moderately corrosive soil. Based on past experience, the designer feels that the cathodic protection system should protect for a 98 percent coating efficiency. Based on Table 2, the designer should need about 2.5 mA/ft^2 of exposed metal. Therefore, the cathodic protection system should provide as a minimum:

(Total pipe surface area) x (2 percent exposed metal) x (2.5 mA/ft^2 of exposed metal) = amount of current

or

$$(\pi dl) \times (0.02) \times \left(\frac{2.5mA}{ft^2}\right) = (\pi \times 2ft \times 100ft) \times (0.02) \times \left(\frac{2.5mA}{ft^2}\right)$$
$$= 31.4\ mA$$

7.4 Cathodic Protection System Capacity

Ohm's Law relates the voltage or driving force and the electrical resistance of a DC circuit to how much current will flow. It may be stated as follows, where E is the voltage driving force, R is the circuit resistance in ohms, and I is the amperage flowing:

$$E/R = I$$

or

$$R = E/I$$

or

$$E = IR$$

Having determined the minimum amount of current that a cathodic protection system must provide, a designer can determine the circuit resistance that must be achieved with a galvanic anode system.

Galvanic anode literature from suppliers normally provides the open circuit potential of their anode materials. The amount of driving voltage in a working galvanic circuit is then the difference in potentials between the anode and the minimum polarized potential of the protected structure (e.g., -0.850V$_{(CSE)}$). Designers sometimes employ the anode open circuit potential when taking this difference. A more conservative approach is to account for polarization of the anode by reducing that potential by 0.05V to 0.10V. For iron or steel, the driving voltage differences with various types of anodes in soil or water are approximate as given in Table 3.

Anode Type	Typical Anode Open Circuit Potential (V$_{(CSE)}$)	Conservative Driving Voltage Between Anode and Protected Iron or Steel (V)
High potential magnesium	1.75	0.85
Standard potential magnesium	1.55	0.65
Zinc	1.10	0.20

Table 3. Properties of magnesium and zinc anodes. Note: 50 mV of anode polarization had been included in the driving voltages.

Thus, for the pipe example above, the designer would need to achieve a circuit resistance of no more than:

$$R = 0.85V \div 0.031A = 27.4\Omega$$

with high potential magnesium anodes, or:

$$R = 0.65V \div 0.031A = 21.0\Omega$$

with standard potential magnesium anodes, or:

$$R = 0.20V \div 0.031A = 6.45\Omega$$

with zinc anodes.

The driving voltage of an impressed current cathodic protection system, which uses an external source of DC current, can be set as needed. However, a high circuit resistance will require more power from a rectifier. A low circuit resistance is desirable since it is more economical. An impressed current system

also normally needs an additional 2V simply to counteract the back-voltage from the anode and carbonaceous backfill used with impressed current anodes (see Section 8 below).

Thus, designing a cathodic protection system with minimum circuit resistance can determine whether a galvanic anode system can be used; and circuit resistance is key to designing an impressed current system that will perform economically.

7.4.1 Cathodic Protection Circuit Resistance

The electrical resistance of a cathodic protection circuit is the sum of:

- Anode grounding resistance.
- Structure grounding resistance.
- Linear structure resistance and bond resistances between electrically connected parts of a structure.
- Resistance of the wiring connecting the anode and structure (usually minor constituents of resistance).
- Other resistances, such as contact resistances (e.g., where cables are mechanically connected) and fringing resistances (e.g., where cables are thermite bonded to structure); however, if properly accomplished, these are normally so minor as to be negligible.

7.4.2 Anode Grounding Resistance

Anodes come in a variety of shapes, sizes, and materials. They include discs, coated wires, and conductive cables. The most popular types, especially for soil service, typically resemble long cylinders. These cylinders may be installed vertically in augured holes or laid down horizontally in a trench. To estimate resistance to ground, a number of equations have been developed that consider:

- The orientation of an anode (horizontal or vertical).
- Anode dimensions
- Resistivity of the environment.
- The number of anodes and their spacing if several are connected together in a common anode bed.

Some important aspects of anode grounding resistance are as follow:

- Anode grounding resistance is directly proportional to soil or water resistivity. For example, grounding resistance of an anode doubles if the environment resistivity doubles.

- Grounding resistance is often almost inversely proportional to anode length; the longer the anode, the lower the resistance.

- Anode diameter is also inversely proportional to grounding resistance; however, it is usually less significant than the anode length.

- Mounting an anode on a dielectric surface (e.g., a coated surface) instead of remotely can double its grounding resistance. Installing an anode close to such a structure may also increase its resistance, but to a lesser degree.

- Incorporating multiple anodes into a single protective anode bed can significantly reduce overall anode bed grounding resistance. This effect results from parallel grounding resistances providing multiple current paths, which is similar to providing multiple parallel resistors. However, unlike parallel resistors, parallel anodes in close proximity mutually interfere with each other. As a result, the overall resistance of multiple anodes is sometimes greater than would be anticipated of multiple resistors.

Designing an effective anode bed can therefore be complex, requiring a thorough understanding of cathodic protection. A thorough treatment of the subject is beyond the scope of this document. However, for sites wishing to undertake limited minor designs and installations on their own, simplified algorithms will be provided here for a commonly-used magnesium anode (either high-potential or standard potential) size and for a commonly used zinc anode size. **[These algorithms must only be used under the following circumstances:**

- **When protecting a mild steel structure in soil; different anodes of widely varying sizes would likely be used in water.**

- **Using a 32-pound, prepackaged (see below under Galvanic Anodes) magnesium anodes, having packaged dimensions 28 in. long and 8 in. in diameter. The bare magnesium material inside the package will have an effective diameter of 7.16 in. and a length of 19.875 in. (approximately 3.11 ft^2 of surface area).**

- **Alternately when the driving voltage requirement is very low, using prepackaged 15-pound zinc type II anodes, having packages dimensions 38 in. long and 5 in. in diameter. The bare zinc material inside the package will have an effective diameter of 1.78 in. and a length of 30 in. (approximately 1.17 ft^2 of surface area).**

- **Burying anode(s) either vertically or horizontally.**

- **Burying anodes at least as deep as the spring line of a pipe or at a similar orientation to other buried protected structures, but not less than 3 feet below ground surface to the nearest point on an anode.**

- **Anodes not closer than one anode length from a structure.**

- **The maximum number of anodes employed will be six (6).**

- **Anodes in a multiple anode bed being spaced 16 feet apart.**

- **When calculations based on the driving voltage difference and overall circuit resistance show that** *galvanic anode cathodic protection* **will provide the needed current.**

Note that any outer plastic or other dielectric packaging around the inner water permeable packaging must be removed before burying an anode!]

For anodes under these circumstances, site personnel will still need to obtain the soil resistivity (ρ) in ohm-cm at the location of the anode bed. They may then conservatively estimate the anode bed grounding resistance from Table 4 below. Hence, a single magnesium anode in 2,000 ohm-cm soil would have a grounding resistance of:

$$R_{1,Mg} = (0.00467 \text{cm}^{-1})(2000 \text{ ohm-cm}) = 9.34 \text{ ohm}$$

While a single zinc anode in the same soil would have a grounding resistance of:

$$R_{1,Zn} = (0.00479 \text{cm}^{-1})(2000 \text{ ohm-cm}) = 9.58 \text{ ohm}$$

[For any other installation, the site must hire a NACE-certified Cathodic Protection Specialist, or a Corrosion Specialist with a strong background in cathodic protection, or a professional engineer qualified in cathodic protection to provide the design and assist with installation.]

Number of Anodes	Mg Anode Grounding Resistance Equation (Ω)	Zn Anode Grounding Resistance Equation (Ω)
1	0.00467ρ	0.00479ρ
2	0.00242ρ	0.00248ρ
3	0.00170ρ	0.00174ρ
4	0.00132ρ	0.00135ρ
5	0.00109ρ	0.00111ρ
6	0.00093ρ	0.00095ρ

Table 4. Galvanic Anode Grounding Resistances Used for FIST 4-5. Note: ρ is <u>soil</u> resistivity around the pre-packaged anode(s).

7.4.3 Protected Structure Grounding Resistance

One can measure the grounding resistance of an in-place structure such as a coated pipe in the field. This measurement procedure is best left to a corrosion professional and involves:

- Applying a current to the structure.
- Measuring the difference in potential in the area of interest when the current is applied and when it is interrupted. The potential at several locations may need to be considered, especially on longer structures.
- Determining the current in the section of the pipe of interest.
- Applying Ohm's Law.

The designer obviously needs to make electrical contact with the pipe through test stations or the like in order to make this determination. However, if a design is needed for a new section of coated pipe being installed, this technique is not usually practical. Furthermore, the pipe grounding resistance will decrease over time due to coating deterioration.

Studies, as might be expected, have shown that areas of pipe with a superior coating application have greater electrical grounding resistance. The exact resistance, however, varies with the soil resistivity, since more current will leak into a low-resistivity soil. By taking the resistance of a coated pipe, multiplying that number by the area, and normalizing the result to 1000 Ω-cm soil, corrosion professionals have developed characteristic numbers for coated pipe of varying coating quality. These quantities are termed the average specific coating resistance (r'_c). The inverse is called the average specific coating conductance (g'). Given a coating efficiency, one can review past findings and get a general idea as to what the average specific coating conductance is for a pipe in question. With this quantity, knowledge of the soil resistivity around the pipe in question, and knowing the surface area of the pipe (A_s), one can estimate the grounding resistance of that structure. The pipe grounding resistance may be calculated by this method as:

$$R_{pipe} = \frac{r'_c}{A_s} \times \frac{\rho}{1000\Omega - cm}$$

A typical table of specific coating resistances is provided in Table 5 below.[20]

Hence, if the 100 feet of 2-foot diameter pipe noted above is in 2,000 ohm-cm soil and a cathodic protection system is to be designed to protect it even when there is 2 percent coating damage (98 percent coating efficiency), then the pipe grounding resistance for design purposed could be estimated as:

$$R_{pipe} = \{(538\Omega - ft^2)/[(\pi) \times (2ft) \times (100ft)]\}$$
$$\times (2000\Omega - cm \div 1000\Omega - cm) = 1.71\Omega$$

Coating Efficiency (%)	Estimated Percent Exposed Metal (%)	Estimated Average Specific Coating Resistance ($r_c^{'}$) in 1000 Ω-cm Soil (Ω-ft^2)
99	1	1076
98	2	538
97	3	359
96	4	269
95	5	229
90	10	127
80	20	63.3

Table 5. Estimated Specific Coating Resistances for Pipe Grounding Resistance Calculations.

7.4.4 Wiring and Structure Linear Resistance

A number of sources provide resistances for cable of various gauges. Wire or cable used in cathodic protection is normally stranded copper. Common cable sizes used within Reclamation include:

- Galvanic anode cables – AWG #12 (1.6200 Ω/1000ft).
- Bonding cable between sections of a structure, such as pipeline sections *if they are not welded to one another* – AWG #6 (0.4030 Ω/1000ft) or greater.
- Structure cable leading to a test station or rectifier – AWG #6 (0.4030 Ω/1000ft).
- Test cable leading to a test station – AWG #12 (1.6200 Ω/1000 ft).

Reclamation normally tries to keep the calculated increase in electrical resistance due to joint bonds per 1,000 feet of pipe at or below 150 percent of the electrical resistance of 1,000 continuous feet of pipe. The percent increase is calculated as follows:

- Percent increase in electrical resistance = $(1 + R_b/R_p)$ x100.
- R_b = Resistance in ohms of joint bonds per 1,000 feet of pipe.
- R_p = Resistance of 1,000 continuous feet of pipe.
- For metallic cylinder pipe, R_p = 0.22/(weight of steel cylinder per foot), or 0.86/(weight of ductile iron cylinder per foot). For reinforced concrete pipe, estimate the weight of steel per foot and employ the R_p formula for steel pipe, dividing by the weight of steel in the concrete cylinder per foot.

When bonding sections of pipe or other structures, Reclamation employs at least two bonds about 1 foot in length to ensure continuity should one be lost. Larger diameter pipe may require several large bonding cables per section in order to reduce structure linear resistance. **[Bonds must be so located not to damage internal pipe linings, gaskets, or the like when thermite welding.]** Tabs welded onto the pipe before lining application may sometimes be needed for attaching bonds and protecting linings.

If our example welded pipe described above is connected to an anode via 50 feet of #12 cable and 20 feet of #6 cable, then the circuit resistance of the wiring is:

$$R_{cable\ \#12} = 50ft. \times \frac{1.62\Omega}{1000ft} = 0.081\Omega$$

$$R_{cable\ \#6} = 20ft. \times \frac{0.4030\Omega}{1000ft} = 0.008\Omega$$

$$R_{cable} = 0.089\Omega$$

Pipe or similar structure resistance is a function of the material of construction resistivity (ρ), the cross-sectional area of the wall (A), and the length of the current path (l), or:

$$R_{pipe} = \rho l / A$$

The resistivity of steel is approximately 1.344×10^{-5} ohm-cm.

Thus if the 100-foot welded pipe used in this example has a wall thickness of 0.375 in., the resistance between the ends of the pipe is:

$$R_{metal} = \frac{\left[(1.344 \times 10^{-5}\Omega - cm) \times \left(100ft \times 30.5\frac{cm}{ft}\right)\right]}{\left\{[(24\ in.)^2 - (23.625in)^2] \times \frac{\pi}{4} \times 6.45\frac{cm^2}{in^2}\right\}} = 0.000453\Omega$$

[Buried or immersed cable or wiring must have insulation that will resist moisture and deterioration.] Reclamation employs cables with high molecular weight polyethylene (HMWPE) insulation in these instances. HMWPE resists water intrusion and soil abrasion. For *impressed current applications*, anode cable insulation often combines an HMWPE outer insulation with an inner fluropolymer insulation layer (Halar® or Kynar®) to resist damage by chlorine generation at the anode.

[Any metal exposed to electrolyte at a buried or immersed cable connection must be adequately coated.] Galvanic or impressed current anodes should be ordered from the manufacturer with the designated cable (i.e., length and gauge) already attached, and the manufacturer must protect the anode to cable connection

from exposure to the electrolyte. Cathodic protection work normally requires a metallurgical bonding process such as thermite welding (e.g., Cadweld®, ThermOweld®, etc.) to attach leads to a structure. A suitable protective coating, such as Bitumastic 50®, Royston Caps®, or the like is then used to protect any exposed metal.

7.4.5 Installation and Placement of Anodes

A low resistivity soil, such as clay, is usually a good site in which to place anodes. Such soil minimizes anode grounding resistance, optimizing current flow. However, when a protected structure passes through soils of greatly varying resistivity, the anode bed may need to be placed in the higher resistivity soil. If this is not done, too little current may flow to that part of the structure in the high-resistivity region. A cathodic protection designer needs to know both the soil resistivity profile through which the structure passes and the resistivity of the anode bed soil. Resistivity variations are often negligible in immersed applications.

In soil, *galvanic anodes* employ a chemical backfill and *impressed current anodes* use a carbonaceous backfill to reduce the contact resistance between the anode and the surrounding soil. A sacrificial anode chemical backfill typically consists of bentonite clay, gypsum, and sometimes sodium sulfate. Galvanic anodes for soil use are usually ordered prepackaged with the chemical backfill in a cloth bag around the anode, and impressed current anodes for similar use are more often supplied bare. **[Note that any outer impermeable bag (e.g., plastic) must be removed before bedding a prepackaged anode.]** If anodes that are not pre-packaged are used in soil, chemical backfill for galvanic anodes or coke breeze for impressed current anodes must be tamped around the anodes as shown typically in Figure 4 (disregard the dimensions). Earth backfill should be placed over the chemical backfill or coke breeze and well tamped in 6-inch to 1-foot lifts to ensure good contact. **[An installed galvanic anode must not be wetted until there is at least a foot of well-tamped soil over the chemical backfill. If the anode does not already have compacted soil around it, the backfill will expand and may later shrink back from the surrounding soil.]**

Reclamation typically buries anode leads a minimum of 2.5 feet below ground surface, surrounded on all sides by at least 6 inches of sand, and with a warning tape 1 foot above the leads. For added reliability, these leads should be continuous (no splices) until they reach a junction box, test station, or other similar protected point above ground. **[All leads must be installed with slack so as not to apply stress to the connection at the anode or at the structure.] [Once they come above ground, leads must be protected against damage by a conduit, test station pipe, or the like.]** Conduits also serve to protect leads in immersed situations. For immersed situations, PVC conduit will normally resist corrosion better than metal conduit.

Relative to a protected structure, there are two basic placement styles for anodes:

- Closely distributed along a structure.
- Near remote earth.
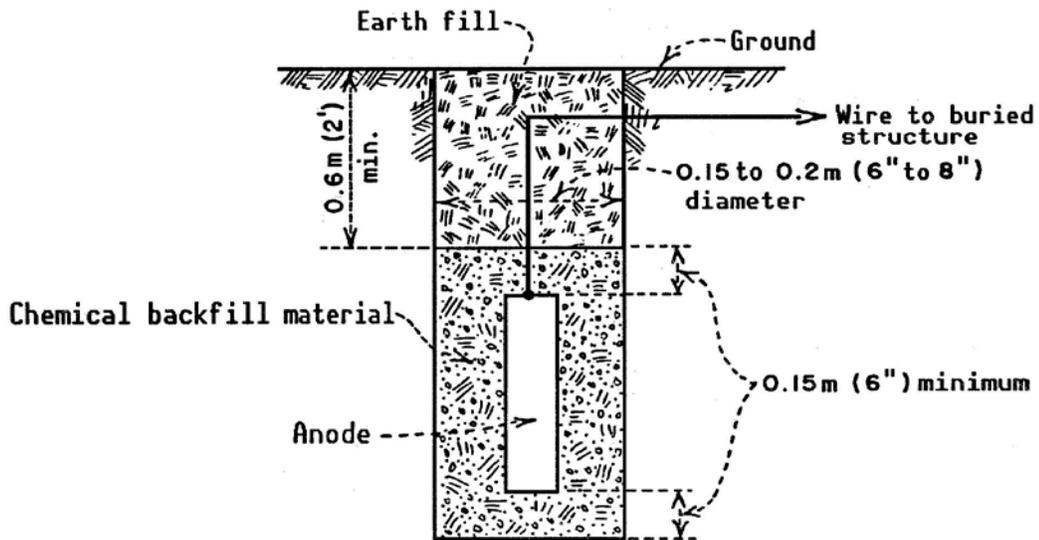
Figure 4. Installation of galvanic anode.

7.4.5.1 Close Distributed Anodes

Closely distributed anodes are either directly mounted on the structure to be protected, or quite close to it. By doing this, the designer places the structure in the strong voltage gradient field of the anodes. As a result, current from the anode has an intense impact, but only on a limited area of structure. Magnesium anodes placed too closely can damage the structure coating; zinc galvanic anodes should not, however, since their driving voltage is sufficiently low. The designer can position multiple anodes so that their voltage gradient fields overlap near their limits.   In this way, the anodes have an additive impact at the overlap so that no location on the protected structure is below the desired level of protection. Closely distributed anodes are sometimes used to protect a "hot spot," a problem area not adequately protected otherwise. Potential testing can be difficult with directly mounted or connected anodes, since it is not possible to take instant-off readings that provide polarized potentials. Design considerations employing close distributed anodes are somewhat different from those for anodes placed near remote earth and will not be covered in any great detail in this document.

Closely distributed anodes not directly on a protected structure may be considered to form approximately a 120 cone of protection. The amount of protection at an intersecting plane perpendicular to the cone is about half that at the center of the circle formed by the intersection. Therefore, when distributing anodes closely about a structure, one must place them so that the cones overlap at their limits,

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additively doubling the protection at that limit and equalizing the protection across the structure.

[Sites wishing to undertake minor close distributed anode designs and installations on their own using the previously described anodes must:

- **Space these anodes 4 feet, 8 inches from the surface of the structure to be protected.**
- **Space these anodes 16 feet from one another.**
- **Place the first and last anodes at the limits of the protected structure.**
- **Perform previously described calculations to confirm that the anode array will provide the needed amount of current.]**

A large, buried pipe, tank, or similar structure may require strings of distributed anodes on each side and at multiple locations around the structure to achieve an even current distribution and adequate cathodic protection everywhere. With anodes spaced 4 feet, 8 inches from a structure, a site may expect any part of a structure 8 feet away from an anode to have about half the protection seen directly under than anode.

7.4.5.2 Remote Earth Anodes

At remote earth from an anode, the voltage gradient field is virtually indistinguishable from point to point. Although true remote earth is theoretically an infinite distance away, being within 5 percent of remote earth may be considered sufficient for the purposes of cathodic protection work. Placing the anodes previously described *at least* 28 feet from the nearest point of a structure to be protected will meet or exceed this criterion. Note, however, that this distance only applies to these two anode sizes.

In narrow rights-of-way, there may be insufficient lateral distance to place anode beds at remote earth. In such instances, cathodic protection designers sometimes use deep well anode beds with an impressed current rectifier. Deep wells place impressed current system anodes in a vertical arrangement beginning at least 100 feet below ground. Deep wells are more costly than shallow anode beds and their design must be left to corrosion professionals.

7.4.6 Test Stations, Junction Boxes, and Bond Boxes

Test stations, as shown in Figure 5, 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 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 leads from a structure. One lead, usually a #12 AWG stranded cable with HMWPE insulation, provides a test

connection while a larger #6 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, one set from each side of the isolation joint. Test stations at intersections with foreign pipes or other structures may have two leads from the foreign structure (**[connections to a foreign structure must be permitted by the owner of that structure]**), two leads from the Reclamation structure, and a connection from an in-place reference cell about 1 foot below the Reclamation 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 leads should be continuous and without splices.

Figure 5. Typical test station with board exposed.

Figure 6. Typical junction box.

When a cathodic protection system employs multiple anodes, the recommended procedure is to bring the leads 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 buss bar. Anode leads pass through a conduit connected to the junction box. The leads can then connect to resistance shunts and often variable resistors that then connect to the buss bar. 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 buss bar. 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. **[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 cable leads. A typical junction box is shown in Figure 6 above.

If multiple structures are collectively protected by one cathodic protection system, their leads may similarly join to a common header in an above ground box, sometimes termed a bond box. A bond box should be similarly constructed and configured like the previously described junction box.

[Junction boxes and bond boxes must be 16-gauge galvanized steel and meet NEMA 3R requirements as a minimum.]

7.4.7 Attenuation

As discussed previously, a cable from a cathodic protection system supplies electrons to a protected structure. These electrons support reduction reactions at exposed metal sites. If a long pipeline has a poor coating, has high linear resistance, and is in low-resistivity soil, the electrons will have difficulty traveling down the pipeline; they will instead leak out to the soil soon after entering the protected structure and be rapidly consumed in producing reduction reactions. As a result, cathodic protection levels near the lead connected to the structure will be acceptable, but will rapidly drop off the further one gets from that point. This effect is called attenuation.

Increasing the current throughout to compensate for attenuation will:

- Increase protection levels near the connection to the structure (these levels may soon exceed prudent limits).
- Improve protection further down the pipeline only by a small amount.

Such structures require additional rectifiers and/or anode beds if recoating and reducing linear resistance are not options. These rectifiers/anode beds need to be spaced so that each cathodic protection system adds to the needed amount of supplemental protection at the limit of the adjacent system.

Large anode bed designs must also consider attenuation. One can reach a point at which an additional anode provides no increase in protective current.

Further discussion of attenuation is beyond the scope of this document.

7.4.8 Anode Service Life – Efficiency and Utilization

Cathodic protection anodes have a limited life. Galvanic anodes protect by sacrificially oxidizing (corroding). Impressed current cathodic protection (ICCP) anodes, being usually made of corrosion-resistant materials, oxidize environmental components around them. However, the environment ICCP anodes produce eventually leads to their consumption as well.

Electrochemical reactions, like all chemical reactions, occur in fixed proportions. For example, when a magnesium atom oxidizes it releases two electrons, so that the following proportions hold:

$$Mg \rightarrow Mg^{+2} + 2e^-$$

Knowing this stoichiometry and the amount of time (t) a current (I) flowed, one can apply Faraday's Law to determine the mass (W) of anode consumed as a result of this current. Faraday's Law may be stated as:

$$W = \left(\frac{M}{nF}\right) It$$

where M is the atomic mass of the anode material, n is the number of electrons in the reaction, and F is Faraday's constant (96,500 coulombs per equivalent; equivalents being M/n). Note that each amp of current is equivalent to 1 coulomb per second.

Knowing this relationship, the theoretical consumption rate (C_r) due to galvanic action for *magnesium will be 8.76 lb/A-yr.*, while that of *zinc will be 23.5 lb/A-yr*. However, in addition to galvanic action, some anode material also gets used up due to direct reaction with the environment. This latter corrosion is termed self-corrosion or autogenous corrosion.

The percent of galvanic anode consumed by galvanic action alone is termed anode efficiency (E). Magnesium anodes are about 50 percent efficient if the anode current density (current flow divided by the surface area of the anode metal) is 20 mA/ft^2 or greater. This means that, under these current density conditions, about twice as much magnesium anode material is needed for a given service life than Faraday's Law would predict. Zinc anodes are much more efficient, providing 90 percent efficiency when their current density is 5 mA/ft^2 or greater. Galvanic anode efficiency is zero when no current is passing and all corrosion is autogenous. Assuming linear efficiency relationships between zero current

density and the limits stated previously provide conservative estimates of anode efficiency when galvanic current is low.

ICCP anodes have no efficiency values as such. However, manufacturers and various technical references provide maximum permissible current densities and consumption rates. Values may vary with the environment, given the differing oxidation reactions that can take place (e.g., a high-chloride environment versus a chloride-free environment). Conservative assumptions are usually the wise path.

Utilization (U) is another factor that determines the service life of an anode. Utilization is the percent or fraction of the original mass that will be considered the end of a service life. A utilization factor allows some margin of error to help ensure that an anode will be refreshed before it is completely used up. Reclamation usually applies an 85 percent utilization factor; however, 90 percent has sometimes been used as well.

Combining this information, the service life (L) of a sacrificial anode weighing W pounds and passing A amps, may be calculated as:

$$L = \frac{WEU}{C_r A}$$

As an example, if a single 32-pound magnesium anode protects a pipe while providing 62 mA of current, then the current density of the magnesium anode would be about 20 mA/ft^2 (62 mA/3.11 ft^2 = 20 mA/ft^2). The efficiency of the anode should then be about 50 percent. One would therefore calculate the service life at 85 percent utilization of the anode to be:

$$L = \frac{(32lb)(0.5)(0.85)}{\left(\frac{8.76lb}{A-yr}\right)(0.062A)} = 25.0yr$$

Reclamation normally strives for a minimum 20-year service life.

Rearranged, this algorithm can conservatively provide an estimate of the maximum current an anode can pass and still provide 20 years of service. Table 6 provides this maximum current information for a 20-year service life of a 32-pound magnesium anode and of a 15-pound zinc anode based on assumptions in this document. **[Sites installing their own GACP systems per this document must not exceed these maximum currents per anode.]**

Anode Type	Max. Current for 20-yr. Service Life (A)
8 in. X 28 in. bag; 32 lb. of Magnesium	0.0776
5 in. X 38 in. bag; 15 lb. of Zinc	0.0244

Table 6. Maximum allowed current per galvanic anode. Note: Assumes utilization factor of 85 percent, magnesium efficiency of 50 percent, and zinc efficiency of 90 percent.

8.0 Sacrificial/Galvanic Anode Systems

8.1   Principles of Operation

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 jealously 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 or sacrificial anode cathodic protection. Corrosion still takes place; we have simply "sacrificed" one metal in place of another we value more. Figure 7 shows a typical installation with a pipe being protected by a magnesium anode. All the cables, including a test cable, are run through a test station.
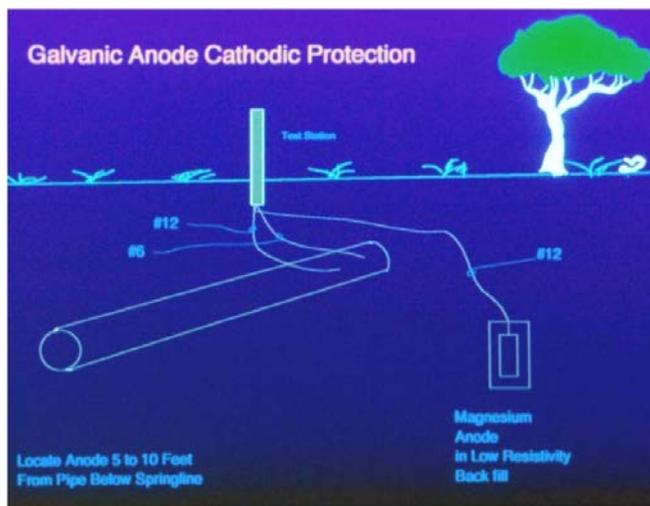
Figure 7. Typical galvanic anode cathodic protection system installation.

Note that, by convention, current is defined as the flow of positive charge. Therefore, current *in the electrolyte* flows from the anode to the cathode or protected structure. *In the wire*, or external circuit, current flows from the structure to the anode; however, the flow of electrons, or negative charge, is in the opposite direction – from the anode to the structure in the wire.

8.2   Galvanic Anodes

Table 1 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 or 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 – the AZ63, the AZ31, and M1.[21] The M1 alloy is a high-potential material that is about 200 mV higher in potential than other magnesium anode alloys. The standard potential magnesium anode has an open circuit potential of about -1.55 V ($_{CSE}$). Either alloy is applicable to soil or fresh water. ASTM B418 (*Standard Specification for Cast and Wrought Galvanic Zinc Anodes*) lists two types of zinc anodes – Type I and Type II.[22] Type I, along with a Mil Spec. A-18001K anode, is intended for use in seawater and brackish water at temperatures less than 50°C. Type II and high-purity zinc anode is 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 for immersion service expose bare metal to the electrolyte while anodes for buried service are pre-packaged in, or otherwise surrounded by, a chemical backfill (see 7.4.5 above, Installation and Placement of Anodes).

Sacrificial anodes provide a relatively small driving voltage when connected to steel (see Table 3) 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 galvanic anodes are shown in Figure 8.
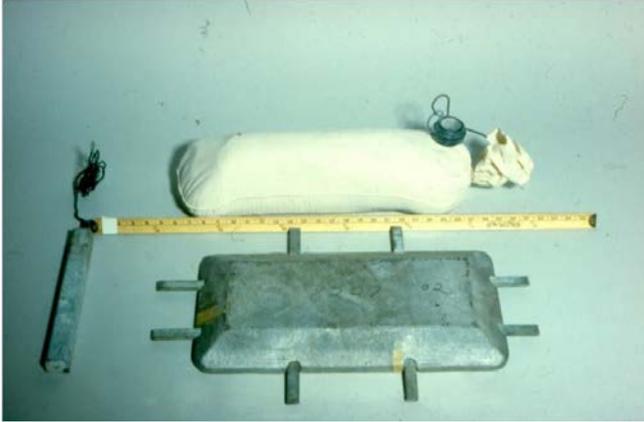
Figure 8. Typical galvanic anodes; note the "bagged" anode for buried installation.

9.0 Impressed Current (Rectifier) Systems

9.1   General Description

External power sources can also deliver cathodic protection DC current to a structure. Figure 9 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.
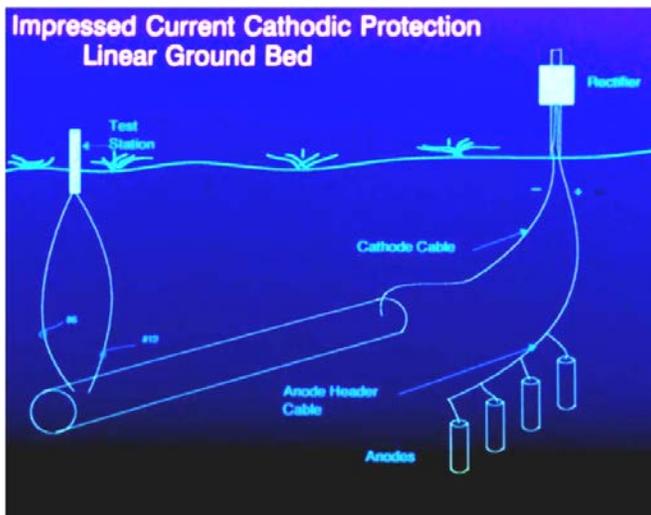
Figure 9. Typical ICCP system installation.

ICCP systems usually introduce current into the electrolyte through anodes made of corrosion-resistant material such as graphite, high-silicon cast iron (HSCI), platinized titanium (Ti) or niobium (Nb), or mixed metal oxide on Ti or Nb.

However, in some instances, scrap iron, abandoned structures, driven steel anodes, and other such materials have been used. Figure 10 below shows some typical ICCP system anode materials. The galvanic potential of the anode is no longer the driving force when using an ICCP system.
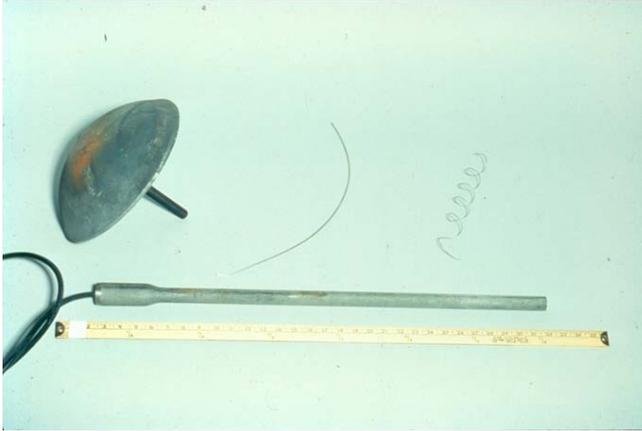
Figure 10. Typical ICCP anodes.

Impressed current systems have a number of 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 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 also less for impressed current systems than for galvanic anode systems. However, impressed current systems also have disadvantages.

The typical ICCP rectifier operates on 110 V AC or greater input power. This can present personnel safety concerns not relevant with low-power galvanic anode systems. Allowing too great a power input from an ICCP system can 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 even 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 impressed current cathodic protection is a rectifier. However, if electrical power is not available, other DC power sources are available. These include:

- Engine generator sets
- Thermoelectric generators
- Solar power supplies
- Wind-driven generators
- Batteries
- Fuel cells

Reclamation rarely uses devices other than rectifiers.

9.2   Rectifiers

The typical rectifier has two basic components. The first component is a step-down 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. Figure 11 shows a typical rectifier cabinet as it might appear in the field. Figure 12 shows a typical board inside the cabinet.

Figure 11. Typical rectifier cabinet.

Figure 12. 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, including:

- Three-phase rectifiers to meet large power requirements (these are usually economical when the power required exceed 2000 watts).
- Oil-cooled rectifiers for severe environmental conditions such as regions of high temperature, dust, or salt air.
- Half-wave or center-tapped bridge rectifiers.
- Silicon-controlled rectifiers.
- Rectifiers with selenium stack rectification sections (these are usually older units).
- Switching-mode rectifiers (these began to immerge in the 1970s).
- Pulsed rectifiers that deliver current in high frequency pulses (1,000 to 5,000 pulses per second) at relatively high voltage, but at a low (15 percent) duty cycle (these are sometimes found on well casings).

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 a certified Cathodic Protection Specialist when installing a new or replacement rectifier or when repairing a rectifier.]

9.3   Impressed Current System Installation

The installation of an impressed current cathodic protection 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 leads connect to a common header in an above-ground junction box. Here each anode lead connects to a shunt resistor to permit current flow measurement. Junction boxes often also contain variable resistors to adjust and balance the current through each anode. 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 rectifier 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. These accessories allow

setting a voltage that will provide 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.

[The design and installation of an impressed current system can call for specialized knowledge and considerable cathodic protection experience. Site personnel must employ a NACE-certified Cathodic Protection Specialist, or a Corrosion Specialist with a strong background in cathodic protection, or a P.E. qualified in cathodic protection.]

10.0 CP System Maintenance and Testing

10.1 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, leads in good condition, and a calibrated reference cell (usually a copper/copper sulfate reference cell). Timely inspections, good record keeping, and acting on the recommendations of the qualified cathodic protection professional who has reviewed the records can head off problems. Operation and maintenance of cathodic protection systems, coating systems requirements, as well as record keeping are covered further in NACE International SP 0169.[13]

The following will describe common requirements for maintaining cathodic protection systems in functional order. **[However, every system must have specific written procedures and documentation forms (see Appendix E for general examples).]** MERL has a list of most-known cathodic protection systems and of Standard Operating Procedures (SOP)/Designer's Operating Criteria; contact MERL to identify any in your area of responsibility. Where they don't presently exist; MERL can develop SOPs for a given installation.

10.1.1 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, removing the electrolyte. **[Since a cathodic protection system will not operate without the electrolyte, the testing procedures described below must not be performed during those times. If a**

structure is to be dewatered, turn off an ICCP system rectifier, and turn it back on when the structure is re-immersed.]

In addition, once re-watered, a cathodically protected structure will require some time to reach a steady-state potential. Readings may not be reliable until pump columns, trashracks, and other immersed structures have been energized for 30 days. The same is true of recently installed immersed or buried systems.

Potential readings on immersed structures are often taken at 3- or 5-foot elevation intervals and at several horizontal locations on or very near a structure. The locations of readings will be described in the specific cathodic protection SOP.

Potential readings on buried structures are typically 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.

10.1.2 General Safety

ICCP systems present more electrical safety concerns (see 10.6.1) than GACP systems. This is due to the low DC voltages involved in the latter. An exception might be made for lightning strikes and the like, however. On the other hand, 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 Figure 14. Ensuring that equipment is screened and that there are no unused or unsealed openings will minimize this issue.

Figure 13. Wasps occupying a junction box. Note the failure to properly connect the conduit at the bottom, providing easy access for the wasps.

10.2 Personnel

Individuals performing maintenance and testing of cathodic protection systems must, as a minimum, have a general understanding of such systems. Maintenance and testing of impressed current systems in particular require a higher level of appreciation for electrical and electronic components and associated hazards. **[Only trained and qualified personnel are to perform the required maintenance and testing on cathodic protection systems.]**

10.3 Equipment Used for Testing

10.3.1 Voltmeter

[The voltmeter used for cathodic protection testing must have high input impedance of 10 megohm or greater. The leads 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 cathodic protection readings involve DC voltage, the setting on a multi-function meter must be adjusted to take such readings.]

Figure 14. Copper/copper sulfate reference cell and components.

10.3.2 Reference Electrode or Cell

A CSE provides the baseline for most electrochemical potential measurements in soil or fresh water. To obtain the standard sign convention, connect the structure to the positive terminal of a typical digital voltmeter and the reference cell to the negative terminal. Place the tip of the reference cell on wetted soil of in water containing the structure of interest; it is usually preferable to locate the cell over or near the structure when taking readings. Reference cells, replacement components, and copper sulfate are available from any reputable cathodic protection supply company. Figure 13 shows a typical reference cell and its components.

CSEs or copper sulfate reference cells are fairly stable and quite rugged for field use. However, **[precautions must be taken to ensure they remain in calibration:]**

- If the solution becomes contaminated, especially by chlorides, the CSE will not provide accurate readings. Check the calibration regularly (see 10.3.3).

- A CSE provides a correct baseline at a *cell* temperature of 77°F (25°C). The baseline will be about 0.5 mV too negative for every degree Fahrenheit (or 0.9 mV/^{o}C) the cell is colder than this temperature (add -0.5 mV to the potential reading/degree Fahrenheit colder than 77°F) and 0.5 mV positive for every degree Fahrenheit the cell is warmer (add +0.5 mV to the potential reading/degree Fahrenheit warmer than 77°F). Keep the reference cell temperature close to 77°F (25°C) or measure the *reference cell temperature* and make corrections to the readings as needed. Note that the outside temperature may not be the cell temperature.

- Sunlight or other ultraviolet (UV) shining through a clear tube has been shown to affect the readings; hence it is best to put opaque tape over areas of clear tube when taking readings.

- If the solution becomes cloudy, clean the reference cell, replace the solution, and recalibrate.

10.3.3 Reference Cell Calibration

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

- **Obtain at least two cells; three would be preferable.**

- **Obtain *distilled or deionized water and reagent-grade copper sulfate crystals.***

- **Disassemble the cells and drain any remaining copper sulfate solution and crystals, and properly dispose.**

- **Rinse the reference cell components to ensure they are clean. Do three final rinses with distilled or deionized water.**

- **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. When completed, rinse the rods with distilled or deionized water.**

- **Reassemble the cells, placing reagent-grade copper sulfate crystals in the bottom and filling them with distilled or deionized 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.**

- **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.**

- **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 the cleaning procedures, refill the cells, and retest 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.**

- **Of the two reference cells within the 5 mV range, set one aside as a reference standard and use the other in the field. Keep 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 few drops of water in the protective end caps, or by keeping the tips in a container of water.]**

10.4 Galvanic Anode Systems

There are comparatively few things that can go wrong with galvanic anode cathodic protection systems. The damage that one will typically see includes:

- Damage to the above-ground junction boxes or test stations where anodes join the structure cable; barriers may help minimize this occurrence.
- Damage to buried cables from excavation, farm equipment, etc.

In addition, soil conditions may change somewhat over time, anodes may be consumed, and structure coatings will deteriorate. These conditions may require adjustments. **[The following procedures must there be followed for GACP systems.]**

10.4.1 Monthly Checks

[To ensure that the equipment is intact, personnel must examine exposed galvanic anode cathodic protection system components on a monthly/ bi-monthly basis. This examination must include:

- **Familiarization with the cathodic protection system as designed and as built.**
- **Looking for damage to test stations and/or junction boxes.**
- **Opening test stations and/or junction boxes to verify connections are intact.**
- **Cleaning out any debris found in test stations and/or junction boxes.**
- **Making or scheduling repairs if needed.**

A bi-monthly schedule may be used if monthly checks are repeatedly acceptable. Personnel must be aware of any safety issues (see 10.1.2).]

10.4.2 Yearly Inspections

[In addition to the monthly checks (see 10.4.1), trained personnel must do the following galvanic anode cathodic protection system training and inspection on a yearly basis.

10.4.2.1 Take Potential Readings

At each test station, take electrochemical potential readings of the protected structures. To take electrochemical potential readings:

1. **Obtain a portable high-impedance voltmeter (see 10.3.1). Set the voltmeter to DC "volts" for structure potential readings.**

2. **Obtain a calibrated copper/copper sulfate reference cell (see 10.3.2 and 10.3.3).**

3. **Connect the structure (e.g., accessed through the test station test lead) to the positive terminal of the typical digital voltmeter for correct sign convention. 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 over or under a pipe being tested (requires coordination with foreign structure owner).

6. Take electrochemical potential readings with current flowing and with current interrupted. Record the sign, the numerical value of the potential, and the type of reference electrode used (e.g., -0.920 $V_{(CSE)}$). Prepared data sheets (see Appendix E for general examples) indicating the date, the station at which each reading is taken, the tester, and other pertinent information make the inspection and reiew procedure more efficient.

10.4.2.2 Measure Anode Current

Measure the current flowing through each anode and record 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:

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

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

10.4.2.3 Review and Maintain Records

Have the data sheets from the annual potential survey reviewed by a qualified corrosion professional, such as a Cathodic Protection Specialist. The reviewer must be provided the record of previous inspection results with which to compare to the latest findings. The reviewer may then recommend adjustments if needed.

The site must maintain a file of annual inspections along with recommendations and actions taken. Good records can show trends before a problem develops.

10.4.2.4 Repairs and Adjustments

Make or schedule repairs and adjustments as recommended by the corrosion professional reviewing the findings of the potential survey. The cathodic protection system must maintain the protection criteria described in the specific equipment SOP and generally described in this publication (see 7.2).]

10.4.2.5 GACP Checklist

The following table summarizes the inspections and maintenance that structures protected by galvanic anode cathodic protection must undergo, as detailed in previous paragraphs:

GACP Procedure	Recommended Interval	Reference
[General condition of test stations, junction boxes, and other equipment	Monthly & Annually	Reclamation Practice (FIST 4-5; sub-para. 10.4.1 and 10.4.2)
Remove debris	Monthly & Annually	Reclamation Practice (FIST 4-5; sub-para. 10.4.1 and 10.4.2)
Structure-to-electrolyte potentials	Annual	Reclamation Practice (FIST 4-5; sub-para. 10.4.2.1)
Current output of anodes	Annual	Reclamation Practice (FIST 4-5; sub-para. 10.4.2.2)
Update and Review of Records	Annual	Reclamation Practice (FIST 4-5; sub-para. 10.4.2.3)
Repairs and adjustments when needed.	Monthly & Annually]	Reclamation Practice (FIST 4-5; sub-para. 10.4.1 and 10.4.2.4)

Table 7. GACP Inspection and Maintenance Checklist.

10.5 Impressed Current Systems

ICCP systems are also subject to test stations and buried cable damage. However, the consequences of damaged test stations and their cables are not generally as serious with ICCP systems since they do not contain leads carrying the protective current. Nonetheless, it is important to maintain test stations since they are needed for routing monitoring. Damage to rectifier leads is obviously serious since it can eliminate cathodic protection to the structure.

What ICCP systems have that sacrificial anode systems do not have is a rectifier or similar DC power source (see 9.1 General Description (of impressed current systems)). Although rectifiers are relatively simple and generally reliable equipment, they are subject to power interruptions and failure of electrical components that are not an issue with sacrificial anode systems. Rectifiers can be put out of service by someone simply tripping the circuit breaker supplying AC power, or by lightning strike. In spike of lightning arrestors normally installed in rectifiers, lightning strikes can still damage rectifier components or completely

destroy the unit. **[The following procedures must therefore be followed for ICCP systems.]**

10.5.1 Safety

Most Reclamation rectifiers are single-phase 120 V AC input voltage; some could be 3-phase and higher voltage. Personnel dealing with ICCP systems must therefore be more safety conscious than when working with GACP systems.

[For protection of personnel, the cabinet of a rectifier must be grounded per NEC and local standards.] However, it is good procedure not to jump to this assumption but to verify that the case is grounded and not energized before taking hold of it. A small handheld AC voltage detector is useful for this purpose. Alternately, one can ground one side of a portable voltmeter (e.g., place the reference cell in the ground or connect to a rod or structure in the ground) then contact the cabinet with a probe connected to the other terminal of the voltmeter set to read AC (never bridge across contact points with extended arms); an ungrounded energized case will show a voltage difference.

[When changing tap settings or performing other functions involving contact points on the front panel of a rectifier, de-energize the unit by tripping the circuit breaker at the AC input. When working behind a rectifier front panel, de-energize the unit at the circuit breaker board or at an intervening cut-off switch and follow all lock-out/tag-out procedures (see FIST 1-1, *Hazardous Energy Control Program*).]

Rectifiers, junction boxes, and the like are normally kept padlocked to prevent unauthorized tampering. **[They must be relocked following testing or maintenance work. In some instances, it may be desirable to fence in a rectifier and lock the area to prevent unauthorized access altogether.]**

[Wasps and other insects may next in CP enclosures (see 10.1.2 above), especially those that haven't been properly sealed. CP workers must be ready for them.]

10.5.2 Monthly Checks

[In addition to the condition of the test stations and junction boxes, personnel must verify monthly/bi-monthly that the rectifier of an ICCP system is energized and that no one has made unauthorized adjustments. Monthly/ bi-monthly checks therefore include:

- **Familiarization with the cathodic protection system as designed and as built.**

- **Verifying that the rectifier tap settings are in the positions recorded on the last inspection sheet.**

- **Verifying that there is DC voltage and current output. Confirming that there is voltage across the rectifier *current shunt* (see 10.5.3.3, part 4), that the current gauge on the panel indicates current flow (be certain the gauge is not frozen in place), or that a warning light (if present) indicates current flow will accomplish this. Ideally, DC voltage and current output should be measured and compared to prior findings.***

- **Looking for scorch marks and indications of excess heat that could indicate present or imminent component failure.**

- **Looking for damage to test stations and/or junction boxes.**

- **Opening test stations and/or junction boxes to verify connections are intact.**

- **Cleaning out any debris found in the rectifier cabinet, test stations, junction boxes, and bond boxes.**

- **Making or scheduling repairs as needed.**

A bi-monthly schedule may be used if monthly checks are repeatedly acceptable; however, long intervals between checks are not generally recommended given the possibility of rectifiers losing power due to lightning, etc. Personnel must be aware of any safety issues (see 10.5.1).]

*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 normally 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 leads are broken and no DC current is flowing.

10.5.3 Yearly Inspections

[As in the case of a sacrificial anode system, trained personnel must do a more thorough inspection of an ICCP system on a yearly basis. In addition to the monthly checks (see 10.5.2), trained personnel must do the following ICCP inspection on a yearly basis.

10.5.3.1 Take Potential Readings

At each test station, take electrochemical potential readings of the protected structures with current flowing and with current interrupted. To take electrochemical potential readings:

1. Obtain a portable high-impedance voltmeter (see 10.3.1). Set the voltmeter to DC "volts" for structure potential readings.

2. Obtain a calibrated copper/copper sulfate reference cell (CSE) (see 10.3.2 and 10.3.3).

3. 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 impressed current cathodic protection system. A typical interruption cycle is 10 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 over or under a pipe being tested (coordinate with the foreign structure owner).

4. Connect the structure (e.g., accessed through the test station test lead) to the positive terminal of the typical digital voltmeter for correct sign convention. Connect the negative voltmeter terminal to the CSE.

5. 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.

6. Take electrochemical potential readings with current flowing and with current interrupted. Record the sign, the numerical value of the potential, and the type of reference electrode used (e.g., -0.920 $V_{(CSE)}$). Prepared data sheets (see Appendix E for general examples) indicating the date, the station at which each reading is taken, the tester, and other pertinent information make the inspection and review procedures more efficient.

10.5.3.2 Measure Anode Current

Measure the current flowing through each anode and record 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 (O.006 V) is measured across a 10 milliohm (0.010 Ω) resistor, then the amperage flow is:

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

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

10.5.3.3 Take Rectifier Readings

Trained personnel must record settings and take DC measurements as found and as left, if any action was taken. Adjustments should not generally be made unless approved by a corrosion professional. An exception to this general rule may be made if the rectifier is found to have tripped off. Perform these activities with the rectifier on and:

1. Record the coarse and fine tap settings. If the rectifier has an infinitely variable knob, record the knob setting.

2. Record the voltage and the amperage 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. (See note in 10.5.2 regarding panel gauges.)

3. Measure and record the voltage across the rectifier DC output connections with a portable voltmeter.

4. 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. The total rectifier amperage should be in close agreement with the sum of anode currents.

10.5.3.4 Review and Maintain Records

Have the data sheets from the annual potential survey reviewed by a qualified corrosion professional, such as a Cathodic Protection Specialist.

The reviewer must be provided the record of previous inspection results with which to compare to the latest findings. The reviewer may then recommend adjustments if needed.

The site must maintain a file of annual inspections along with recommendations and actions taken. Good records can show trends before a problem develops.

10.5.3.6 ICCP Checklist

The following table summarizes the inspections and maintenance that structures protected by impressed current cathodic protection must undergo, as detailed in previous paragraphs:

ICCP Procedure	Recommended Interval	Reference
[General condition of rectifier, test stations, junction boxes, and other equipment	Monthly & Annually	Reclamation Practice (FIST 4-5; sub-para. 10.5.2 and 10.5.3)
Remove debris	Monthly & Annually	Reclamation Practice (FIST 4-5; sub-para. 10.5.2 and 10.5.3)
Structure-to-electrolyte potentials	Annual	Reclamation Practice (FIST 4-5; sub-para. 10.5.3.1)
Current output of anodes	Annual	Reclamation Practice (FIST 4-5; sub-para. 10.5.3.2)
Rectifier tap settings, D.C. voltage, and current output	Monthly & Annual	Reclamation Practice (FIST 4-5; sub-para. 10.5.3.3)
Update and Review of Records	Annual	Reclamation Practice (FIST 4-5; sub-para. 10.5.3.4)
Repairs and adjustments when needed.	Monthly & Annually]	Reclamation Practice (FIST 4-5; sub-para. 10.5.2 and 10.5.3.5)

Table 8. ICCP Inspection and Maintenance Checklist.

Appendix A – Simple GACP Designs

General Considerations

The designer of a cathodic protection system needs to consider a number of factors, including:

- What kind of system should be used – galvanic or impressed current?
- If impressed current, what rectifier specifications (e.g., volts and amps)?
- Should anodes be placed at remote earth or should a distributed design be used?
- What service life is needed?
- What type of anode should be used?
- What size of anode should be used?
- How many anodes?
- Will this system cause interference corrosion on other structures; or will the cathodic protection on other structures induce corrosion on this one?

Along with these factors, specific data should include:

- Information as to aggressiveness of the environment, including chemistry, flow conditions, and resistivity.
- Soil or water resistivity around the structure to be protected and where anodes may be located.
- The dimensions of the structure protected.
- The type and quality of coating on the structure.
- Electrical isolation points and whether other structures are electrically continuous with one in question.
- The location of other structures with relation to the one in question, and the cathodic protection system specifications on those structures.

The following examples are for small, simple, buried structures that might be protected using either the 32-pound magnesium anode or the 15-pound zinc anode previously described in this document. In keeping with previous editions of this document, the examples are intended for site personnel who may wish to attempt in-house cathodic protection for such structures. Note, however, that there is no short-cut for obtaining reliable soil resistivity readings and that these readings are crucial to a correct design. The simplified calculations use conservative assumptions associated with the data tabulated herein. Given the low voltage nature of galvanic anode systems, interference corrosion on other structures while possible is unlikely. Site personnel may nonetheless find it useful to have a

MERL corrosion professional review their design calculations prior to proceeding with ordering materials and installation.

[For cathodic protection of larger structures requiring the use of more than six anodes, an impressed current rectifier system, or for immersed applications, site personnel must obtain the specialized assistance of a corrosion professional.]

Problem 1:

A new 4-inch (D) schedule 40 (0.237 inch wall thickness) coated welded steel pipe 150 feet long will be buried 6 feet below ground in a sandy clay soil. The new pipe will be electrically isolated at both ends. Determine if site personnel can use the galvanic anodes described in this document to protect this pipe. If so, design the system. The anodes need to provide the usual Reclamation 20-year life.

Required data:

- Soil resistivity in ohm-centimeters for possible anode locations and around the structure.
- Pipe protective coating efficiency or percent bare design basis.
- Current density needed for protection.

Data and assumptions for this problem:

1. Soil resistivity testing indicates that two locations each about 30 feet away from the subject pipe have soil resistivities of 1,572 ohm-centimeters on the northwest side and 2,593 ohm-centimeters on the southeast side in the 5- to 10-foot layer of soil. Soil resistivity readings taken along the pipe run indicate an average and relatively consistent soil resistivity of 2,019 ohm-centimeters.
2. The coating is new and in excellent condition. The maintenance supervisor suggests that "customary" coating deterioration be assumed. It will therefore be assumed that the cathodic protection system must be conservatively designed to protect the pipe with 2 percent bare metal (98 percent coating efficiency, or 0.02 bare fraction) of metal exposed through the coating.
3. Based on tabulated data (see Table 2), it appears that a cathodic protection system will need to provide 2 mA/ft^2 of bare steel for adequate protection.

Solution:

1. The responsible site engineer first determines the amount of current that will be needed given the data and base assumptions. The cathodic protection current (I) required is the product of estimated area of bare steel (A_{bare}) in square feet times the required current per square foot. If:

$$A_{bare} = (\pi DL)(0.02)$$

Then

$$I = \left(\frac{2mA}{sq.ft}\right) A_{bare}$$

For 150 feet of 4-inch pipe:

$$I = \left(\frac{2mA}{sq.ft}\right)\left(\pi \times \frac{4in}{12in/ft}\right)(150ft)(0.02) = 6.28mA \; or \; 0.00628A$$

The engineer, seeing that such a small amount of current is needed, is confident that galvanic anodes can be used to protect the pipe.

2. The engineer next determines the individual resistances that make up the cathodic protection circuit. Indications are that there is a likely anode bed site on the northwest side of the pipe that has low resistivity, which should minimize the anode grounding resistance. Knowing the area, the engineer also knows that this location is also about 10 feet from a building and that the test station and/or junction box could be placed near the building for protection. The engineer therefore decides to place an anode bed in that location and proceeds to estimate the cathodic protection system circuit resistance.

   A. Pipe grounding resistance:

      Since the design is to protect the pipe at 98 percent coating efficiency (2 percent bare steel), the tabulated values (see Table 5) above allow an estimate of pipe grounding resistance as follows:

$$R_{pipe} = \frac{\left(\frac{2019\Omega - cm}{1000\Omega - cm}\right)(538\Omega - sq.ft)}{\left(\pi \times \frac{4in}{\frac{12in}{ft}} \times 150ft\right)} = 6.92\Omega$$

   B. Anode grounding resistance:

      The engineer is not certain which anode to use and will therefore consider either magnesium or zinc. The grounding resistances based on Table 4 above are:

$$R_{Mg \; anode} = 0.00467\rho = 0.00467(1572 \; \Omega\text{-cm}) = 7.34 \; \Omega$$

      Or

$$R_{Zn \; anode} = 0.00479\rho = 0.00479(1572 \; \Omega\text{-cm}) = 7.53 \; \Omega$$

C. Cable resistances:

Since the tentative location of the test station and/or junction box is about 40 feet from the pipe and the engineer needs to bring the structure cable up about 5 feet, in addition to some slack, the engineer decides to allow for 50 feet of #6 AWG cable from the pipe. Since plans are to have the anode bed near the test station, 20 feet of #12 AWG cable will be assumed from either anode. Total cable resistance is calculated as:

$$R_{cable} = \left(\frac{0.4030\Omega}{1000ft}\right) 50ft + \left(\frac{1.6200\Omega}{1000ft}\right) 20ft = 0.0526\Omega$$

D. Pipe metal resistance:

The engineer plans to connect the cathodic protection to one end of the pipe, leaving a maximum of 150 feet for the cathodic protection current to travel through steel. A quick estimate shows that this resistance will be negligible:

$$R_{metal} = \frac{(1.344 X 10^{-5}\Omega - cm)\left(150ftX30.5\frac{cm}{ft}\right)}{\frac{((4.5in)^2 - (4.026in)^2)\pi}{4} \times \frac{6.45sq.cm.}{sq.in.}} = 0.003\Omega$$

E. Total circuit resistance:

With the selected magnesium anode, total circuit resistance is:

$$R_{total} = R_{pipe} + R_{anode} + R_{cable} + R_{metal}$$
$$= 6.92\Omega + 7.34\Omega + 0.0526\Omega + 0.003\Omega$$
$$= 14.3\Omega$$

The alternative zinc anode would provide a total circuit resistance of:

$$R_{total} = R_{pipe} + R_{anode} + R_{cable} + R_{metal}$$
$$= 6.92\Omega + 7.53\Omega + 0.0526\Omega + 0.003\Omega$$
$$= 14.5\Omega$$

3. Based on this circuit resistance and knowing that a structure potential of at least -0.850 V$_{(CSE)}$ is needed with a magnesium anode providing a driving voltage of 0.65 V (see Table 3), the engineer now uses Ohm's Law to determine whether a single anode will provide the required current:

$$\frac{E}{R_{total}} = I$$

$$\frac{0.650V}{14.3\Omega} = 0.0455A$$

Hence, the engineer has plenty of capacity with a single 32-pound anode, magnesium anode. A variable resistor should be installed in the circuit to control the structure potential. If instead a single 15-pound zinc anode were used, the amount of current the system could supple would be:

$$\frac{E}{R_{total}} = I$$

$$\frac{0.200V}{14.5\Omega} = 0.0138A$$

This system would still have the capacity to generate about twice the current needed. Note too that either one of these anodes will provide in excess of 20 years of service life since the maximum current output for that longevity has not been exceeded (see Table 6).

The site engineer recommends to the maintenance supervisor that they install a single 15-pound prepackaged zinc anode, indicating the site 30 feet from the pipe and on the northwest side where the anode is to be bedded at or below the spring line of the pipe. The test station is to be placed near the building for damage protection and a 100-milliohm shunt (will make current measurements easier) and a variable resistor are to be supplied in the test station.

Problem 2:

Determine the cathodic protection requirements, including the amount of current needed and the type and number of anodes, to cathodically protect 80 feet (L) of new 4-inch (D) schedule 40 (0.237 inch wall thickness) coated welded steel pipe buried in the ground. There is a retaining wall 10 feet to one side of the pipe and a road 15 feet on the other; the anodes must be kept between these features. Road salts used to deal with icing in the winter have made the soil in the area severely corrosive. The pipe is buried 6 feet below ground and is electrically isolated at both ends.

Required data:

- Soil resistivity in ohm-centimeters for possible anode locations and around the structure.
- Pipe protective coating efficiency or percent bare design basis.
- Current density needed for protection.

Data and assumptions for this problem:

1. Soil resistivity readings taken throughout the area between the road and the retaining wall indicate an average soil resistivity of 760 ohm-centimeters without much variation.
2. The pipe is new and well-coated, but it will be assumed that the cathodic protection system will eventually need to protect the pipe with 2 percent bare metal (0.02 fraction bare) exposed through the coating.
3. Based on Table 2, it appears that a cathodic protection system may need to provide 6 mA/ft^2 of bare steel for adequate protection since this appears to be very corrosive soil.

Solution:

1. The site engineer knows a remote anode system cannot be employed since anodes cannot be placed at least 28 feet from the pipe; a distributed anode system will therefore be considered. The engineer first determines the amount of current needed given the data on hand and the base assumptions. The cathodic protection current (I) required is the product of estimated area of bare steel (A$_{bare}$) in square feet times the required current per square foot. If:

$$A_{bare} = (\pi DL)(0.02)$$

Then

$$I = \left(\frac{6mA}{sq.ft}\right) A_{bare}$$

For 80 feet of 4-inch pipe:

$$I = \left(\frac{6mA}{sq.ft}\right)\left(\pi \times \frac{4in}{12in/ft}\right)(80ft)(0.02) = 10.1mA \text{ or } 0.0101A$$

2. In order to protect 80 feet of pipe with anodes every 16 feet, the engineer must employ 6 anodes (one at either end, each covering the first 8 feet of pipe from the ends and 4 more anodes between these). Given that the pipe is only 4 inches in diameter, anodes should *not* be needed on both sides of the pipe; they will, however, be staggered. The engineer next determines the individual resistances that make up the cathodic protection circuit.

   A. Pipe grounding resistance:

   Since the design is to protect the pipe at 98 percent coating efficiency (2 percent bare steel), Table 5 allows an estimate of pipe grounding resistance as follows:

$$R_{pipe} = \frac{538\Omega - ft^2}{\left(\pi\left(\frac{4in}{\frac{12in}{ft}}\right)80ft\right)} \times \left(\frac{760\Omega - cm}{1000\Omega - cm}\right) = 4.88\Omega$$

B. Anode grounding resistance:

He estimates the combined grounding resistance of the 6 anodes based on Table 4 above as:

$$R_{Mg\ anode} = 0.00093\rho = 0.00093(760\Omega - cm) = 0.707\Omega$$

Or for six zinc anodes:

$$R_{Zn\ anode} = 0.00095\rho = 0.00095(760\Omega - cm) = 0.722\Omega$$

C. Cable resistances:

The tentative location of the test station/junction box will be near the center of the pipe, where the 6 anode leads will connect to about 10 feet of #6 AWG cable from the pipe. The engineer assumes an average of 25 feet of #12 AWG cable from each anode (some will actually be shorter and some will be longer). Since these short runs of cable are in parallel, the engineer estimates the combined resistance of the cables to be 1/6 the resistance of one anode cable, so that the combined cable resistance is approximately:

$$R_{cable} = \left(\frac{0.4030\Omega}{1000ft}\right)10ft + \left(\frac{1}{6}\right)\left(\frac{1.6200\Omega}{1000ft}\right)25ft = 0.0108\Omega$$

D. Pipe metal resistance:

The engineer plans to connect the cathodic protection to the center of the pipe, leaving only a maximum of 40 feet for the cathodic protection system to travel through steel, and 2 parallel paths (one in each direction). A quick estimate of one side shows that this resistance will again be negligible:

$$R_{metal} = 1/2\{\frac{(1.344X10^{-5}\Omega - cm)\left(40ftX30.5\frac{cm}{ft}\right)}{\frac{((4.5in)^2 - (4.026in)^2)\pi}{4} \times \frac{6.45sq.\,cm.}{sq.\,in.}}\}$$
$$= 0.0004\Omega$$

E. Total circuit resistance:

With magnesium anodes, total circuit resistance is:

$R_{\textbf{Mg} \text{ total}} = R_{\text{pipe}} + R_{\text{anode}} + R_{\text{cable}} + R_{\text{metal}} = 4.88\ \Omega + 0.707\ \Omega + 0.0108\ \Omega + 0.0004\ \text{ohm} = 5.60\ \Omega$

The alternative zinc anodes would provide a total circuit resistance of:

$R_{\textbf{Zn} \text{ total}} = R_{\text{pipe}} + R_{\text{anode}} + R_{\text{cable}} + R_{\text{metal}} = 4.88\ \Omega + 0.722\ \Omega + 0.0108\ \Omega + 0.0004\ \text{ohm} = 5.61\ \Omega$

3. Based on this circuit resistance and knowing that a structure potential of -0.850 $V_{\text{(CSE)}}$ needs to be held with standard potential magnesium anodes having a -1.550 $V_{\text{(CSE)}}$ potential, the engineer now uses Ohm's Law and Table 3 to determine whether 6 closely distributed anodes will provide the required current and the minimum 20-year service life:

$$E/R_{\text{total}} = I$$

$$(0.650\ \text{V})/5.60\ \Omega = 0.116\ \text{A total}$$

$$0.116\ \text{A}/6\ \text{anodes} = 0.0193\ \text{A/anode}$$

Hence, since only 0.0101 A is needed to protect the pipe, the engineer has plenty of capacity and adequate service life with 32-pound standard potential magnesium anodes; variable resistors will be installed in the circuit to control the structure potential.

If instead six 15-pound zinc anodes were used, the amount of current the system could supply and the individual current per anode would be (see Table 3):

$$(0.200)/5.61\ \Omega = 0.0357\ \text{A total}$$

$$0.0357\ \text{A}/6\ \text{anodes} = 0.00594\ \text{A/anode}$$

Since only 0.0101 A is needed to protect the pipe, the engineer again would have plenty of current and the design would meet a minimum 20-year service life. The engineer's recommendation, therefore, calls for a close distributed zinc anode cathodic protection system with 6 anodes spaced 4 feet, 8 inches from the pipe and spaced 16 feet apart. Since there are only 6 anodes, all the cables will be run to a junction box where each anode will pass through a 0.100 Ω shunt resistor and a variable resistor for balancing anode currents. A separate test lead will be provided on the junction box board. The junction box will be placed near the retaining wall where it should be out of harm's way.

Appendix B – Failed Pipe Reporting Form

(See sub-paragraph 2.3, Taking Action and Getting Help)

(A useful form for reporting a failed pipe to the Technical Service Center)

POM- 503 (7-13)
Bureau of Reclamation

RECLAMATION
Managing Water in the West

FAILED PIPE REPORTING FORM

Person Reporting: _____   Date: _____

Project and Location: _____

Age of Pipe: _____   Buried or Above Ground: _____

Pipe Diameter: _____   Pipe Design Press: _____   Use: _____

Questions			Comments
Pipe Material			
	Steel		
	Gray Cast Iron[a]		
	Ductile Iron[a]		
	Prestressed[b]		
	Pretensioned[b]		
	Reinforced concrete[b]		
	Plastic[c]		
	Other		
Coating (outside)			
	Bonded dielectric (paint, tape, etc.), describe:		
	Mortar		
	Thin black shop coat on cast or ductile iron		
	Polyethylene wrap		
	None		
	Other		
Condition of Coating[d]			
Lining Inside			
	Bonded dielectric, describe:		
	Mortar		
	None		
	Other		
Condition of lining[d]			
Ground conditions[e]			

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POM- 503 (7-13)
Bureau of Reclamation

RECLAMATION
Managing Water in the West

FAILED PIPE REPORTING FORM

Person Reporting: _____   Date: _____

Project and Location: _____

Age of Pipe: _____   Buried or Above Ground _____

Pipe Diameter: _____   Pipe Design Press: _____   Use: _____

Questions			Comments
Is pipe cathodically protected?			
	Rectifier		
	Sacrificial anode		
Is pipe monitored and how?			
Are there other structures near this pipe?[f]			
Nature of failure			
	Hole		
		From outside[g]	
		From inside[h]	
	Cracking[i]		
	Weeping[j]		
	Pits		
	Mechanical damage[k]		
	Other		
Location of failure[l]			
	Clock position		
	At weld		
		Girth weld	
		Axial weld	
	At bell and spigot		
	At flange		
	Other		
Maintenance History			
Action taken on this occasion and est. cost			

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RECLAMATION
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FAILED PIPE REPORTING FORM

Additional Comments

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POM-503 (7-13)
Bureau of Reclamation

RECLAMATION
Managing Water in the West
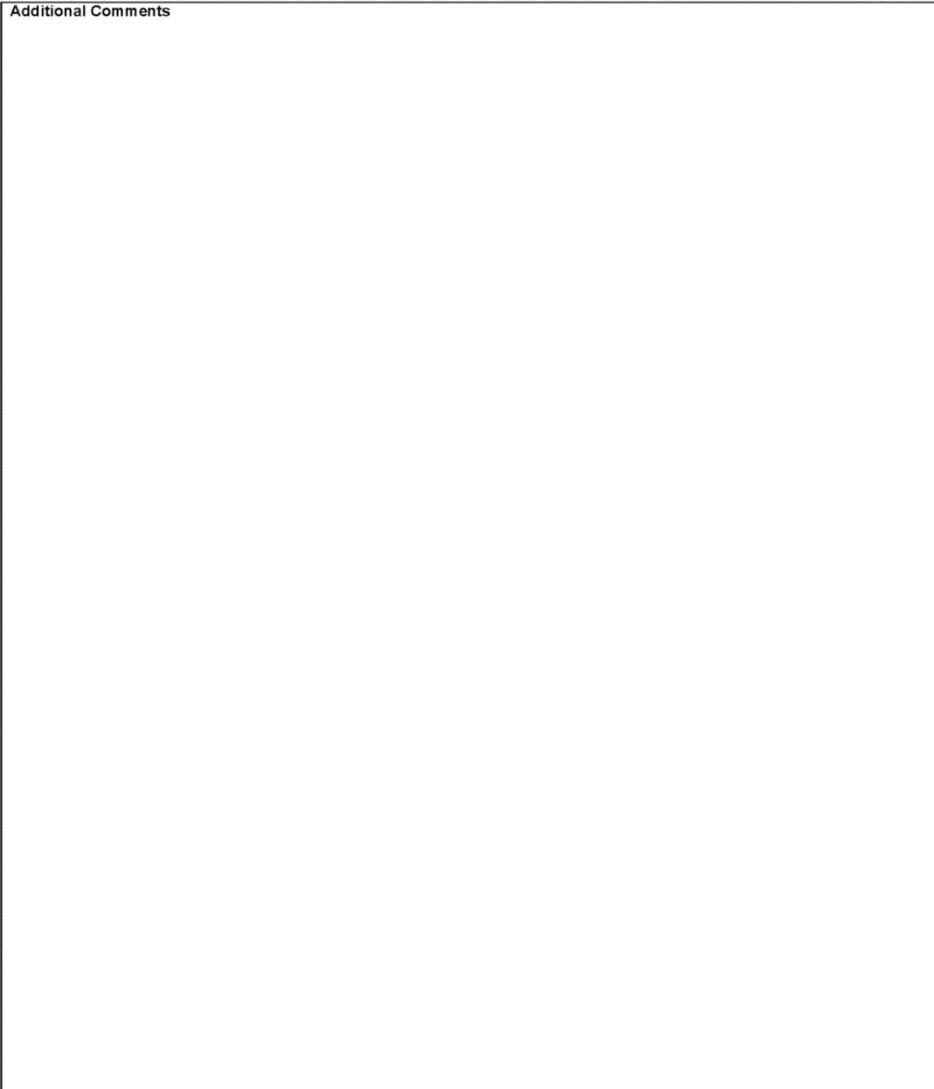
FAILED PIPE REPORTING FORM

Notes and Instructions:

a: Gray cast iron will fracture when struck forcefully and the fracture surface will be a dark charcoal gray. Unless it is quite cold, ductile iron will bend when struck forcefully.

b: Pre-stressed, pre-tensioned, and reinforced concrete pipes may be difficult to distinguish from one another. If the pipe has wire rods (1/4 in. or less) wound on a concrete core not containing a steel cylinder, then it is a non-cylinder pre-stressed concrete pipe. If this pipe has an embedded 16 gauge steel cylinder in the core, then it is an embedded cylinder pre-stressed concrete pipe. A third variation, rarely if ever used on Reclamation projects, is the lined cylinder pre-stressed concrete pipe in which the 16 gauge steel cylinder is external to the concrete core and the wire rods are directly on the steel cylinder. Pre-tensioned concrete cylinder pipe resembles this latter variation of pre-stressed pipe; however, the wire rod is 1/4 in. or thicker, the steel cylinder is thicker. If there is axial as well as circumferential reinforcement present, then this is reinforced concrete pipe; this pipe may have 1/2 in. or thicker rebar or a rod cage embedded in the concrete. Describe in the comments column whether this pipe has a cylinder or not, the size of the reinforcing rod or wire, thickness of the cylinder, if any, and any other distinguishing characteristics and details noted (e.g., manufacturer).

c: Describe in the comments column what kind of plastic (PVC, polyethylene, FRP etc.), the manufacturer, and any other details known.

d: Coatings (outside pipe) and linings (inside pipe) may soften, form blister, which may be dry or contain liquid, crack, peel away from the pipe, have pinholes (typically rust spots showing on a painted surface), or they may show scorch marks from nearby welding, or other features. Describe these or other findings in as much detail as possible.

e: Describe the type of backfill used (e.g., sand, pea gravel, etc.), whether the area is wet or dry (e.g., swampy area; leaking sewer pipe in area; etc.), smells (e.g., rotten egg odor), and any other distinguishing features of the ground and site where the pipe is buried.

f: Describe what the structure is (e.g., pipe, cable, etc.) and if it is known to be under cathodic protection, whether there is a resistance bond to the structure on this form, etc.

g: A corrosion hole that starts on the outside is typically narrower on the inside of the pipe.

h: A corrosion hole that starts on the inside is typically narrower on the outside of the pipe.

i: Indicate number of cracks, their orientation (e.g., axial, circumferential, etc.), size, etc.

j: Weeping may indicate selective leaching has taken place (e.g., graphitic corrosion of gray cast iron). Areas suffering from selective leaching may not show metal loss but are soft; they can easily be breached by a shovel or other tool. Note in the comments whether this appearance is observed or if other features are present.

k: Describe the nature and source of the mechanical damage if known (e.g., installation damage).

l: Facing downstream, consider the top of the pipe to be 12 o'clock; on a vertical run of pipe, consider North to be 12 o'clock. In the comment column, also provide distance from next pipe joint or weld downstream of the failure point. If at a weld, bell and spigot, or flange, clarify specifically where (e.g., edge of weld; middle of weld bead; 1/4 in. from toe of weld; etc.).

Send completed forms, pictures, sketches, and any supplemental information to:

Attn: Group Manager
Materials Engineering and Research Laboratory (MERL)
Denver Federal Center
Bldg. 56, Rm. 1430
P.O. Box 25007 (86-68180)
Denver, CO 80225-0007

Fax: 303-445-6341
E-mail: wkepler@do.usbr.gov

Appendices

Appendix C – References

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Appendix D – Definitions

Anion

Negatively charged ions in the electrolyte. Anions are attracted to and move toward the anode under influence of a potential gradient. Some may react at the anode.

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.

Cation

Positivity charged ion in an electrolyte. Cations are attracted to and move toward the cathode under influence of a potential gradient. Some may react at the cathode.

Coating

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

Concentration cell

A corrosion cell whose voltage gradient is the result of inhomogeneities or differential chemical conditions at sites on the structure within the electrolyte.

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. Dry and wet cell batteries are common examples (when shorted across the terminals).

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 tests 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 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-centimeters, ohm-meters, ohm-feet, or the like.

Electrolyte

The medium (such as an aqueous solution, moist soil, or solution of chemicals) through which the current (positive charge) of a corrosion cell flows (i.e., from the anode to the cathode by migration of anions and cations).

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).

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-type corrosion

Corrosion similar to that produced by a galvanic cell.

Internal circuit

The part of a corrosion cell circuit in which the current flows through the electrolyte via ions or radicals (the solution part of the circuit).

Ion

An electrically charged atom (e.g., Na^+, Cl^-, etc.); sometimes used when speaking of radicals as well.

Local cell corrosion

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

Long-line corrosion

Current flowing through the earth between an anodic and a cathodic area that returns along an underground metallic structure. (Usually used only where the areas are separated by considerable distance and where the current flow results from concentration cell action).

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.

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

The change from the corrosion potential as a result of current flow across the electrode/electrolyte interface.

Potential

In cathodic protection work, the voltage difference between a structure and a reference electrode, all in a continuous electrolyte.

Radical

An electrically charged group of atoms (e.g., OH-, $SO4^{-2}$, etc.); sometimes loosely referred to as ions.

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/millivolt.

Static potential

The potential of a metal before any polarization and with no current flowing through the electrolyte where the potential is measured; sometimes also called native potential.

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).

Test station

A location with electronic connection to a structure for cathodic protection testing.

Tuberculation

The formation of localized corrosion products scattered over the surface in the form of knob-like mounds called tubercles.

Appendix E – Sample CP Data Forms

(See sub-paragraph 10.1)

POM- 500 (7-13)
Bureau of Reclamation

RECLAMATION
Managing Water in the West

VOLTAGE CONTROLLED RECTIFIER DATA SHEET

Project: _____ Structure: _____

Rectifier Model/Rating: _____ _____ VDC _____ ADC

Date: _____ Tested By: _____

Rectifier Shunt Rating				Multiplication Factor:			
		As Found			As Left		
Tap Settings							
Gauge Readings		V		A		V	A
Portable Meter Readings		V	mV	A		V	mV	A

Junction Box Anode Current Output				
Anode Shunts		Ohms	(mV/1000)/Ohms = A	

Anode #	As Found		As Left	
1	mV	A	mV	A
2	mV	A	mV	A
3	mV	A	mV	A
4	mV	A	mV	A
5	mV	A	mV	A
6	mV	A	mV	A
Total:		A		A

Comments:

POM-501 (7-13)
Bureau of Reclamation

RECLAMATION
Managing Water in the West

POTENTIAL READINGS

Project: _____ Structure: _____

Date: _____ Tested By: _____

Voltmeter: _____

Voltmeter to Ref. Cell Connections: _____

Location	Cable Connected to Meter		Potential (mV)
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	
		On	
		Instant Off	

Comments:

_____

_____

_____

_____

_____

_____

_____

_____

_____

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POM-502 (7-13)
Bureau of Reclamation

RECLAMATION
Managing Water in the West

GALVANIC ANODE TEST STATION READINGS

Project: _____ Structure: _____

Date: _____ Tested By: _____

Voltmeter: _____

Voltmeter Terminal to Which Ref.Cell is Connected: _____

Location	Cable Connected to Meter			Potential (mV)	
			On		
			Instant Off		
	Shunt Rating: Ω		Shunt Current	mV	A
			On		
			Instant Off		
	Shunt Rating: Ω		Shunt Current	mV	A
			On		
			Instant Off		
	Shunt Rating: Ω		Shunt Current	mV	A
			On		
			Instant Off		
	Shunt Rating: Ω		Shunt Current	mV	A
			On		
			Instant Off		
	Shunt Rating: Ω		Shunt Current	mV	A
			On		
			Instant Off		
	Shunt Rating: Ω		Shunt Current	mV	A
			On		
			Instant Off		
	Shunt Rating: Ω		Shunt Current	mV	A

Comments: