



*An Online CPD Course
brought to you by
CEDengineering.ca*

An Introduction to Cathodic Protection Principles

Course No: E05-006
Credit: 5 PDH

J. Paul Guyer, P.E., R.A., Fellow ASCE, Fellow AEI



Continuing Education and Development, Inc.

P: (877) 322-5800
info@cedengineering.ca

This course was adapted from the Unified Facilities Criteria of the United States government, which is in the public domain.

CONTENTS

- 1. THE CORROSION PROCESS**
- 2. TYPES OF CORROSION**
- 3. RATE OF CORROSION**
- 4. GALVANIC SERIES**
- 5. INTRODUCTION TO CATHODIC PROTECTION**
- 6. GALVANIC CATHODIC PROTECTION**
- 7. IMPRESSED CURRENT CATHODIC PROTECTION**

1. THE CORROSION PROCESS. Understanding the principles of cathodic protection systems is based upon understanding the nature of the corrosion process. The corrosion of metals is an electrochemical process. That is, it is an electrical circuit where the exchange of electrons (electricity) is conducted by chemical reactions in part of the circuit. These chemical reactions occur at the surface of the metal exposed to the electrolyte. Oxidation reactions (corrosion) occur at the surface of the anode and reduction reactions occur at the surface of the cathode. Corrosion control systems which relocate these oxidation reactions, by making the protected structure a cathode in a larger corrosion cell, is called a “cathodic” protection system.” The cathodic protection anodes are installed to become the anode in this larger corrosion cell and provide the location for all oxidation reactions in the cell. To describe the principles of operation of cathodic protection in detail, the exact nature of the corrosion process must be described in detail.

1.1 CORROSION CELL. Corrosion is the deterioration of a material through reaction with its environment. In the case of a metal, this deterioration occurs mainly through an electrochemical process. The electrochemical process consists of four distinct parts: anode, cathode, electrolyte, and metallic path. These four parts constitute what is called the “corrosion cell”. Electrochemical corrosion occurs only when all four parts of the corrosion cell are present. To understand the operation of a cathodic protection system, it is extremely important to understand these four parts of the electrochemical corrosion cell.

1.1.1 ANODE. The most obvious part of the corrosion cell is the anode. This is the location where corrosion occurs. The anode is the point in a corrosion cell where electricity is passed by chemical means from the surface of the metal to the electrolyte. This chemical reaction is an oxidation reaction, which is characterized by the metal losing an electron and combining with another element, usually oxygen. In the case of steel, the resulting material is iron oxide (rust).

1.1.2 CATHODE. The second part of the corrosion cell is the cathode. This is the location where protection occurs. The cathode is the point in a corrosion cell where electricity is

passed by chemical means from the electrolyte to the surface of the metal. This chemical reaction is a reduction reaction, which is characterized by the metal passing electrons to the electrolyte.

ANODE

An electrode where oxidation reactions
(corrosion) occurs
Antonym - Cathode

CATHODE

An electrode where reduction reactions
(protection) occurs
Antonym - Anode

1.1.3 ANODE/CATHODE RELATIONSHIP. An electrode becomes either an anode or a cathode in an electrochemical corrosion cell depending upon its electrical potential compared to the other electrode. This electrical potential difference is the electromotive force of the cell and is the voltage difference between the anode and the cathode. The electrode which is more electrically active, or more negative in voltage, undergoes the corrosion, so by definition is the anode. The electrode that is more noble (less negative in potential) passes electrons to the electrolyte (reduction reactions) and by definition is the cathode and does not undergo corrosion (oxidation reactions). As previously discussed, there are four distinct parts to the electrochemical corrosion cell, all four parts must be present for a complete circuit to exist and for current to flow (corrosion to occur).

1.1.4 ELECTROLYTE. The third part of the corrosion cell is the electrolyte. The electrolyte is the location where ions flow. The electrolyte is any material in contact with both the anode and the cathode that will allow ions to migrate. The electrolyte is the part of a corrosion cell which allows oxidation and reduction reactions to occur. The electrolyte includes the source of elements or atoms that are required for ion transfer to and from the metal electrodes (anode and cathode).

1.1.5 METALLIC PATH. The fourth part of the corrosion cell is the metallic path. The metallic path completes the circuit and allows the electrons to flow. The metallic path is any metal that contacts both the anode and the cathode and allows electrons to flow. This electron flow must be present for electrochemical corrosion to occur. In the case of

a tank or pipeline, this can be the tank or pipe itself, or it can be a metallic bond to a different metallic structure.

Again, all four parts of the corrosion cell must be present for electrochemical corrosion to occur. When all four parts are present, a closed circuit condition exists, and current will flow through this circuit. Corrosion only occurs at the anode of the cell, which is where the oxidation reactions occur. A familiar example of the corrosion cell is the common dry cell battery. In this case, two different metals, one being an anode and one being a cathode, are placed in contact with a continuous electrolyte, and when a metallic path is supplied to the circuit, current flows.

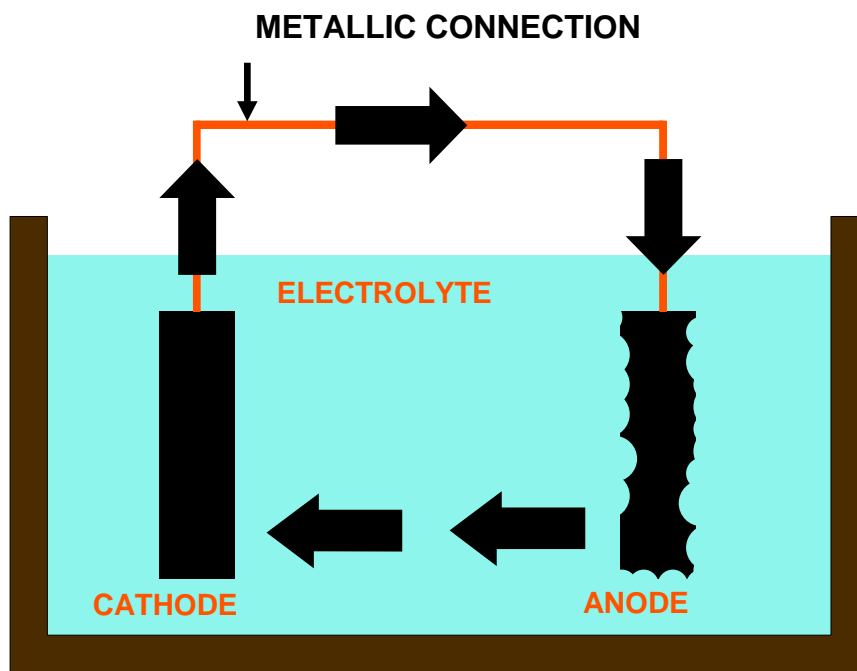


Figure 1
The Corrosion Cell

The corrosion reaction should be considered as a cyclic phenomenon where each of the components of the cell must be present and functioning in order for the overall electrochemical corrosion reaction to proceed. If any one of the components of the electrochemical cell are removed or if the individual reactions at either the anode or the

cathode can be prevented from occurring, then the entire corrosion process can be prevented.

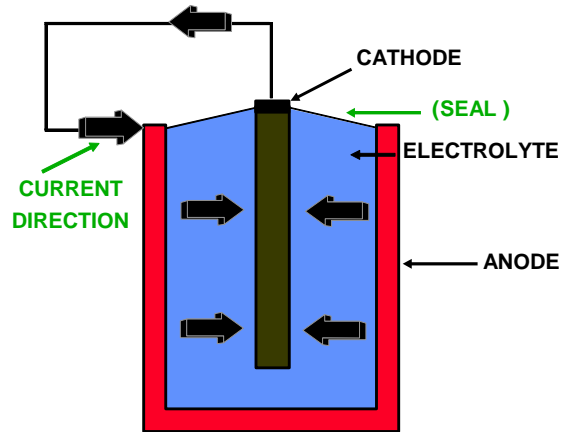
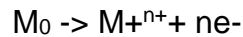


Figure 2
Corrosion Cell, The Dry Cell Battery

1.1.6 ANODE REACTION. At the anode the metal atoms give up one or more electrons and become metal ions. In chemical shorthand the general formula for this reaction is written:

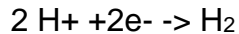


M_0 represents a metal atom such as iron or copper in a metallic structure. The arrow represents the direction in which the reaction is occurring. The symbol M^+ represents a metal ion. Metal ions formed in the corrosion reaction leave the metal structure and enter the environment (electrolyte). The symbol e^- represents the negatively charged electron released by the formation of the metal ion. The free electron that is formed in the corrosion reaction remains within the metal structure. For a specific anodic reaction such as the case with the corrosion of copper, the reaction would be written:



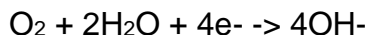
This represents the reaction of one copper atom to form one copper ion with a charge of +2 and two electrons. Note that there is no change in total charge ($0 = +2 + -2$). All metals can react to form metal ions and electrons. It is characteristic of anodic reactions that metal ions and electrons are produced.

1.1.7 CATHODE REACTION. At the cathode there are many possible reactions. The simplest common cathodic reaction is the reaction of hydrogen ions, which are present in water solutions, with electrons to form hydrogen gas. In chemical shorthand this reaction is written:



This represents the reaction of two hydrogen ions (2H^+) with two electrons (e^-) to form two hydrogen atoms, which then combine to form one molecule of hydrogen (H_2) gas. As in the case of anodic reactions, there is no change in net charge in this reaction ($+2 + -2 = 0$).

Another common reaction at the cathode is the reaction of electrons with dissolved oxygen and the breakdown of water into hydroxyl ions. In chemical shorthand this reaction is written:



This represents the reduction of dissolved oxygen (O_2) in alkaline electrolytes where oxygen and the breakdown of two water molecules ($2\text{H}_2\text{O}$) results in the formation of four hydroxyl ions (4OH^-).

1.1.8 OTHER CATHODIC REACTIONS. In other cathodic reactions, different ions may react with electrons, but the important characteristic of every cathodic reaction is the rebonding (gaining) of electrons, which is the main characteristic of a reduction reaction. Metal ion reduction and metal deposition may also occur. Note that there is no direct

involvement of the metal itself in the cathodic reaction, except that if metal ions are present, they may be reduced (gain their electron(s) back) or deposited. The metal does not become an ion, does not lose an electron, and cannot combine with another atom or element (oxidize or rust). Although the cathodic reaction must occur for the corrosion reaction to proceed there is no corrosion occurring at the cathode. This reduction reaction is normally called protection; since the metal is protected from becoming an ion, it is protected from corrosion. This process also results in many factors which would otherwise slow the corrosion rate: the reduction of hydrogen ions (which causes pH to change in the alkaline direction); the formation of hydroxyl ions (which also causes pH to change in the alkaline direction); the breakdown of water (which causes an increase in resistivity in the electrolyte); and the formation of a hydrogen coating on the cathode (which causes an increase in the cathode to electrolyte resistance).

The electrons formed at the anode flow through the metallic electron path and are re-bonded at the cathode. The electrolyte provides the ions necessary for the cathodic reaction and serves to dissolve the metal ions formed at the anode. The most common electrolyte is water or a water based solution. The water may be tap water, seawater, water held in the pores of a soil or water which has precipitated from the air as rain or dew. It is important to note that corrosion and cathodic protection current discussed in this publication and the NACE International publication is a conventional or positive current flow.

2. TYPES OF CORROSION. Basically, there are four ways corrosion can occur. Corrosion can occur through a chemical reaction or three general types of electrochemical reactions. The three general types of electrochemical reactions that occur depend on the cause of the potential difference between the anode and the cathode. This potential difference can be caused by differences in the environment, differences in the metal, or by external electrical sources of DC current. Understanding this principle leads to an understanding of the principles of operation of cathodic protection systems. Each of these three types of corrosion will be explained in detail, with examples of each. These three types are general corrosion, concentration cell corrosion (electrochemical cell caused by differences in the electrolyte), galvanic corrosion (electrochemical cell caused by differences in the metal), and stray current corrosion (electrochemical cell caused by external electrical sources).

2.1 GENERAL CORROSION. This type of corrosion is chemical or electrochemical in nature. However, there are no discrete anode or cathode areas. This form of corrosion is uniform over the surface of the metal exposed to the environment. The metal gradually becomes thinner and eventually fails. The energy state of the metal is basically what causes this reaction. Referred to as the “dust-to-dust” process, high levels of energy are added to the raw material to produce the metal. This high energy level causes an unnaturally high electrical potential. One law of chemistry is that all materials will tend to revert to its lowest energy level, or its natural state. After high levels of energy are added to the metal, when it is exposed to the environment (an electrolyte), it will tend to revert to its natural state. This process is normally extremely slow, and is dependent on the ion concentration of the electrolyte that it is exposed to. Only under very extreme conditions (acidic electrolyte) can this form of corrosion be significant. The corrosion rate for steel climbs drastically at a pH below 4; at a pH of about 3, the steel will dissolve.

General corrosion tends to slow down over time because the potential gradually becomes lower. Failures of pipelines or tanks would not quickly occur from this type of corrosion since no pitting or penetration of the structure occurs, just a general corrosion over the entire surface (except under very extreme circumstances where the metal could dissolve

in an acid electrolyte). However, in nature, the metal is not completely uniform and the electrolyte is not completely homogeneous, resulting in electrochemical corrosion cells that greatly overshadow this mild form of corrosion.

2.2 CONCENTRATION CELL CORROSION. This type of corrosion is caused by an electrochemical corrosion cell. The potential difference (electromotive force) is caused by a difference in concentration of some component in the electrolyte. Any difference in the electrolyte contacting the metal, forms discrete anode and cathode regions in the metal. Any metal exposed to an electrolyte exhibits a measurable potential or voltage. The same metal has a different electrical potential in different electrolytes, or electrolytes with different concentrations of any component. This potential difference forces the metal to develop anodic and cathodic regions. When there is also an electrolyte and a metallic path, the circuit is complete, current flows, and electrochemical corrosion will occur.

Soil is a combination of many different materials. There are also many different types of soil, and even the same type of soil varies greatly in the concentration of its constituents. Therefore, there is no such thing as a truly homogeneous soil. These soil variations cause potential differences (electromotive force) on the metal surface resulting in electrochemical corrosion cells. Liquids tend to be more uniform but can vary in the concentration of some components, such as oxygen varies by depth and flow rates. Biological organisms are present in virtually all-natural aqueous environments. These organisms tend to attach to and grow on the surface of structural materials, resulting in the formation of a biological film, or biofilm. These films are different from the surrounding electrolyte and have many adverse effects. Following are examples of common forms of concentration cell corrosion.

2.2.1 DISSIMILAR ENVIRONMENT. Pipelines tend to pass through many different types of soils. The metal exhibits different electrical potentials in different soils. The electrical potential in those soils determines which areas become anodic and which areas become cathodic. Since both the anode and cathode are electrically continuous and the electrolyte is in contact with both, current flows, resulting in oxidation and reduction

reactions (corrosion and protection). The area of the pipeline or tank, which is the anode, corrodes. Since the ground tends to consist of horizontal layers of dissimilar soils, pipelines that traverse several layers of soil tend to be affected by this type of corrosion frequently. Water and oil well casings are prime examples of this type of electrochemical corrosion cell. Other examples are pipelines that go through areas of generally different materials such as rock, gravel, sand, loam, clay, or different combinations of these materials.

There are over 50 general types of soil that have been characterized for corrosion properties. Each of the different types of soils has different soil resistivity values. In areas where the soil resistivity values vary greatly in relatively short distances, dissimilar environment corrosion cells are formed. These types of electrochemical corrosion cells are most serious when the anode is relatively small, soil resistivity is the lowest, and the electrical potential difference is the greatest. Examples of corrosive soils are Merced (alkali) silt loam, Montezuma (alkali) clay adobe, muck, and Fargo clay loam.

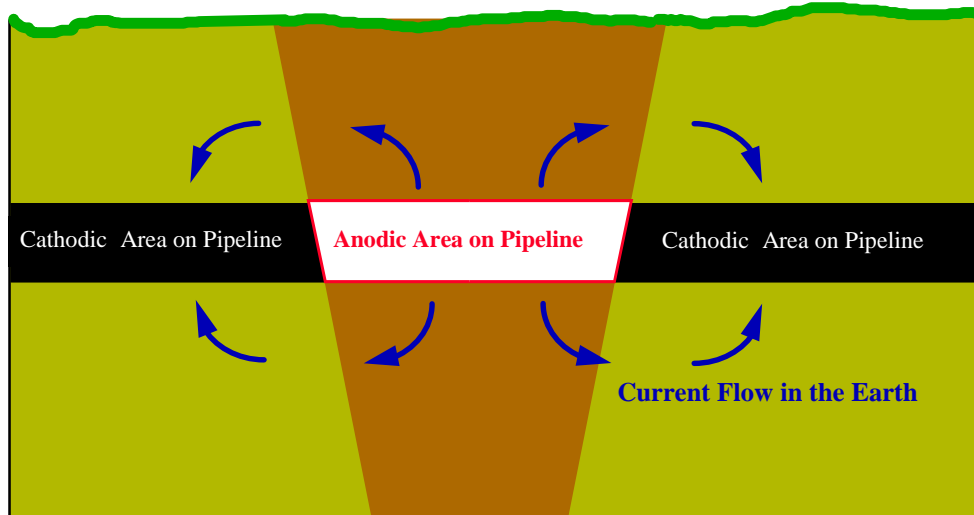


Figure 3
Concentration Cell Caused by Different Environments

2.2.2 OXYGEN CONCENTRATION. Pipelines or tanks that are exposed to an electrolyte with a low oxygen concentration are generally anodic to the same material exposed to an

electrolyte with a high oxygen content. This is most severe when a pipeline or tank is placed on the bottom of the excavation, then backfill is placed around the remaining part of the structure. The backfill contains a relatively high amount of oxygen during the excavation and backfill operation. This can also occur when the metal is exposed to areas that have different levels of oxygen content.

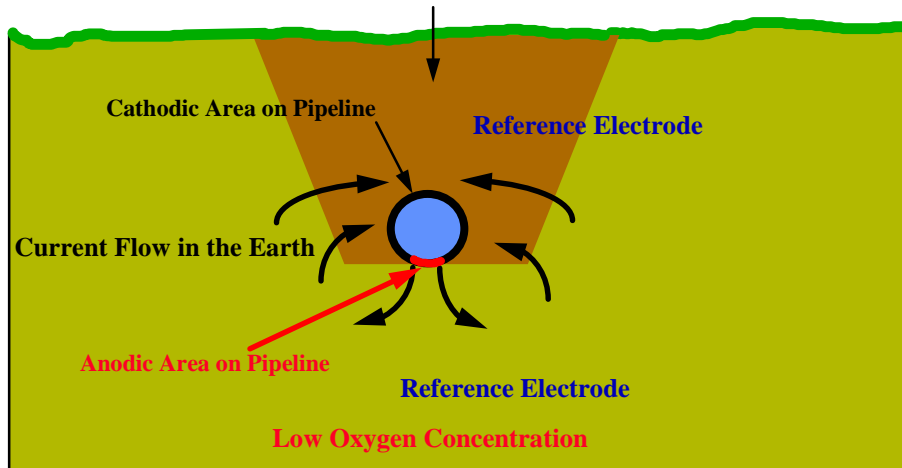


Figure 4

Concentration Cell Caused by Different Concentrations of Oxygen

2.2.3 MOIST/DRY ELECTROLYTE. Pipelines or tanks that are exposed to areas of low and high water content in the electrolyte also exhibit different potentials in these different areas. Generally, the area with more water content becomes the anode in this electrochemical corrosion cell. This is most severe when a pipeline passes through a swampy area adjacent to dry areas or a tank is located in dry soil, but the water table in the soil saturates the tank bottom.

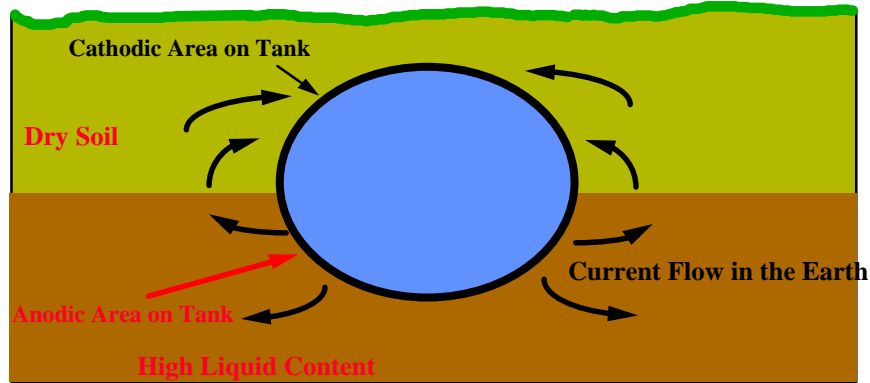


Figure 5

Concentration Cell Caused by Different Concentrations of Water

2.2.4 NON-HOMOGENEOUS SOIL. Pipelines or tanks that are exposed to an electrolyte that is not homogeneous exhibit different electrical potentials in the different components of the soil. This can occur in any soil that is a mixture of materials from microscopic to substantially sized components. The area(s) with the higher potential becomes the anode in this electrochemical corrosion cell. This is most severe when a pipeline or tank is placed in an electrolyte with components that cause large potential differences or where there are small anodic areas and large cathodic areas.

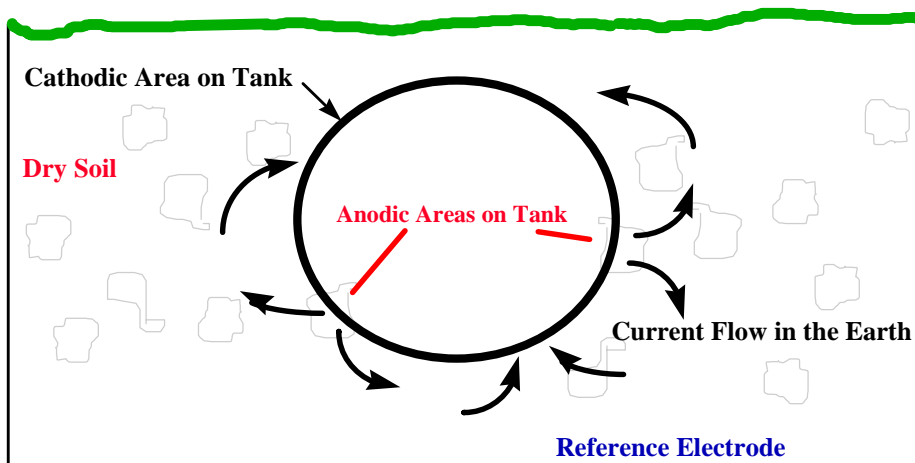


Figure 6

Concentration Cell Caused by Non-Homogeneous Soil

2.2.5 CONCRETE/SOIL INTERFACE. Pipelines or tanks that are in contact with cement and exposed to another electrolyte exhibit different potentials in each area. The area not in contact with cement becomes the anode in this electrochemical corrosion cell. A pipeline or tank that is in contact with concrete and soil (or water) may be a very severe corrosion cell, because of the high potential difference of the metal in the two different electrolytes.

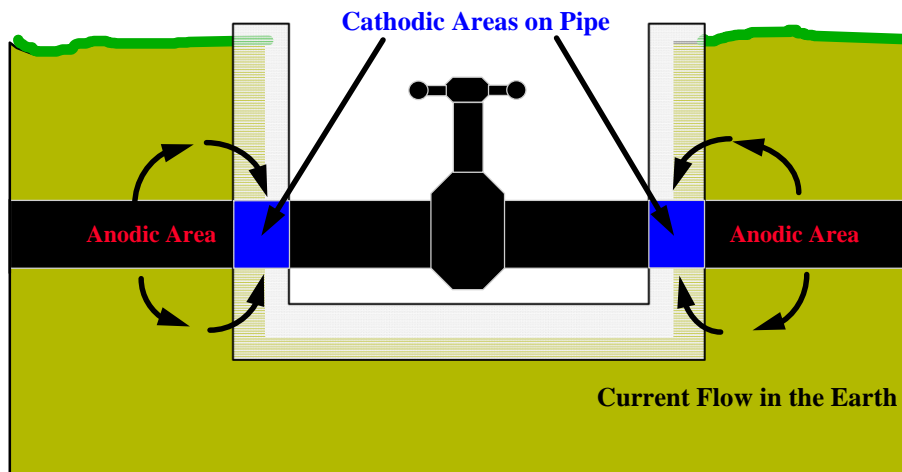


Figure 7

Concentration Cell Caused by Concrete and Soil Electrolytes

2.2.6 BACKFILL IMPURITIES. This is similar to the non-homogeneous soil concentration cells, except that the “backfill impurities” are materials that do not normally occur in the soil, but are foreign materials mixed into the electrolyte during or between the excavation and the backfill process. This can be any material that forms anodic or cathodic areas on the structure. It can also be an isolating material that forms different conditions in the electrolyte, or a metallic material which actually becomes an anode or cathode when in contact with the structure (galvanic corrosion).

2.2.7 BIOLOGICAL EFFECTS. Biological organisms may attach to and grow on the surface of a metal, causing a different environment that in some cases may be extremely

corrosive to the metal. Most bacteria that have been implicated in corrosion grow best at temperatures of 15 °C to 45 °C (60 °F to 115 °F). These bacteria are generally classed by their oxygen requirements, which vary widely with species, and may be aerobic or anaerobic. Their metabolism products influence the electrochemical reaction by forming materials or films (slime) that act as a diffusion barrier, or change ion concentrations and pH. Some bacteria are capable of being directly involved in the oxidation or reduction of metal ions and can shift the chemical equilibrium that influences the corrosion rate. Aerobic bacteria form oxygen and chemical concentration cells, and in the presence of bacteria capable of oxidizing ferrous ions, further accelerate corrosion. Many produce mineral or organic acids that may also breakdown structure coatings. The breakdown products are then sometimes usable as food, leading to accelerated corrosion.

2.3 GALVANIC CORROSION. This type of corrosion is caused by an electrochemical corrosion cell developed by a potential difference in the metal that makes one part of the cell an anode, and the other part of the cell the cathode. Different metals have different potentials in the same electrolyte. This potential difference is the driving force, or the voltage, of the cell. As with any electrochemical corrosion cell, if the electrolyte is continuous from the anode to the cathode and there is a metallic path present for the electron, the circuit is completed and current will flow and electrochemical corrosion will occur.

2.3.1 DISSIMILAR METALS. The most obvious form of this type of corrosion is when two different kinds of metals are in the electrolyte and metallically bonded or shorted in some manner. All metals exhibit an electrical potential; each metal has its distinctive potential or voltage. When two different metals are connected, the metal with the most negative potential is the anode; the less negative metal is the cathode. An “active” metal is a metal with a high negative potential, which also means it is anodic when compared to most other metals. A “noble” metal is a metal with a low negative potential, which also means it is cathodic when compared to most other metals. Dissimilar metal corrosion is most severe when the potential difference between the two metals, or “driving voltage,” is the greatest. Examples of active metals are new steel, aluminum, stainless steel (in the

active state), zinc, and magnesium. Examples of noble metals are corroded steel, stainless steel (in the passivated state), copper, bronze, carbon, gold, and platinum. One example of this type of corrosion occurs when coated steel pipelines are metallurgically connected to bare copper grounding systems or other copper pipelines (usually water lines).

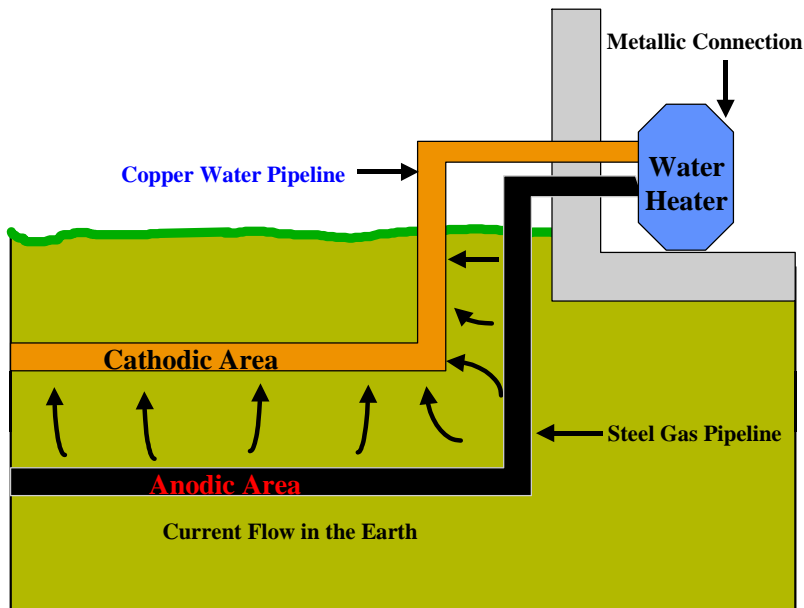


Figure 8
Galvanic Corrosion Cell Caused by Different Metals

2.3.2 OLD-TO-NEW SYNDROME. This type of corrosion can also be rather severe. Steel is unique among metals because of the high energy put into the process of producing the steel (Paragraph 2.1). New steel is more active than corroded steel. The potential difference between the high negative potential of the new steel and the low negative potential of the old steel is the driving force, or voltage, of this electrochemical corrosion cell. A severe and common example of this type of corrosion is when an old bare steel pipeline fails, and a small section of the pipeline is replaced with a coated section of the new steel. The new section is the anode and corrodes to protect the large cathode, resulting in failure of the new section.

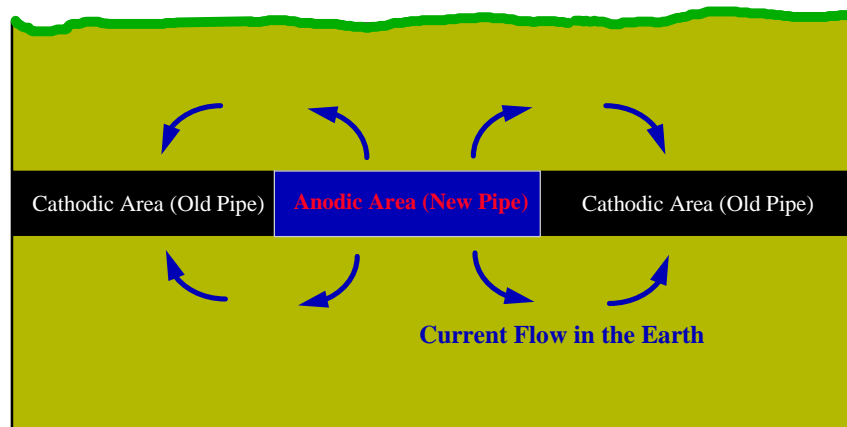


Figure 9

Galvanic Corrosion Cell Caused by Old and New Steel

2.3.3 DISSIMILAR ALLOYS. The most obvious example of this type of corrosion is different metal alloys. For example, there are over 200 different alloys of stainless steel. Also, metals are not 100 percent pure. They normally contain small percentages of other types of metals. Different batches of a metal vary in content of these other metals. Different manufacturers may use different raw materials and even the same manufacturer may use raw materials from different sources. Each batch of metal may be slightly different in electrical potential. Even in the same batch of metal, the concentration of these other materials may vary slightly throughout the finished product. All these differences will produce the electromotive force for this type of corrosion to occur.

2.3.4 IMPURITIES IN METAL. No manufacturing process is perfect. Small impurities may be mixed into the metal as it is produced or cooled. Impurities at the surface of the metal may become part of the electrolyte causing concentration cell corrosion, or if metallic, they may be anodic (corrodes and leaves a pit behind), or cathodic (corroding surrounding metal).

2.3.5 MARRED OR SCRATCHED SURFACE. A marred or scratched surface becomes anodic to the surrounding metallic surface. This is similar to the old-to-new syndrome, where new steel is anodic to the old steel. This electrochemical corrosion cell is set up

by the difference in the electrical potential of the scratched surface compared to the remaining surface of the structure. Threaded pipe, bolts, marks from pipe wrenches and other tools, and marks from shovels and backhoes are common examples of this type of electrochemical corrosion cell. This situation is further aggravated because the metal thickness is also reduced in these areas.

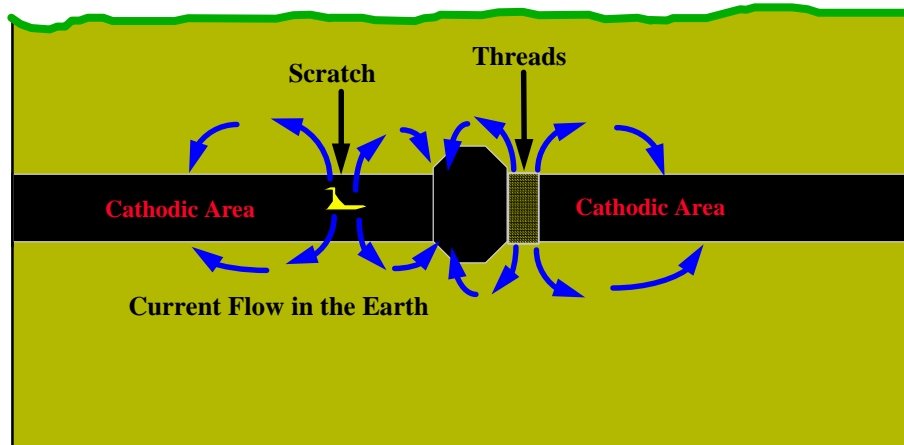


Figure 10

Galvanic Corrosion Cell Caused by Marred and Scratched Surfaces

2.3.6 STRESSED METALLIC SECTION. Metal that is under stress becomes anodic to metal that is not under stress. Bolts, bends, structural or mechanical stresses, and soil movement are common examples. This situation results in the metal shearing or cracking from the stress long before corrosion has penetrated the entire thickness of the structure.

2.3.7 TEMPERATURE. Metal that is at an elevated temperature becomes anodic to the same metal at a lower temperature. As previously discussed, a more active metal is anodic to a more noble metal. Since elevated temperature makes a metal more active, it becomes anodic to the rest of the metal. This electrochemical corrosion cell may cause accelerated corrosion on metals that are at elevated temperatures.

2.3.8 SIMULTANEOUS SOURCES OF CORROSION. Each of these previously discussed types of electrochemical corrosion cells may cause significant corrosion, but in

many cases there are a combination of many different types of corrosion simultaneously at work to make corrosive situations even worse on the metal surface. Understanding the actual cause of corrosion is of utmost importance in maintaining a submerged or buried metallic structure, such as a pipeline or storage tank. When corrosion is noted, or when a corrosion leak occurs, it is essential that the cause of the corrosion be identified so that corrective action can be taken. Once the type of corrosion is understood, the method of repairing the cause of the corrosion can be easily determined and future leaks can be prevented. In many cases, the location of the anodic area can be predicted by understanding the process of corrosion. These anodic areas tend to be in the worst possible places. Examples are pipeline rivers or swamp crossings, pipelines entering pits or foundations, pipelines under stress and pipelines at elevated temperatures. In a majority of leak situations, the primary concern is to patch the hole in the pipeline or tank. Without an understanding of corrosion and corrosion control, a bad situation can be made even worse. Even considering the criticality of stopping a gushing leak, it is imperative to fix the cause of the leak. This means taking action to identify and mitigate the cause of the leak. In some situations it may be a failed insulator or broken bond wire which actually caused the leak. Probably the most common cause of corrosion leaks are the methods or materials used from previous leak repairs, breaking or shorting the continuity. An example of many types of corrosion at work simultaneously can be demonstrated by the following figure, which shows most of the different types of corrosion discussed.

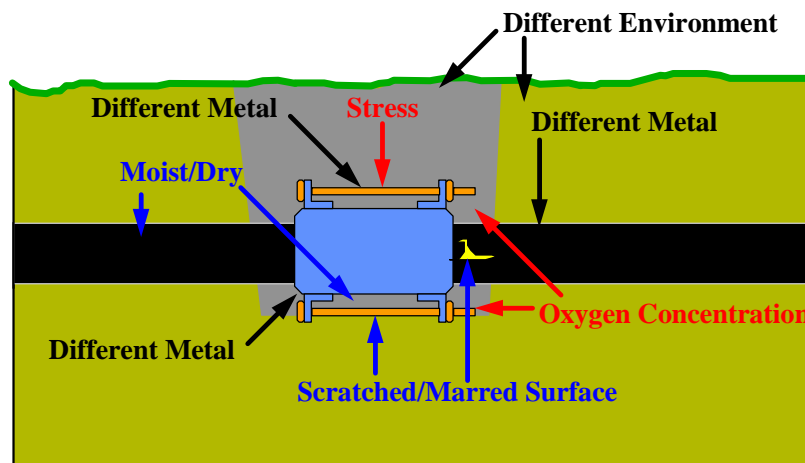


Figure 11. Combination of Many Different Corrosion Cells at Work

2.4 STRAY CURRENT CORROSION. This type of electrochemical corrosion cell is caused by an electromotive force from an external source affecting the structure by developing a potential gradient in the electrolyte or by inducing a current in the metal, which forces part of the structure to become an anode and another part a cathode. This pickup and discharge of current occurs when a metallic structure offers a path of lower resistance for current flowing in the electrolyte. This type of corrosion can be extremely severe because of very high voltages that can be forced into the earth by various sources. The potential gradient in the electrolyte forces one part of the structure to pick up current (become a cathode) and another part of the structure to discharge current (become an anode). Stray current corrosion occurs where the current from the external source leaves the metal structure and enters back into the electrolyte, normally near the external power source cathode. The external power source is the driving force, or the voltage, of the cell. Stray current corrosion is different from natural corrosion because it is caused by an externally induced electrical current and is basically independent of such environmental factors as concentration cells, resistivity, pH and galvanic cells. The amount of current (corrosion) depends on the external power source, and the resistance of the path through the metallic structure compared to the resistance of the path between the external source's anode and cathode.

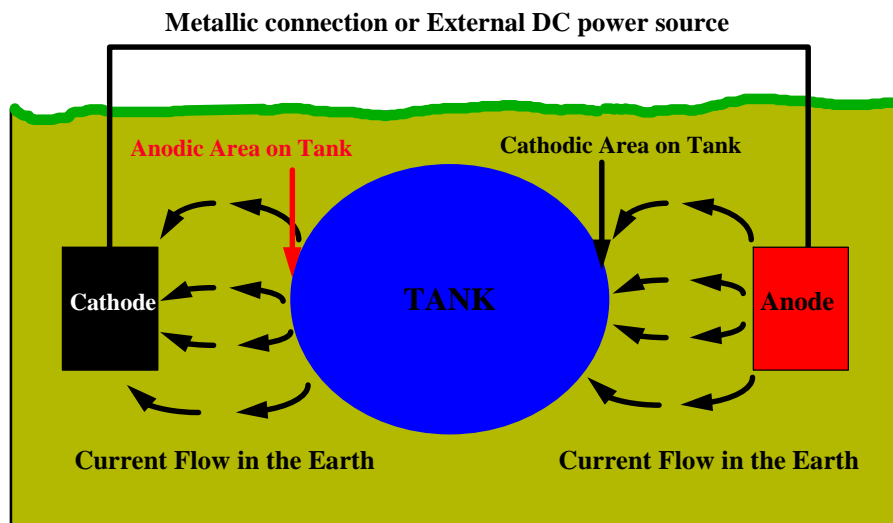


Figure 12

Stray Current Corrosion Cell Caused by External Anode and Cathode

An example of stray current corrosion is caused by impressed current cathodic protection systems, where a “foreign” electrically continuous structure passes near the protected structures anodes and then crosses the protected structure (cathode). This corrosion is usually found after failures in the foreign structure. Stray current corrosion is the most severe form of corrosion because the metallic structure is forced to become an anode and the amount of current translates directly into metal loss. If the amount of current leaving a structure to enter the electrolyte can be measured, this can be directly translated into metallic weight loss. Different metals have specific amounts of weight loss when exposed to current discharge. This weight loss is normally measured in pounds (or kilograms) of metal lost due to a current of one amp for a period of one year (one amp-year). For example, if a stray current of just two amps were present on a steel pipeline, the result would be a loss of 18.2 kilograms (40.2 pounds) of steel in one year. For a coated pipeline, this could result in a penetration at a defect in the coating in an extremely short period of time, sometimes only a few days.

METAL (ION)	WEIGHT LOSS (KILOGRAMS)	WEIGHT LOSS (POUNDS)
Magnesium	4.00	8.8
Aluminum	2.95	6.5
Zinc (Zn ⁺⁺)	10.66	23.6
Chromium	5.65	12.5
Cadmium	18.39	40.5
Iron (Fe ⁺⁺)	9.13	20.1
Cobalt	9.63	21.2
Nickel	9.58	21.1
Copper (Cu ⁺)	20.77	45.6
Copper (Cu ⁺⁺)	10.39	22.8
Tin	19.39	42.7
Lead (Pb ⁺⁺)	33.87	74.5
Carbon (C ⁺)	1.91	4.2
Carbon (C ⁺⁺⁺⁺)	1.00	2.2

Table 1

Weight Loss of Specific Metals at a Current of One Ampere for One Year (1 Amp-Year)

2.4.1 DC TRANSIT SYSTEMS. Electrified railroads, subway systems, street railway systems, mining systems, and trolleys that operate on DC are major sources of stray current corrosion. These systems may operate load currents of thousands of amperes at a common operating potential of 600 volts. Tracks are laid at ground level and are not completely insulated from the earth. Some part of the load current may travel through the earth. In the event of a track fault, these currents could be extremely high. Buried or submerged metallic structures in the vicinity (several miles) of these tracks could be subject to stray current effects. Pipelines that run parallel, cross under the tracks, or are located near the DC substation, are especially prone to these stray currents. If there are high resistance joints in the pipeline, the current may bypass the joint, leaving the pipeline on one side of the joint, and returning on the other side. Since the source of the stray current is moving, it may be necessary to monitor the metallic structure over a 24-hour period to see if these currents affect it.

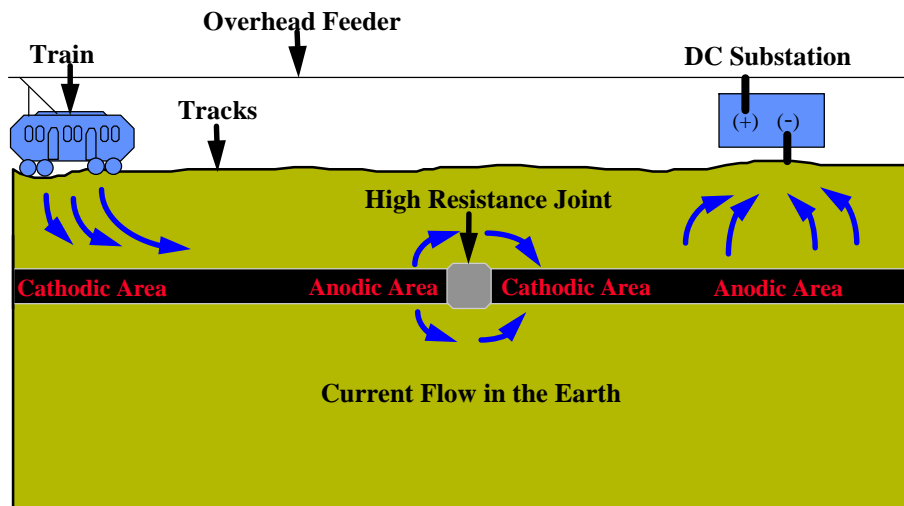


Figure 13

Stray Current Corrosion Cell Caused by a DC Transit System

2.4.2 HIGH VOLTAGE DIRECT CURRENT (HVDC) ELECTRIC TRANSMISSION LINES. Power distribution systems are another source of stray currents. Most power systems are AC, although sometimes DC systems with grounded neutral may be used. These transmission lines, under fault conditions, may use the earth as the return path for

the DC current. Because DC requires only two-wire instead of three-wire transmission, it is sometimes used when large amounts of power needs to be transported large distances. Conversion units are located at each end of the transmission lines. Each of these conversion units are connected to a large ground grid. Any unbalanced load would result in a current in the earth between these two ground grids. These unbalanced currents are naturally not constant; they vary in direction and magnitude. HVDC line voltages may be 750,000 volts or higher.

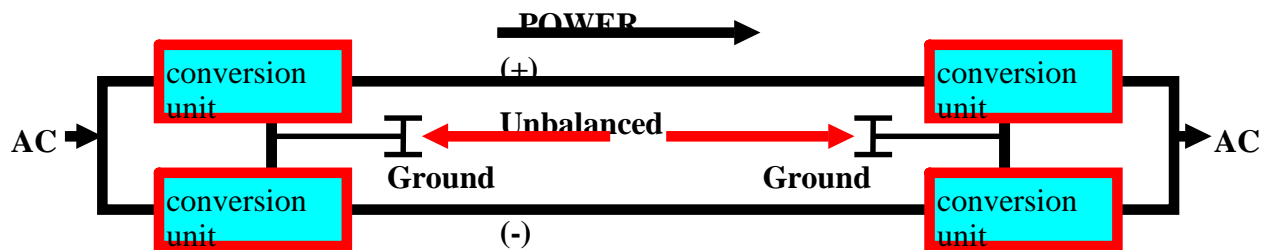


Figure 14

Stray Current Corrosion Cell Caused by an HVDC Transmission System

2.4.3 WELDING OPERATIONS. DC welders are a source of DC current. One example of this type of electrochemical corrosion cell occurs when an electric welding machine on board a metallic ship with a grounded DC line on shore, forces the current to leave the bottom of the ship (anode) to return to the grounding system (cathode).

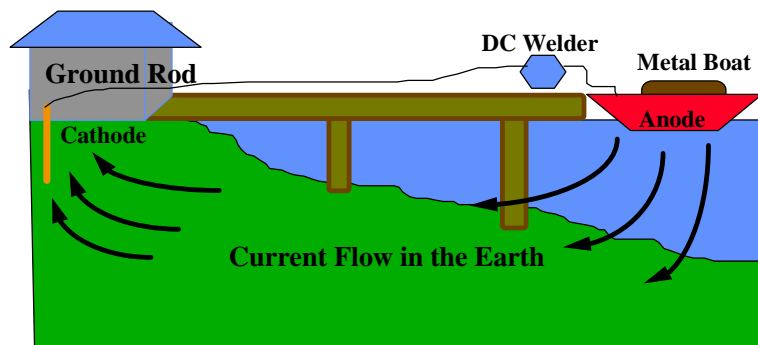


Figure 15

Stray Current Corrosion Cell Caused by a DC Welding Operation

2.4.4 CATHODIC PROTECTION SYSTEMS. Cathodic protection systems are a major source of stray current on other metallic structures. An example of this electrochemical corrosion cell is when a foreign pipeline passes near an anode, and then crosses the protected structure (cathode).

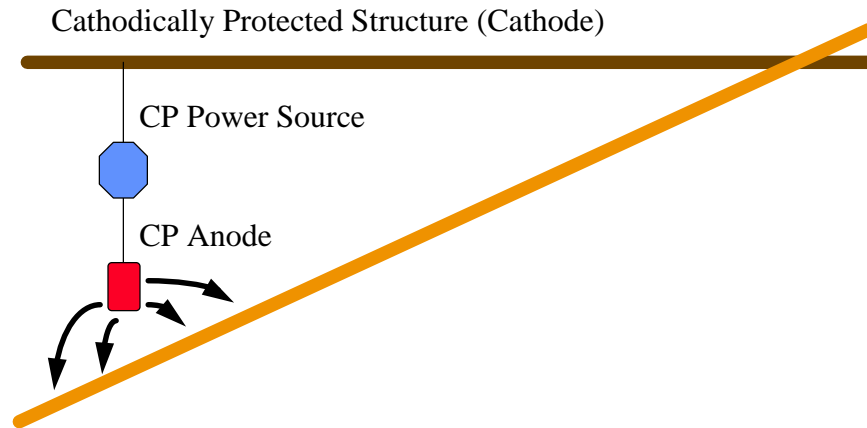


Figure 16

Stray Current Corrosion Cell Caused by a Cathodic Protection System

2.4.5 TELLURIC CURRENTS. Disturbances in the earth's magnetic field sometimes cause induced current in metallic structures. Some areas may be prone to these effects due to mineral deposits or other physical or environmental characteristics. These currents may also be caused by severe sun spot activities. The varying earth's magnetic field intercepting the metallic pipeline generates a voltage on the structure. Where this current leaves the structure to enter into the earth, corrosion occurs.

3. RATE OF CORROSION. Since almost all corrosion is an electrochemical reaction, anything that affects the speed of a chemical reaction or the amount of current flow will affect the rate of corrosion. Ohms law is applicable to the electrical portion of the corrosion cell. The rate of corrosion is directly proportional to the amount of current that flows in the electrochemical corrosion cell. If the current can be measured, an exact calculation of the metal loss can be made. This means that a measurement in amps or milliamps can be mathematically calculated in kilograms (pounds) per amp year. One amp year is one amp flowing for a period of one year. Different metals have different consumption rates.

3.1 ELECTRICAL EFFECTS ON THE RATE OF CORROSION. Any factor that affects the amount of current flowing in a circuit will affect the rate of the electrical portion of the electrochemical reaction (corrosion). Following is a description and example of the factors affecting the rate of the electrical portion of corrosion.

3.1.1 POTENTIAL DIFFERENCE. The potential difference between the anode and the cathode is electromotive force and can be measured as voltage. The greater this difference, or voltage, the greater the potential of corrosion. The voltage is directly proportional to the current, and therefore the corrosion, in an electrochemical cell. If the voltage is doubled, and all other factors remain the same, the amount of corrosion doubles.

3.1.2 RESISTIVITY OF THE ELECTROLYTE. The resistivity of the electrolyte is normally a significant factor in determining the rate of corrosion. This is an uncontrollable characteristic of the soil or water (the electrolyte). The definition of an electrolyte is a material that will allow ions to migrate, and the resistivity is the rate at which it allows ions to migrate. Resistivity is the inverse of the conductivity and is measured in ohm-centimeters. Resistivity is inversely proportional to current, and therefore to corrosion, in an electrochemical cell. If the resistivity is doubled, and all other factors remain the same, the amount of corrosion is cut in half.

3.1.3 CONTACT RESISTANCE. The contact resistance of the anode to electrolyte and of the cathode to electrolyte has the same effect as resistivity, since it is a measure of resistance. The lower the resistance, the greater the current (corrosion). If the contact resistance of the anode or the cathode is doubled, and all other factors remain the same, the amount of corrosion is cut in half. Note that if the contact resistance of both the anode and the cathode is doubled, the amount of corrosion is only one-fourth of its original value.

3.1.4 COATING OF THE STRUCTURE. Coating of the structure normally raises the contact resistance of the anode and the cathode since most coatings are dielectric in nature (non-conductive). See Paragraph 3.1.3.

3.1.5 POLARIZATION OF THE STRUCTURE. Polarization is the change of the electrode potential as a result of the electrochemical current flow and usually results in the formation of a film on the electrode surface called a “polarization film.” Polarization film consists partly of a thin film of hydrogen on the cathode surface. This polarization film and other changes have beneficial effects at the cathode. The layer of hydrogen acts as an additional coating, water is driven away from the surface of the cathode, ion concentration in the electrolyte is reduced, the contact resistance of the electrode to electrolyte is raised, and essentially, corrosion cell current no longer flows or is reduced to a small fraction of its previous value.

3.1.6 AMOUNT OF CURRENT FLOW. The amount of current flow directly influences the rate of corrosion. Corrosion can be determined from the amount of current flow. Each metal has definite characteristics in the number of electrons given up in the oxidation process and the number of atoms in a kilogram (pound) of the metal. This can, therefore, be translated to kilograms (pounds) per amp. The normal unit of measure encompasses a one year period, kilograms (pounds) per amp-year.

3.2 CHEMICAL EFFECTS ON THE RATE OF CORROSION. Any factor that affects the speed of a chemical reaction will affect the rate of the chemical portion of the

electrochemical reaction (corrosion). The following is a description and example of the factors affecting the rate of the chemical portion of corrosion.

3.2.1 TEMPERATURE. Temperature is a complex external variable. Generally, as temperature increases, corrosion increases. However this also depends on availability of oxygen. The corrosion rate of iron in a system closed to the atmosphere has been shown to increase almost linearly with temperature from about 40 °C to 160 °C (105 °F to 320 °F). However, in an open system, the corrosion rate increases up to about 80 °C (175 °F) and then decreases. It should also be noted that the pH of a liquid will become more acidic as the temperature is raised, also affecting the corrosion rate. For example, 25 parts-per-million alkalinity water at a pH of 9.4 at 26.7 °C (80 °F), has a pH of 8.0 at 93.3 °C (200 °F).

3.2.2 ION CONCENTRATION. Ion concentration has an effect similar to pH, except that the corrosion rates of some metals are affected by the presence of certain ions. For example, aluminum corrodes not only by alkalis, but shows pronounced attack by traces of copper ions in aqueous media and is subject to rapid attack by mercury metal, mercury ions, and anhydrous chlorinated solvents. For iron, chloride and chloride ions may increase the corrosion rate in some electrolytes. However, bromide and iodide ions may inhibit corrosion (slow down the rate of corrosion). The effect of concentration of one component on corrosion is often dependent on other environmental variables, such as the presence of salts, availability of oxygen, and differences in oxygen solubility, pH, and temperature.

3.2.3 ELECTRON CONCENTRATION. High concentrations of free electrons in the electrolyte around the cathode can inhibit corrosion by that saturation reaching the maximum ion migration rate of the environment. Very low concentrations of free electrons in the electrolyte around the cathode may increase the corrosion rate by the chemical nature of equilibrium, where the electrons readily migrate into the environment.

3.2.4 PH OF THE ELECTROLYTE. The pH of the soil or water electrolyte in an electrochemical corrosion cell affects the rate of the corrosion by speeding or slowing the chemical reactions at the anode and/or the cathode. The pH of an electrolyte is basically the concentration of hydrogen ions. A pH below 4 increases the corrosion rate of mild steel. At a pH of 3 the corrosion rate increases tremendously. Amphoteric metals also show an increase in the corrosion rate in alkaline environments. Aluminum and lead are examples of amphoteric metals.

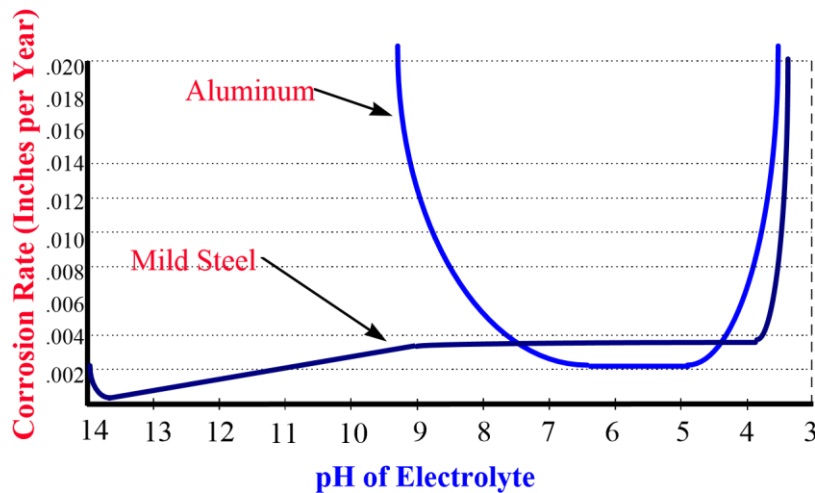


Figure 17

Effect of Electrolyte pH on the Rate of Corrosion

3.2.5 COATING OF THE STRUCTURE. The coating of a structure may affect the ion migration rate at the anode and at the cathode. Slowing the migration rate corresponds to slowing the corrosion rate. Structure coatings may also affect other environmental factors such as the temperature, pH, and ion concentration.

3.2.6 POLARIZATION OF THE STRUCTURE. Polarization acts as an additional coating, and affects pH levels and ion concentration in the electrolyte adjacent to the structure.

3.3 AREA RELATIONSHIPS. The relative size of the anodic area and the cathodic area can greatly affect the rate of corrosion, especially under stray current conditions. When

the anodic area is very small, and the cathodic area is large, the corrosion is concentrated and generally becomes more severe. Under stray current conditions, this size relationship is extremely critical. The current density at the cathode under stray current conditions can be extremely high, resulting in failure of the structure in an extremely short period of time.

4. GALVANIC SERIES. The two major factors affecting the rate of corrosion in an electrochemical corrosion cell are the electrical characteristics of the electrolyte (resistivity), and the voltage difference between the anode and the cathode. The resistivity of the electrolyte is normally not a controllable characteristic, but it is measurable. The voltage or potential of the metal anode and cathode is also a measurable characteristic. The voltage measured is the voltage difference between the two electrodes. Since this voltage is dependent only on a voltage difference, there must be a reference that all other electrodes can be measured against, to give a relational table, or series, of the potential of any given electrode. As stated earlier, all metals have different potentials, and any given metal has different potentials in different electrolytes. For an electrode to be used as a reference to measure other electrodes, the metal and the electrolyte in contact with the metal must be specified. Once this is done, the electrode becomes a reference electrode.

Many types of reference electrodes have been used. In the laboratory the hydrogen/hydrogen (hydrogen electrode, hydrogen electrolyte) is common. For field use, the copper/copper sulfate (copper electrode, fully saturated copper sulfate electrolyte) is in common use, except in salt water where silver/silver chloride (silver electrode, silver chloride electrolyte) is used and must be adjusted by the factor or the chloride content of the electrolyte. These references are merely stable electrodes with a known potential used to measure the potential of unknown electrodes. Using these references, the potential value of any metal in any electrolyte can be recorded for future reference and compared to other electrodes. A table of such measurements is called a galvanic series of measurements. Each table must specify the reference electrode used to accomplish the measurements, and the electrolyte the unknown electrodes were in, to allow for interpretation by corrosion experts. This series can then be used to determine which electrode will be the anode (and corrode) in an electrochemical corrosion cell.

GALVANIC SERIES OF METALS: METAL OR ALLOY REFERENCE:	SILVER/SILVER CHLORIDE	SATURATED CALOMEL	COPPER/COPPER SULFATE
ELECTROLYTE	FLOWING SEAWATER	SEAWATER	NEUTRAL SOILS AND WATER
Pure Magnesium		-1.60 to -1.64	-1.75
Standard Magnesium			-1.55
Zinc		-0.98 to -1.04	-1.10
Aluminum Alloy	-0.79	-0.77 to -1.00	-1.05
Pure Aluminum			-0.80
Low-Carbon Steel (clean and shiny)	-0.61	-0.60 to -0.72	-0.50 to -0.80
Low-Carbon Steel (rusted)			-0.20 to -0.50
Cast Iron (not graphitized)	-0.61	-0.60 to -0.72	-0.50
Lead		-0.18 to -0.23	-0.50
Low-Carbon Steel (in concrete)			-0.20
Brass			
Copper, Brass, Bronze	-0.36		-0.20
High-Silicon Cast Iron			-0.20
Mill Scale on Steel			-0.20
Carbon, Graphite, Coke	+0.25		+0.30

Table 2

Electrical Potential of Metals with Various Reference Cells

Note that there is a substantial difference between the potential of steel and all other metals potentials. Steel varies greatly from clean and shiny to rusty (Paragraph 2.3.2 and Figure 9).

5. INTRODUCTION TO CATHODIC PROTECTION. Cathodic protection (CP) is the prevention of corrosion by making a metal, which would ordinarily behave like an anode and corrode, behave like a cathode and be free from corrosive attack. Essentially, CP is predetermining the anode in the corrosion cell, or making a large corrosion cell to overcome the other smaller corrosion cells. In cathodic protection this is achieved in one of two basic ways. The first way is by using the galvanic series (Table 2) to select a more active metal, install that metal in the electrolyte and provide a metallic path. This method is called sacrificial cathodic protection, or galvanic cathodic protection. The galvanically more active metal (anode) is installed to sacrifice itself to protect the structure (cathode). The voltage (and resultant current) is merely the potential difference of the two different types of metal. The second basic method of cathodic protection is applying a source of DC current that forces the current to flow from an installed anode(s) to the structure, causing the entire structure to be a cathode. This method is called impressed current cathodic protection. A rectifier, solar cell, battery, generator, or some other DC power supply is installed in the circuit. The selection of anode material is free from the galvanic series considerations and anodes are chosen which are economical, or metals which have a small weight loss per ampere year of current (Table 1). The current required for cathodic protection depends upon the metal being protected and the environment. The potentials required to determine adequate protection (criteria) are given in Chapter 6 of this handbook. To achieve these protective potentials, current must flow from the anode to the structure being protected. The amount of current required to protect a given structure is proportional to the area of the structure that is exposed to the electrolyte. Therefore, current requirements are usually given as current densities in units of amperes or milliamperes (0.001 amperes) per square meter (foot) of exposed surface. Coatings are dielectric in nature, and to some degree, isolate the structure from the electrolyte. For coated structures, the amount of current required is much lower than for bare structures, as only those areas where the coating has been damaged or has deteriorated, require or will receive current. The coating efficiency is the percent of the structure that is effectively isolated from the electrolyte. Efficiencies of coatings can vary greatly due to the type of coating, quality of surface preparation, quality of application, structure handling, structure installation, backfill techniques, and backfill material used. Coatings efficiencies normally

range from about 80 percent up to 99.7 percent. Current requirements for coated structures are best determined by actual testing after the structure is installed. The current densities required for cathodic protection depend on the metal being protected and the environment. Typical values for the current densities required for cathodic protection of bare steel structures are shown in Table 3. Typical values of the current densities required for cathodic protection of coated steel structures are shown in Table 4.

ENVIRONMENT	MILLIAMPERES	
	PER SQUARE METER	PER SQUARE FOOT
Soil with resistivity >30,000 ohm-cm	10.7– 21.5	1- 2
Soil with resistivity 10,000 — 30,000 ohm-cm	21.5– 32.3	2- 3
Soil with resistivity 1,000 — and 10,000 ohm-cm	43.0– 64.6	4- 6
Soil with resistivity <1,000 ohm-cm	75.3– 269.1	7- 25
Highly aggressive soil with anaerobic bacteria	161.5– 430.5	15- 40
Still fresh water	21.5– 43.0	2- 4
Moving fresh water	43.0– 64.6	4- 6
Turbulent fresh water	53.8– 161.4	5- 15
Hot fresh water	53.8– 161.4	5- 15
Still seawater	10.7– 32.3	1- 3
Moving seawater	32.3– 269.1	3- 25
Concrete	5.4– 16.1	0.5– 1.5

Table 3
Current Requirements for Cathodic Protection of Bare Steel

MILLIAMPERES PER SQUARE METER (FOOT)			
STRUCTURE	BARE	COATED	COATING EFFICIENCY
Pipeline, epoxy or other high performance coating	10.76(1)	0.010–0.054(0.001–0.005)	99.5 - 99.9
Pipeline, reinforced coal tar or asphalt enamel	10.76(1)	0.054–0.269(0.005–0.025)	97.5 - 99.5
Pipeline, grease coating with wrapper	10.76(1)	0.538–1.615(0.05–0.15)	85.0 - 95.0
Pipeline, asphalt mastic ½” thick	10.76(1)	0.001–0.005(0.001–0.005)	99.5 - 99.9
Pipeline, old asphalt or other deteriorated coating	10.76(1)	0.538–3.767(0.05–0.35)	65.0 - 95.0
Pipeline, old paint coating	10.76(1)	1.076–0.522(0.10–0.30)	70.0 - 90.0
Tank bottoms	32.29(3)	0.538–21.529(0.05–2.00)	33.3 - 98.3
Tanks for cold potable water	32.29(3)	0.538–21.529(0.05–2.00)	33.3 - 98.3
Tanks for cold sea water	53.82(5)	0.538–43.056(0.05–4.00)	20.0 - 99.0
Hot potable water tanks	53.82(5)	0.522–32.292(0.30–3.00)	40.0 - 94.0
Steel sheet piling fresh water side	53.82(5)	1.076–16.146(0.10–1.50)	70.0 - 98.0
Steel sheet piling sea water side	53.82(5)	1.076–21.529(0.10–2.00)	60.0 - 98.0
Steel sheet piling soil side	21.5 (2)	0.215–4.304(0.002-0.40)	80.0 - 99.0

Table 4
Current Requirements for Cathodic Protection of Coated Steel

6. GALVANIC CATHODIC PROTECTION. In galvanic anode systems, the current required for cathodic protection is supplied by the corrosion of an active metal. Sacrificial anode systems depend upon the differences in corrosion potential that are established by the corrosion reactions that occur on different metals or alloys. For example, the natural corrosion potential difference of iron referenced to a copper/copper sulfate reference electrode is commonly found to be between -0.4 and -0.6 volts DC. The natural corrosion potential of zinc referenced to a copper/copper sulfate reference electrode is about -1.1 volts. Thus, if the two metals are electrically connected, the potential difference between the iron and the zinc is approximately 0.5 to 0.7 volts DC, and the corrosion of the zinc becomes the source of current and prevents corrosion of the iron cathode. This is illustrated in Figures 18 and 19. Zinc, magnesium, and aluminum alloys all have potentials that are sufficiently more negative than iron or steel and may be useful for the protection of those structures in many environments. Other metals such as copper and copper alloys have a lower potential than iron or steel and are easily protected by steel (and many other metals). Materials such as aluminum alloys that have a higher potential than iron or steel are more difficult to protect, but even aluminum alloys can be effectively protected by magnesium alloys or commercially pure magnesium. In the process of providing electrons for the cathodic protection of a less active metal, the more active metal (anode) corrodes. The more active metal (anode) is sacrificed to protect the less active metal (cathode). The amount of corrosion is dependent on the metal being used as an anode and is directly proportional to the amount of current supplied. Another factor is the anode efficiency, which accounts for the anode's self-corrosion rate and the corrosion rate for the amount of cathodic protection current. To provide a uniform electrolyte around an anode in soil, maintain moisture, and lower the resistance of anode-to-earth, a special backfill is used. This backfill is normally 75 percent gypsum, 20 percent bentonite, and 5 percent sodium sulfate. The anodes in galvanic cathodic protection systems must be periodically inspected and replaced when consumed. In many cases, when the sacrificial anodes have failed, the entire system is replaced with an impressed current system. Sacrificial anode cathodic protection systems are fundamentally very simple. The simplest systems consist of an anode fabricated from an active metal such as zinc that is directly connected to the structure in an area where it will be exposed to the same

environment as the structure being protected. This type of system is widely used in the protection of ships and waterfront structures.

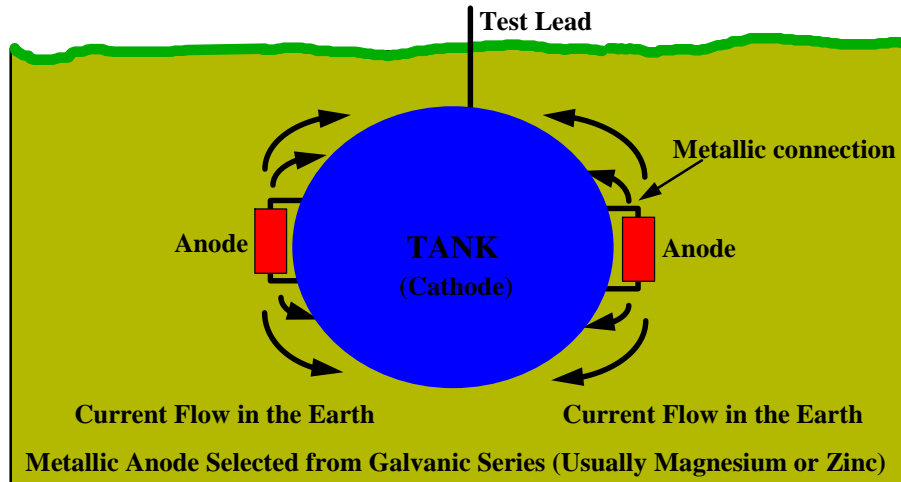


Figure 18

Direct Attachment Galvanic (Sacrificial) Cathodic Protection System

For the protection of underground structures such as pipelines, the anodes are not usually attached directly to the structure, but are placed in the soil, evenly distributed a short distance from the pipeline, and are connected to the pipeline by a wire, usually through a test station. This type of sacrificial anode system is shown in Figure 19. The application of galvanic anodes is limited by the small potential difference (normally less than 1 volt DC) that can be obtained. Galvanic systems generally can only be economically used on small or well-coated structures in low resistivity electrolytes. Refer to Tables 8 and 9 for available voltage and estimated output of various sacrificial anodes in different resistivity electrolytes. Since the amount of cathodic protection is dependent on the current density supplied to the protected structure, the electrolyte resistivity determines the amount of current that the limited voltage will supply. The amount of metal exposed to the electrolyte determines the amount of current required. Uncoated (bare) structures may require an exorbitant number of anodes for adequate protection. In higher resistivity electrolytes, the small anode-structure voltage difference would yield (Ohms law) an extremely small amount of anode current, hence requiring a large amount of anodes. High purity

magnesium anodes have the highest potential available, but in high resistivity soil there would not be sufficient current to protect a structure unless it had a very good coating (Table 9).

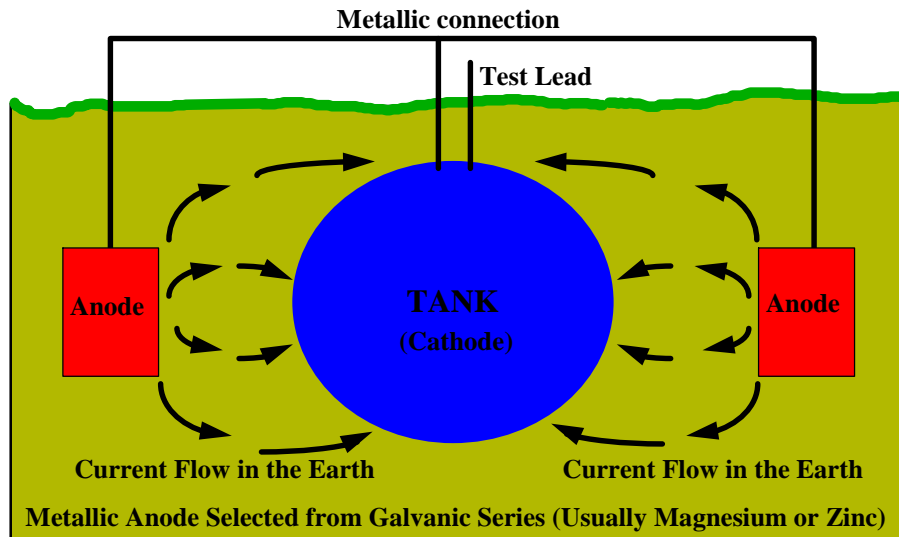


Figure 19

Distributed Sacrificial (Galvanic) Cathodic Protection System

6.1 GALVANIC ANODE TYPES. There are three materials that are commonly used as galvanic anodes: magnesium, aluminum alloy, and zinc. Each material has different grades or types available. Each type is available in a multitude of sizes and shapes.

6.1.1 MAGNESIUM ANODES. Magnesium is the most commonly used sacrificial anode material for the protection of buried structures. Magnesium anodes are also used for the protection of the interiors of water tanks and heaters, heat exchangers and condensers, and waterfront structures. Magnesium anodes are available as castings and extrusions weighing from 0.45 kilograms to over 90.72 kilograms (1 to over 200 pounds) and in a wide variety of shapes. In addition, magnesium alloy anode material is available as a “ribbon” anode that consists of a 10 gauge steel wire surrounded by standard alloy magnesium 9.5 millimeters by 19 millimeters (3/8-inch by 3/4-inch). Two different anode compositions are commonly used. They are the standard alloy and a commercially pure

or “high potential” alloy. The high purity alloy has the highest electrical potential available for any sacrificial anode, approximately 1.75 volts DC to copper/copper sulfate in soil. The standard alloy has the next highest electrical potential available, approximately -1.55 volts to copper/copper sulfate in soil. The composition of each alloy is given in Table 5. The consumption rate for magnesium is 4 kilograms (8.8 pounds) per amp year. The efficiency for providing cathodic protection, considering the self-consumption rate, is higher for the standard alloy than the high purity alloy. For design purposes, the efficiency of both types is 50 percent. It is important that replacement anodes be of the same type as the originals, as the design of the system is dependent on the anode material used, unless replacement of the entire system is accomplished. Anodes of the incorrect type could lead to insufficient protection.

ELEMENT	STANDARD	HIGH POTENTIAL
Aluminum	5.3 - 6.7%	0.1% max
Manganese	0.15% min	0.5 - 1.3%
Zinc	2.5 - 3.5%	
Copper	0.2% max	0.02% max
Silicon	0.1% max	
Iron	0.003% max	0.03% max
Nickel	0.002% min	0.001% max
Other Metals	0.3% maxi	0.3% max total 0.05% max. each
Magnesium	Remainder	Remainder

Table 5
Composition of Magnesium Anodes

6.1.2 ZINC ANODES. Zinc anodes are commonly available in weights from 2.27 kilograms to 113.4 kilograms (5 pounds to 250 pounds) in the form of plates, bars, and rods as shown in MIL-HDBK-1004/10 (Table 10). Zinc is also available as ribbon anodes in 16-millimeter by 22.2-millimeter (5/8-inch by 7/8-inch), 13-millimeter by 14.3millimeter (1/2-inch by 9/16-inch), and 8.7-millimeter by 11.9-millimeter (11/32-inch by 15/32-inch)

sizes, each with a 2.5-millimeter (1/10-inch) diameter galvanized steel wire core. Zinc anodes are most commonly used in immersion service either in fresh or salt water. They are, however, occasionally used in the protection of buried structures when special circumstances are encountered, usually in soil resistivities below 2,000 ohm-centimeters with extremely well coated structures. Two zinc anode compositions are commonly available. They are a standard alloy formulated for use in fresh water and soil and an alloy specially formulated for use in seawater. The composition of these alloys is given in Table 6. As is the case for magnesium alloy anodes, consumed zinc anodes should be replaced with zinc anodes of the same type and size as those originally installed, unless the entire anode system is replaced. Anodes of the incorrect type could lead to insufficient protection. The electrical potential of zinc anodes is approximately -1.10 volts DC to copper/copper sulfate in soil. In some fresh waters, the potential can reverse at temperatures above 58.3 °C (140 °F); consequently, zinc should not be used in those cases. The consumption rate for zinc is 10.6 kilograms (23.5 pounds) per amp year. The efficiency is greater for zinc than magnesium. For design purposes, the efficiency of zinc is 90 percent.

ELEMENT	STANDARD ALLOY	SEAWATER ALLOY
Aluminum	0.005% max	0.10% - 0.50%
Cadmium	0.003% max	0.03% - 0.15%
Iron	0.00014% max	0.005% max
Lead	0.003% max	0.006% max
Copper	-	0.005% max
Silicon	-	0.125% max
Zinc	Remainder	Remainder
NOTES:		
Standard Alloy, Specification ASTM B148-97, Type II		
Seawater Alloy, Specification ASTM B148-97, Type I		

Table 6
Compositions of Zinc Anodes

6.1.3 ALUMINUM ANODES. Aluminum galvanic anodes are a more recent development than either zinc or magnesium alloys. Their primary use is in the protection of structures in seawater. However, they have occasionally been used in fresh water or in soil. When the original anodes used are aluminum alloy and their performance has been satisfactory, they should be replaced with anodes of the same type. Early formulations of aluminum alloys for use as a sacrificial anode contained mercury. While the amount of mercury contained in the alloy is small, the mercury tends to concentrate in the anode stubs that remain after the bulk of the anode has been consumed. Precautions should be taken during removal of the stubs, especially by methods that generate heat, to prevent mercury poisoning. Mercury containing aluminum alloy anode stubs should be disposed of properly. The electrical potential of type I and type II aluminum anodes is approximately 1.10 volts DC to copper/copper sulfate in soil, and for type III, -1.15 volts DC. The consumption rate for aluminum anodes is Type I, 21 kilograms (6.8 pounds) per amp year, Type II, 5.2 kilograms (11.4 pounds) per amp year, and Type III, 3.4 kilograms (7.6 pounds) per amp year. It is important that replacement anodes be of the same type as the originals, as the design of the system is dependent on the anode material used. However, the Type III anodes are now used almost exclusively to avoid the detrimental and safety hazards of mercury.

ELEMENT	TYPE I	TYPE II	TYPE III
Zinc	0.35% - 0.50%	3.5% - 5.0%	3.0%
Silicon	0.10% max	-	0.1%
Mercury	0.035% - 0.048%	0.035% - 0.048%	-
Indium	-	-	0.015% max
Aluminum	Remainder	Remainder	Remainder

Table 7
Compositions of Aluminum Anodes

POTENTIAL DIFFERENCE (DRIVING FORCE) FOR CATHODIC PROTECTION

Protected Structure	MAGNESIUM ANODES		ZINC ANODES		ALUMINUM ANODES		
	Standard	High Purity	Standard	Seawater	Type I	Type II	Type III
Steel	0.7	0.9	0.25	0.25	0.25	0.25	0.3
Aluminum	0.45	0.65	0	0	0	0	0.05
Stainless Steel	0.7	0.9	0.25	0.25	0.25	0.25	0.3
Copper	1.05	1.25	0.6	0.6	0.6	0.6	0.65

Table 8
Sacrificial Anodes Available Voltage for Cathodic Protection

ESTIMATED ANODE CURRENT OUTPUT IN MILLIAMPERES (mA) (SEE NOTE)										
ANODE MATERIAL	SIZE(INCHES)	WEIGHT 500 (POUNDS)	ELECTROLYTE RESISTIVITY (OHM-CM)							
			500	1000	2000	4000	8000	16000	32000	64000
High Purity Magnesium	3x3x5	3	127	64	32	16	8	4	2	1
High Purity Magnesium	2.75x2.75x26	9	242	121	61	30	15	8	4	2
High Purity Magnesium	3.75x3.75x60	40	413	206	103	52	26	13	6	3
High Purity Magnesium	3x3x78	42	456	228	114	57	29	14	7	4
Magnesium	3x3x5	3	102	51	25	13	6	3	2	1
Magnesium	2.75x2.75x26	9	194	97	48	24	12	6	3	2
Magnesium	3.75x3.75x60	40	330	165	83	41	21	10	5	3
Magnesium	3x3x78	42	365	182	91	46	23	11	6	3
Zinc	3x3x5	3	42	21	11	5	3	1	1	0
Zinc	2.75x2.75x26	9	81	40	20	10	5	3	1	1
Zinc	3.75x3.75x60	40	138	69	34	17	9	4	2	1
Zinc	3x3x78	42	152	76	38	19	10	5	2	1

Note: For protection of well-coated steel (single vertical anode, 3 meters (10 feet) from structure).

Table 9
Estimated Output Current of Sacrificial Anodes

Table	TITLE
12	Standard Alloy Magnesium Anodes, Standard Sizes for Use in Soil
13	Standard Alloy Magnesium Anodes, Standard Sizes for Use in Water
14	Standard Alloy Magnesium Anodes, Standard Sizes for Use in Condensers and Heat Exchangers
15	Standard Alloy Magnesium Anodes, Elongated for High Current Output
16	High Potential Alloy Magnesium Anodes, for Use in Soil or Water
17	Standard Alloy Magnesium Anodes, Extruded Rod for Use in Water Tanks and Heaters
18	Standard Sizes of Zinc Anodes, for Use in Soil or Fresh Water
19	Special Sizes of Zinc Anodes, for Use in Soil or Fresh Water
20	Standard Sizes of Zinc Anodes, for Use in Seawater
21	Special Sizes of Zinc Anodes, for Use in Seawater
22	Aluminum Pier and Piling Anodes, Standard Sizes
23	Type I Aluminum Alloy Anodes, Standard Sizes for Offshore Use
24	Type III Aluminum Alloy Anodes for Offshore Use
25	Aluminum Alloy Hull Anodes, Standard Sizes (Types I, II, and III)
26	Aluminum Alloy Bracelet Anodes, Standard Sizes

Table 10. Applicable Tables In MIL-HDBK-1004/10

6.2 ADVANTAGES AND DISADVANTAGES OF GALVANIC ANODE SYSTEMS

6.2.1 ADVANTAGES

- Economically feasible when installed with the structure.
- Very little operation or maintenance requirements (very small chance of premature failure or breakdown).
- Extremely small possibility of overprotection (which may cause coating damage or hydrogen embrittlement).
- Small likelihood of stray current causing interference damage to other metallic (foreign) structures.

6.2.2 DISADVANTAGES

- Small driving voltage available (limited potential difference).
- Extremely small current available in higher resistivity electrolytes.
- Not economically feasible to install or replace anodes on large or extensive existing structures.

6.3 INSTALLATION OF GALVANIC ANODES. Galvanic anodes used to protect buried structures are normally buried a short distance from the structure and connected to the structure using an insulated copper wire. Chemical backfill material is almost always used around sacrificial anodes in soil. The backfill may be installed dry, as a water slurry, or as part of a prepackaged unit. The special backfill is used to provide a uniform electrolyte, maintain moisture, and lower the resistance to earth to allow the anode to produce the required electrical current in an efficient and reliable manner. This backfill is normally 75 percent gypsum, 20 percent bentonite, and 5 percent sodium sulfate. Figure 20 shows the desired result of the installation of a sacrificial anode with backfill. It is not normally necessary to remove the consumed anodes.

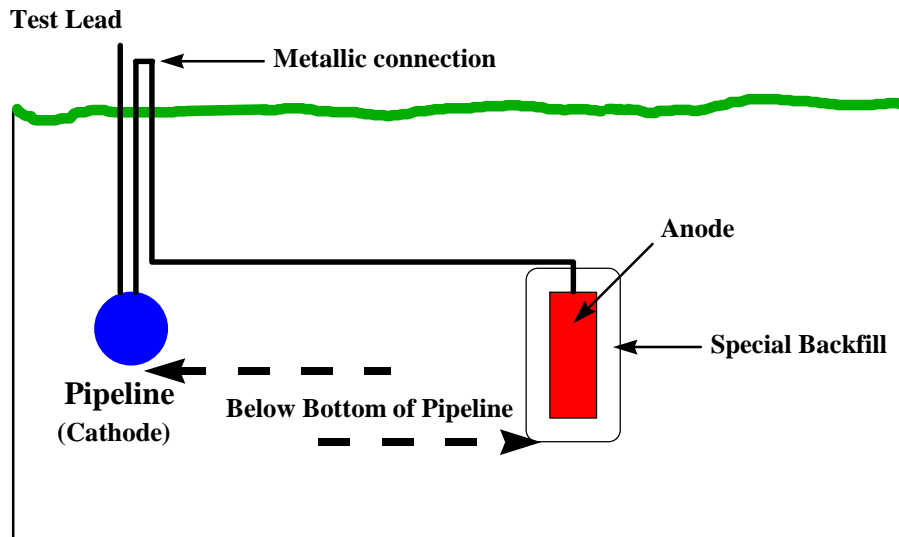


Figure 20
Galvanic Anode Installation

Galvanic anodes used in immersion service are usually either directly attached to the surface being protected, or are suspended adjacent to it. When replacement of such anodes is necessary, they should be replaced using the same anodes as were originally used. All mounting hardware should be carefully inspected and repaired or replaced as necessary to ensure that the anodes remain in place and that electrical contact is maintained.

6.4 GALVANIC ANODE CONNECTION TO STRUCTURE. Electrical contact between the galvanic anodes and the structure being protected is vital to the protection of the structure. In directly attached systems, this contact is achieved through the mounting system. The anodes are either directly welded or bolted to the structure. For anodes suspended in water, contact with the structure is achieved either through the mounting system or through insulated copper jumper wires that are welded to both the anode core and to the structure being protected. In systems where the anodes are not directly mounted on the structure being protected, connection is normally achieved using an insulated copper wire. The wire is either cast into the anode during manufacture or welded to the anode core. Connection to the structure usually is achieved by welding the wire to the structure. When additional wire is required for the connection, wire of the proper size using type TW insulation is usually used.

Thermite welding is widely used in installation, maintenance, and repair of cathodic protection systems. The process can be used to connect wires to the structure or anode cores or to connect two or more wires together. All connections and splices should be insulated when exposed to soil or water to prevent loss of good electrical contact.

Clamps are also used for connection of anode wires to the structure; or, more commonly, for splicing. To ensure good electrical connection, the clamps and wires must be clean and the clamps must be properly tightened. Clamped connections should be insulated when exposed to soil or water in order to prevent loss of good electrical contact.

6.5 GALVANIC TEST STATIONS. Test stations are included in galvanic anode cathodic protection systems on buried structures to facilitate inspection of the system. The test stations may be located above the surface in connection boxes or in subsurface test stations mounted flush on grade. Typical test stations are shown in Figures 21 and 22.

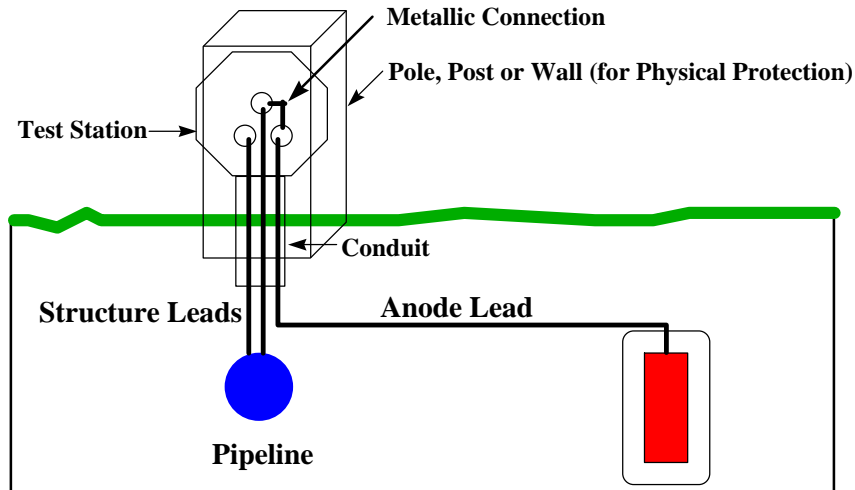


Figure 21
Above Grade Test Station

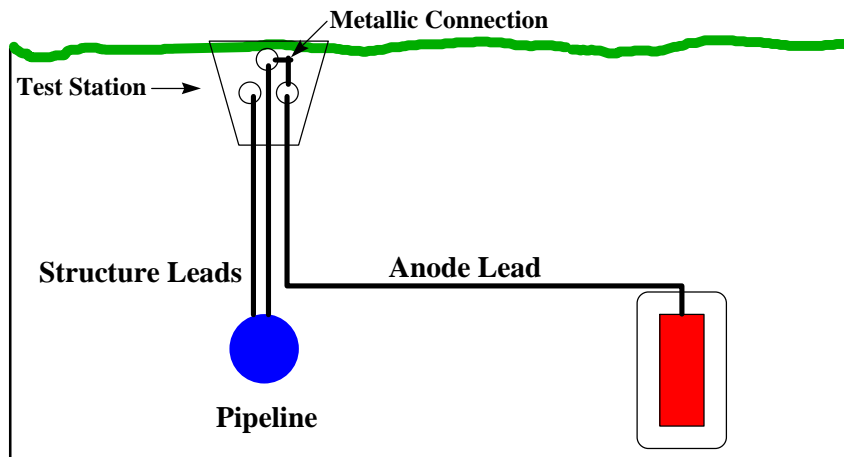


Figure 22
Subsurface Test Station

Test stations are used to conduct many different tests in cathodic protection systems. For galvanic anode systems, the most common test station measures the potential of the structure nearest the anode, the potential of the structure farthest from the anode, the potential of the anode, and the amount of current being supplied by an anode or group of anodes. The connections in this type of test station are shown in Figure 23.

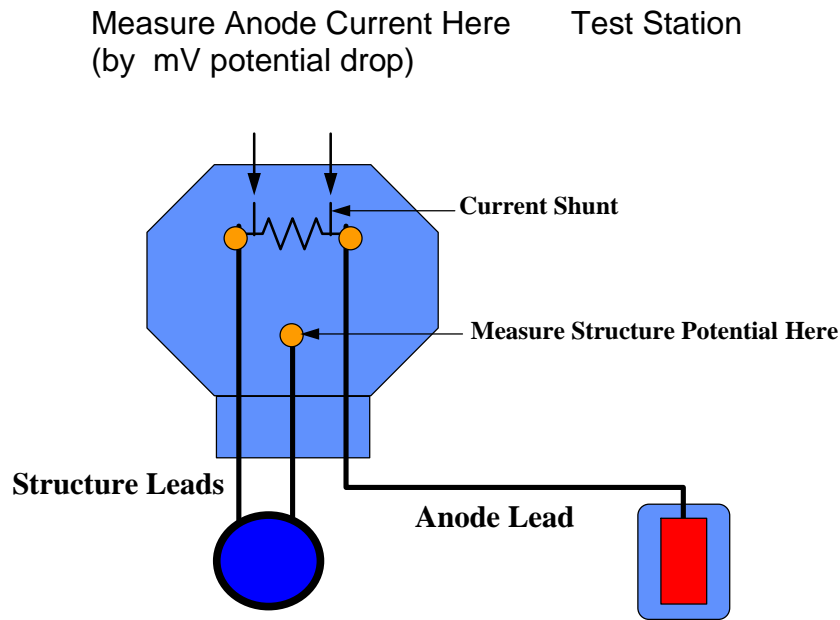


Figure 23
Potential - Current Test Station Connections

Normally, a test station has three wires as shown in Figure 23. Some test stations may not have current shunts, may not have a separate structure potential measurement lead, may have multiple anode leads, may just have one structure lead (anodes connected directly to structure), or there may be multiple anodes with a single lead. Other types of test stations are described in the sections that describe the various tests performed using the test stations. It is important that the connections in the test stations be maintained in their original condition after use or when damaged. If the identities of the test station leads are unknown, the leads can be disconnected and the potential of each lead to a copper/copper sulfate reference electrode can be taken. Using the galvanic series (Table 2), the leads may be easily identified:

- High purity magnesium -1.75
- Standard magnesium -1.55
- Zinc -1.2, aluminum -1.1
- Structure leads -0.2 to -0.8 or slightly higher if other anodes are still attached

7. IMPRESSED CURRENT CATHODIC PROTECTION. As in galvanic anode systems, impressed current systems supply current for cathodic protection of a metal surface. However, in the case of an impressed current system, the protective current is supplied by a rectifier (or other DC power source) instead of by the natural potential difference of the anode to the structure. As shown in Figure 19, the potential difference between the anode and cathode is forced from a non-reactive anode bed by the action of additional energy from a rectifier to force the electron flow that would be normally produced in the corrosion reaction. The energy for the “electron energy pump” action of the rectifier is provided by ordinary alternating current. The effect of these electrons at the structure being protected is the same as that derived from the sacrificial anode type of cathodic protection system. However, the anode material serves only as a source of electrons and anodic (oxidation) electrochemical reactions.

In practice, materials such as graphite, high silicon cast iron (HSCI), platinum or mixed metal oxide, are used for impressed current cathodic protection system anodes because they are slowly consumed (they have a very low kilogram (pound) per amp year weight loss). To provide a uniform electrolyte, a lower resistance to earth, and venting of gases and acids, a special backfill is used. This earth contact backfill is normally coke breeze or calcined fluid petroleum coke. Anodes in impressed current systems must be periodically inspected and replaced if consumed or otherwise damaged. As is the case for any electrical equipment, rectifiers used for impressed current cathodic protection systems require preventive maintenance and recurring operational checkouts to ensure proper operation. Impressed current system anode leads must have a special insulation to preclude the copper lead wire from becoming part of the anode system. Since the power source is forcing everything connected to the positive terminal to act as an anode (and corrode) any defect or nick in the insulation of the anode lead wire would result in copper metal loss ending in failure of the anode system.

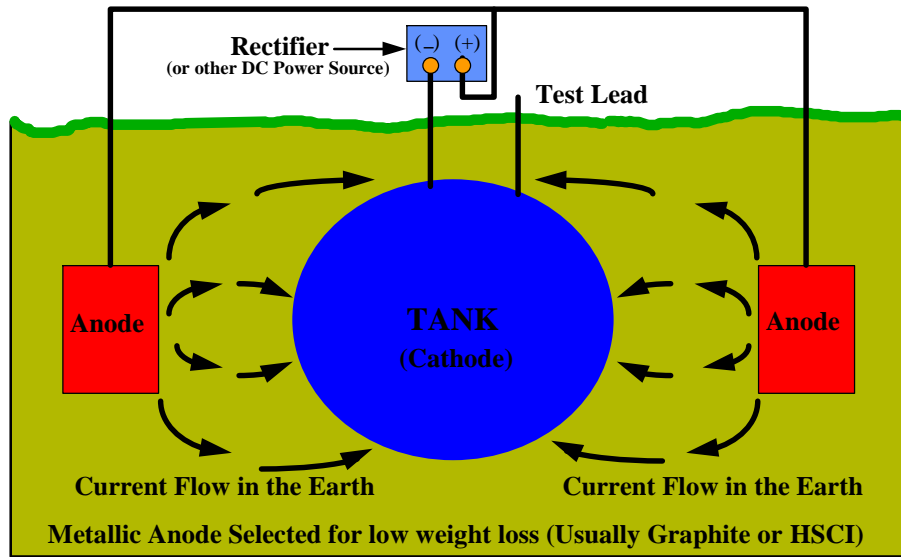


Figure 24
Impressed Current Cathodic Protection System

Impressed current systems are fundamentally the same as galvanic anode systems in their operation, except that in impressed current systems a rectifier or other direct current power source is used to increase the potential of the electrons from the anodes to provide the desired protective current. Thus, as shown in Figure 24, in addition to an anode and a connection to the structure being protected, an impressed current cathodic protection system uses a rectifier or other power source. A battery, solar cell, direct current generator, or thermoelectric generator may be used as a power source. However, nearly all impressed current cathodic protection systems use alternating current or solar powered rectifiers as a power source.

7.1 IMPRESSED CURRENT RECTIFIERS. Rectifiers used for cathodic protection commonly use an adjustable step down transformer, rectifier stacks, a shunt to measure output current, meters to indicate output current and voltage, circuit breakers, lightning arresters, and transformer tap connections, all in one case. The function of the rectifier is to convert alternating current into controlled (pulsating) direct current. A typical pole mounted rectifier for cathodic protection service is shown in Figure 25.

7.1.1 RECTIFIER STACKS ARE OF TWO GENERAL TYPES: SELENIUM PLATES OR SILICON DIODES. In high voltage or high current units, silicon diodes should be used. Selenium units have a higher voltage drop (less efficient) and are less affected by voltage surges, and they “age” over time and must be eventually replaced. Silicon diode units are susceptible to damage by voltage or current spikes and must be protected from these surges by metal oxide varistors (surge protectors). Normal lightning protection should also be provided to all units.

7.1.2 RECTIFIERS ARE EITHER AUTOMATICALLY CONTROLLED OR MANUALLY CONTROLLED. On manually controlled units, the transformer tap connections normally encircle the “center tap” connections. The center tap connections are the input to the stacks, and the negative and positive lugs are the output from the stacks. Automatic rectifiers are sometimes used when the structure size (elevated water tanks which vary in water levels) is constantly changing, or when the cathodic protection circuit resistance (anode-to-earth resistance due to extreme dry-to-wet conditions) changes significantly at a given location. These units can be potential controlled, current-controlled, or voltage-controlled. Potential-controlled units are normally used in elevated water tanks to maintain a set potential on a permanent reference cell located inside the tank. Since in this condition the amount of structure to be protected is constantly changing as the water level changes, the amount of current required is constantly changing, so a current-controlled or voltage-controlled unit must not be used. When the cathodic protection circuit resistance changes significantly at a given location due to the anode-to-earth resistance being affected by extreme dry-to-wet conditions, current-controlled units are used to maintain the correct current applied to the structure being protected. Voltage-controlled units must not be used in this case, but potential-controlled units could be used, with an added permanent reference cell (which adds another component which could possibly be damaged or fail).

7.1.3 THERE ARE NORMALLY METERS AND/OR A SHUNT INLINE between the stacks and the output lug, lightning protection on the AC input and the DC output, output

filters and/or capacitors to increase efficiency, and circuit breakers to turn the unit on and off.

7.1.4 QUICK DISCONNECTS, usually near the rectifier, are normally fused and serve to turn power off to the rectifier.

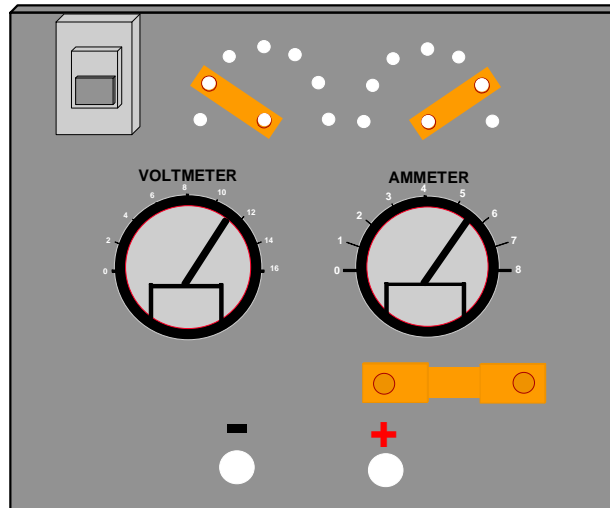


Figure 25

Impressed Current Cathodic Protection System Rectifier

7.2 IMPRESSED CURRENT ANODE MATERIALS. The anodes of an impressed current system provide the means for the protective current to enter the electrolyte. Since the anodes form the corroding part of the system, the best material is one that has a low rate of weight loss per ampere-year (Table 11). The most commonly used materials for impressed current anodes are graphite and high-silicon cast iron. Aluminum is sometimes used in water storage tanks. In areas where heavy icing is not a problem, high silicon cast iron anodes are used instead of aluminum for lower long-term cost. Platinum coated titanium or niobium anodes and mixed metal oxide anodes are becoming more prevalent as impressed current anode material. Before the 1970s, there were only three types of anodes primarily used for impressed current groundbeds: high silicon cast iron, graphite, and scrap steel. As technology progressed, so did the types of materials that are commonly used by corrosion personnel. The materials have specialized

applications and, when installation and operating costs are assessed, very few anodes can be used universally for any type of application and still achieve a desirable design life. In most soils, anodes evolve oxygen and the anode oxidizes as the current is discharged. In chloride containing soils or water, anodes evolve chlorine gas that forms hydrochloric acid, and the anodes break down chemically. The whole purpose of this explanation is to point out that some anodes perform well in the presence of oxygen and others in the presence of acids.

METAL	WEIGHT LOSS	
	KILOGRAMS (POUNDS) PER AMPERE YEAR	
Carbon (Graphite)	1 (2.2)	
Iron	9.1	(20.1)
Aluminum	2.9	(6.5)
Lead	33.9	(74.5)
Copper	10.3	(22.8)
Zinc	10.7	(23.6)
Magnesium	4	(8.8)
Nickel	9.6	(21.1)
Silver	35.2	(77.6)
Tin	19	(42)

Table 11

Electrochemical Equivalents of Common Structural Metals

7.2.1 HIGH SILICON CAST IRON. Cast iron anodes are produced in two alloy types with the principal addition of chromium, developed in 1959, to improve the life in chloride soils and water. Table 12 shows the metallurgical composition of the two alloys. The principal reason for superior cast iron performance is the formation of a silicon oxide (SiO₂) film that forms on the anode surface, reducing the rate of oxidation, and retarding the consumption rate. The anodes have good electrical properties, and the resistance of the alloy is 72 micro-ohms per cubic centimeter at 20 °C. To be successful in soils, the anodes are

backfilled with metallurgical or petroleum coke breeze to reduce the anode resistance and increase the effective anode surface area. Even when the anodes are pre-packaged in coke breeze filled canisters, filling the annular space between the canister and the soil with additional coke breeze is a recommended practice. In seawater, the anode will discharge current at very low voltages and, therefore, does not require backfill. Manufacturers of cast iron anodes developed cable-to-anode connection procedures which distributors are required to follow. Therefore, there has been a lower incidence of connection failures, compared to graphite anodes. The anodes exhibit superior conductivity and experience very little change in resistance with time, unless the anode is damaged. The high tensile strength of the metal is an asset in some circumstances, except that their very low elongation makes them brittle and subject to fracture from severe mechanical and thermal shock.

Cast iron anodes are manufactured in a wide variety of dimensions, shapes, and weights. Refer to Table 13 for a description of the various sizes. A proprietary type of cast iron anode, originally manufactured from “off-specification” corrosion resistance piping, is called a tubular anode. This uses the ASTM 518 Grade 2 chromium alloy and has demonstrated since 1971 to have superior resistance to “end effect,” common to anodes with poor connection resistance values.

Element		ASTM 518	
		Grade 1	Grade 2
Silicon		14.2 - 14.75%	14.2 - 14.75%
Manganese		1.5% max.	1.5% max.
Chromium		-	3.25 - 5.0%
Carbon		0.75 - 1.15%	0.75 - 1.15%
Copper		0.50% max.	0.50% max.
Iron		Balance	Balance
Consumption Rate	Soil	0.45 kg (1 lb)/amp-year	0.34 kg (0.75 lb)/amp-year
	Seawater	8.4 kg (18.5 lb)/amp-year	0.11 kg (0.25 lb)/amp-year

Table 12
Cast Iron Composition

Size (inches)	Nominal Weight (kg[lb])	Area (m ² [ft ²])	Cable Size (maximum)
1.1 x 9	0.45(1)	0.018(0.2)	#8
1.5 x 9	1.8(4)	0.029(0.3)	#6
2 x 9	2.26(5)	0.037(0.4)	#4
3 x 3	2.72(6)	0.023(0.25)	N/A
1 x 30	3.18(7)	0.065(0.7)	#6
1 x 60	5.44(12)	0.13(1.4)	#6
1.5 x 60	5.44(12)	0.093(1.0)	#6
1.5 x 30	5.9(13)	0.093(1.0)	#6
6 x 2.5	7.26(16)	0.046(0.5)	N/A
1.5 x 60	11.34(25)	0.18(2.0)	#6
1.5 x 60	11.8(26)	0.18(2.0)	#6
1.5 x 60	11.8(26)	0.18(2.0)	#6
2 x 30	13.61(30)	0.12(1.3)	#1/0
2 x 60	19.96(44)	0.24(2.6)	#6
12 x 3.5	24(53)	0.093(1.0)	N/A
2 x 60	27.2(60)	0.26(2.8)	#1/0
3 x 36	36.29(80)	0.23(2.5)	#1/0
3 x 60	49.9(110)	0.37(4.0)	#1/0
4.5 x 60	99.8(220)	0.54(5.8)	#1/0

Table 13
Cast Iron Anodes

7.2.2 GRAPHITE ANODES. Graphite rods have been used as an impressed current material for many years. The basic configurations consist of round or square rods, manufactured from a slurry of powdered petroleum coke and coal tar resin. The coal tar is used as a bonding agent to hold the graphite particles together and then baked for a month at high temperatures to fuse the mixture. This process increases the resistance to oxidation and subsequent breakdown. There are many types of graphite compositions and the type used for cathodic protection groundbeds is one of the most porous. The porosity allows moisture penetration to eventually migrate to the connection, causing failure at the cable connection. A denser anode is expensive; therefore, the porosity is reduced by impregnating the rods with an inexpensive filler of linseed oil, microcrystalline wax, or a phenolic-based resin. There is controversy concerning the best type of fillers and even whether a filler really reduces moisture penetration over long periods of time.

Some fillers have caused deep well anode ground beds to become fouled and develop a high circuit resistance when the anodes have been driven at high current density levels.

It is very important to have a proper anode-to-cable connection with any anode material. For years, the manufacturers of graphite anodes had no specification for a proper anode lead wire connection. This led to varying procedures and numerous failures attributable to poor material, poor workmanship, and no quality control parameters prior to shipment. Many users have developed their own assembly standards that make graphite anodes a customized and, consequently, a more expensive product than it could be, if an industry standard existed. Additional specification details should include:

- Type of container - lead, brass, molten, compression.
- Connection depth/diameter – 76 mm (3 in), 102 mm (4 in), 127 mm (5 in), centered.
- Connection sealant - thermoplastic, thermosetting (epoxy).
- Cable sealant - TFE tubing, shrink cap, encapsulation.
- Impregnation - wax, linseed oil, resin.
- Sizes - 3"x30", 3"x60", 4"x40", 4"x80".

Graphite should not be operated at current densities exceeding 10.76 amperes per square meter (1 ampere per square foot) in soil or 2.70 amperes per square meter (0.25 amperes per square foot) in water. Unfortunately, graphite is brittle and may be easily damaged during transportation, either bare or packaged. Special handling and padding is necessary to prevent cracking and breaking.

7.2.3 ALUMINUM ANODES. Occasionally, aluminum is used as an impressed current anode for protecting the interior of water tanks. Because it is relatively inexpensive compared to other impressed current materials, anodes are provided in ½ inch-diameter by ten-foot-long screwed-rod sections. These are for use in tanks where seasonal icing usually destroys the anode lead wire connection, requiring annual replacement. This type of anode system does not contaminate potable water, but the consumption rate of 4.1

kilograms (9 pounds) per amp-year limits the cost effectiveness on the basis of cost per year of service compared to other anode systems.

7.2.4 LEAD-SILVER ANODES. Lead alloy anodes are only used in free flowing seawater applications and may employ various metals such as antimony lead, tin and 1% or 2% silver. Commonly supplied in rod or strip form, of 1.5-inch diameter by 10 inches long, they have been used extensively in Europe with a 2 percent silver alloy which doubles the life. Upon initial startup, the consumption rate is about 1.3 kilograms (3 pounds) per amp-year, and eventually a black, passive film of lead peroxide forms to extend the life of the anode surface, resulting in consumption of about 0.09 kilograms (0.2 pounds) per amp-year. Normal current density ranges from 3 to 25 amps per square foot. In silting or low chloride conditions, this oxide film does not form, and the anode is consumed rapidly. Cable connections are made by drilling a hole, and silver soldering the lead wire at the base of the hole. The connection cavity is then filled with epoxy to prevent moisture penetration. Installation is accomplished by hanging the anodes from a structure, dock, or pier, in a perforated FRP pipe or by a support device to maintain its position. This support is important to prevent ice damage and keep the anodes from coming in contact with mud or silt.

7.2.5 PLATINUM ANODES. Platinum can be used as an anode coating for almost every type of cathodic protection installation. Structures in a vast array of environments such as underground, offshore, concrete, power plants, and the internals of piping, tanks, and machinery have used platinum for cathodic protection systems. Since platinum has such a low consumption rate, 0.00008 kilograms (0.00018 pounds) per amp-year, only a small amount is needed for a twenty-year anode life. Pure platinum, by itself, would be too expensive. The platinum is normally coated over noble base metals such as titanium and niobium. When anodes are in the form of wire and rods, there may be a copper core to increase the conductivity for lengths in excess of 7.6 meters (25 feet), since titanium and niobium are relatively poor electrical conductors compared to copper. The passive film on titanium starts to break down at 10 volts anode-to-cathode potential, and is limited to low resistance environments such as seawater. Niobium has a breakdown voltage of 120

volts anode-to-cathode potential, and is used in higher resistance electrolytes. Current densities range from 50 amps in soils to 500 amps in seawater, depending on the anode surface area and thickness of the coating.

Platinum has been coated on base metals using many techniques, including sputtering, electrode positioning, cladding, and metallurgically bonding. A consensus of knowledgeable engineers finds that metallurgically bonded anodes seem to experience fewer failures because the metals are compressed together in an oxygen-free vacuum. This provides an oxide-free, low resistance, and complete bond between the metals, thereby maximizing design life. Cladding involves wrapping a thin sheet of platinum around a rod and spot-welding the platinum to the base metal at the overlap area. The limited weld area allows the underlying base metal to oxidize, thus increasing resistance and achieving minimal design life. The smooth surface has little bearing on the life, because the surface becomes irregular once current is discharged. Electro-deposition techniques plate a film of platinum on the base metal, but the process results in a porous surface that is less likely to achieve full life due to high resistance oxide film formation. Thermal decomposition and welded techniques exhibit the same problems as cladding and, as of the late 1980s, are rarely used.

The anode-to-cable connection is critical, and improper connections can result in premature failure. Users should assure that the anodes are manufactured in compliance with their specifications by skilled personnel under the guidance of established quality control methods. The major disadvantage of platinum is its poor resistance to anode acid evolution in static electrolytes, rippled direct current, and half wave rectifiers. Use of a three-phase transformer rectifier in seawater systems has been known to double the life of platinum anodes by reducing the ripple on the DC output.

7.2.6 CERAMIC AND MIXED-METAL OXIDE ANODES. Mixed-metal oxide anodes were developed in Europe during the early 1960s for use in the industrial production of chlorine and caustic soda. The first known use of the technology for cathodic protection occurred in Italy to protect a seawater jetty in 1971. These anodes exhibit favorable

design life characteristics while providing current at very high-density levels. The oxide film is not susceptible to rapid deterioration due to anode acid generation, rippled direct current, or half wave rectification, as is common with other precious metal anodes. The composition of the anode consists of a titanium rod, wire, tube or expanded mesh with the oxide film baked on the base metal. Sometimes they may be referred to as dimensionally stable, ceramic, or linear distributed anodes. In oxygen evolution environments such as soils, the oxide consists of ruthenium crystals and titanium halide salts in an aqueous solution that is applied like paint, on the base metal, and baked at 400 °C to 800 °C, forming a rutile oxide. In chlorine evolving environments such as seawater, the oxide consists of an aqueous solution of iridium and platinum powder that is also baked at high temperatures to achieve a desirable film. After baking, the rutile oxide develops a matte black appearance and is highly resistant to abrasion. Some manufacturers produce variations of the oxide films specifically for chloride or non-chloride electrolytes and they are not interchangeable. Normally, titanium will experience physical breakdown around 10 volts, but the oxide film is so highly conductive (0.00001 ohm-cm resistivity), that the current, which takes the path of least resistance, is discharged from the oxide rather than the base metal even with a rectifier voltage of 90 volts in soils. This is in contrast to the insulating titanium dioxide film that naturally forms on the surface of bare titanium. When the mixed metal oxide film has been consumed, the insulating titanium dioxide film will cover the anode and not allow current to discharge unless the applied voltage is greater than 10 volts in seawater, or 50 to 70 volts in fresh water.

A ceramic anode has been developed. Good performance of the ceramic anode has been demonstrated in a wide variety of applications. The following data details the maximum recommended current densities for various electrolytes:

- Soil, mud, fresh water: 100 amps per square meter (9.3 amps per square foot - 20 years).
- Seawater: 600 amps per square meter (55.7 amps per square foot - 15 years).

Anodes in soil or mud must be backfilled with fine, low resistance, calcined petroleum coke breeze for maximum life and performance. Even when the anode is pre-packaged with petroleum coke, conservative engineering judgment would dictate that the anode package be surrounded with metallurgical coke, prior to finishing the backfilling with native soil. Consumption rates at these densities range from 0.5 milligrams per amp-year in seawater to 5 milligrams per amp-year in coke breeze, fresh water, and sea mud. As with any anode, the connection must be constructed so as to be moisture proof, water tight and have no more than 0.001 ohms of resistance. Advantages of mixed metal oxide anodes:

- Lightweight and unbreakable
- Negligible consumption rate
- Inert to acid generation
- Dimensionally stable
- High current density output
- Cost-effective

7.2.7 POLYMER CONDUCTIVE ANODES. In 1982, a new anode material was test-marketed. The material provides a small amount of current in restricted spaces, such as internal pipe surfaces, heat exchangers, utility ducts, and areas shielded from conventional groundbed current. The material resembles an electrical cable but actually consists of a stranded copper conductor with an extruded, conductive polyethylene jacket. This concept is used in underground concentric power cables as a conductive shield around the ground wires. The polymer contains carbon granules that discharge the current, leaving behind a polymer matrix. The anode should be backfilled in carbonaceous coke breeze for maximum life. Some manufacturers offer an optional plastic mesh to separate the anode from the cathode in restricted spaces, preventing electrical shorting between the anode and cathode. Currently, the material is available in four different diameters and the current output ranges from 9.8 to 29.5 milliamperes per linear meter (3 to 9 milliamperes per linear foot).

Table	TITLE
1	Current Requirements for Cathodic Protection of Bare Steel
2	Current Requirements for Cathodic Protection of Coated Steel
5	Adjusting Factor for Multiple Anodes (F)
6	Correction Factor - Short Line Coating Conductance
7	Results of Structure-to-Electrolyte Potential Measurements
8	Standard HSCBCI Anodes
9	Special HSCBCI Anodes
10	Standard Wire Characteristics
11	M Factors for Determining Economic Wire Size (Cost of Losses in 100 Feet of Copper Cable at 1 Cent per kWh)

Table 14
Applicable Tables In MIL-HDBK-1004/10

7.3 TYPES OF IMPRESSED CURRENT ANODE BEDS. The types of impressed current anode beds are dependent on the placement, orientation, and depth of the anodes. Impressed current anode beds are normally placed in remote earth, and distribute current over long distances of the protected structure (pipelines, tank farms, distribution systems etc.). Distributed impressed current groundbeds are sometimes used for small structures (valves, tanks), and the anodes are evenly distributed along the structure to be protected, each anode protecting a small portion of the whole structure. Distributed impressed current systems are commonly used to protect the interiors of water storage tanks, both ground level and elevated structures. The remote type of groundbed can be installed near the surface, either horizontally or vertically, or they can be installed deep. Distributed systems are installed like the previously discussed sacrificial anodes, with the addition of a continuous header cable which connects the anodes to the rectifier (or other power source) and a structure lead from the power source to the protected structure.

7.3.1 VERTICAL REMOTE IMPRESSED CURRENT CP SYSTEMS. These systems are commonly used for pipelines in remote areas. This is usually the most economical choice when there are no other utilities in the area and there is sufficient room to locate the anodes remote from the structure. Vertical placement of the anodes in the earth tends to lower the total resistance to earth of the system (versus horizontal placement). The

distance to remote earth varies according to the resistivity of the earth, usually 91 to 213 meters (300 to 700 feet). Soil resistivity testing should be done in the area of a proposed anode bed to locate an area of low resistance to place the anodes. Care must be taken to ensure that that low resistance area is not continuous to the protected structure. Poor current distribution may occur if this condition occurs. In some cases, the best location for an anode bed may be in higher resistivity earth. The resistance of the anode bed can be lowered by adding additional anodes, using longer anodes, or by increasing the spacing of the anodes.

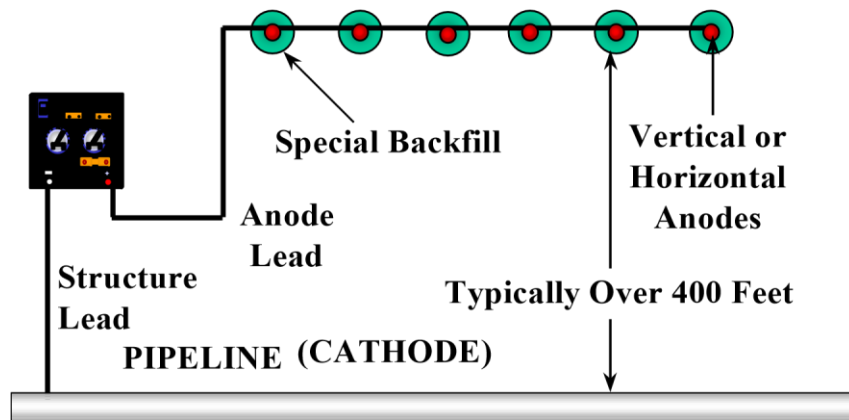


Figure 26

Vertical Remote Impressed Current Cathodic Protection System

7.3.2 HORIZONTAL REMOTE IMPRESSED CURRENT CP SYSTEMS. These systems are commonly used for pipelines in remote areas where a rock stratum is located near the surface or where other soil conditions would require horizontal installation to ensure the anode is in a uniform environment. This is usually the most economical choice when there are no other utilities in the area, there is sufficient room to locate the anodes remote from the structure, and there is a rock strata near the surface. Horizontal placement of the anodes in the earth tends to raise the total resistance to earth of the system (versus vertical). The distance to remote earth varies according to the resistivity of the earth, usually 91 to 213 meters (300 to 700 feet). Soil resistivity testing can be done in the area of a proposed anode bed to locate an area of low resistance to place the anodes. Care

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

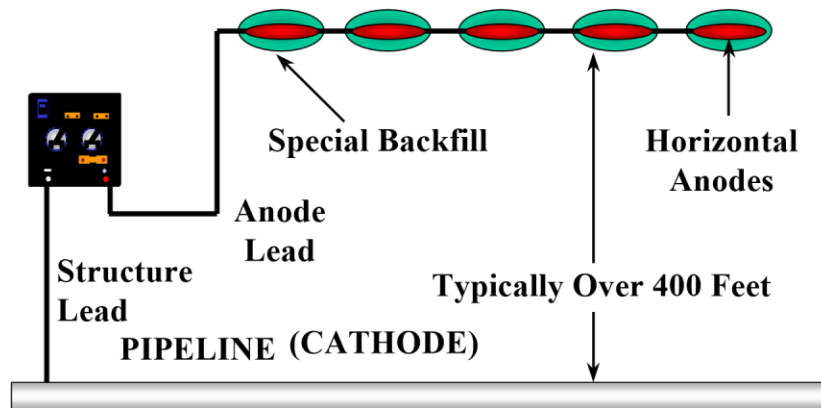


Figure 27

Horizontal Remote Impressed Current Cathodic Protection System

7.3.3 DISTRIBUTED IMPRESSED CURRENT CP SYSTEMS. These systems are commonly used to protect small structures. This is usually the most economical choice when the structure is small or the anodes cannot be placed in remote earth. This type of anode bed is used to protect water tank interiors, ground level tank bottoms, underground storage tanks, or a short pipeline. Anodes are distributed along the pipeline, or around the surface of the tank (interior for water tanks, exterior for underground tanks). The distance from the structure is normally 1.5 to 3 meters (5 to 10 feet), and the distance between anodes is normally double that distance (3 to 6 meters [10 to 20 feet]). In some cases, the anode is continuous, and is placed in a grid pattern on tanks, or along the side of a pipeline.

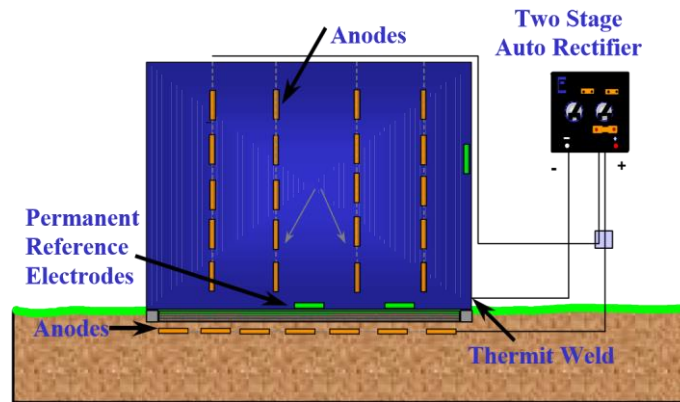


Figure 28

Distributed Impressed Current Cathodic Protection System

7.3.4 DEEP REMOTE IMPRESSED CURRENT CP SYSTEMS. These systems are commonly used to protect large structures in built up areas. This is usually the most economical choice when the structure is large, in an area with many other utilities, or the anodes cannot be placed near the surface. This type of anode bed is used to protect pipeline distribution systems, aboveground tank farms, and pipelines in built-up areas. The anodes are placed in remote earth by drilling deep below the surface. The typical deep anode bed is 30.5 meters (100 feet) to the top anode, and from 61 to 183 meters (200 to 600 feet) to the bottom anode. The anodes can be on individual leads, spaced on a continuous cable, or be a continuous anode wire. This type of anode bed can have a much higher current capacity than typical surface anode systems. This type of system minimizes interference to other metallic structures. This system requires special consideration for backfill, cable insulation, and venting.

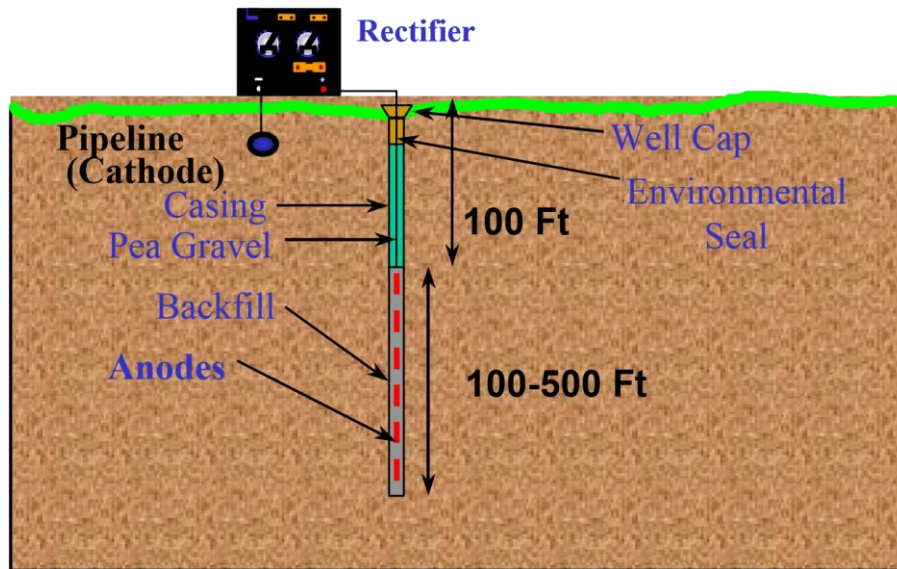


Figure 29

Deep Remote Impressed Current Cathodic Protection System

7.4 ADVANTAGES AND DISADVANTAGES OF IMPRESSED CURRENT ANODE SYSTEMS

7.4.1 ADVANTAGES:

- Economically feasible when installed on existing structures.
- Large voltage available (potential difference limited only by the size of power supply).
- Large current available, even in very high resistivity electrolytes.
- Can provide sufficient current to protect very large, poorly coated, or uncoated structures.
- Economically feasible to replace anode system when required.

7.4.2 DISADVANTAGES:

- Significant operation and maintenance requirements.
- Relatively large chance of premature failure or breakdown.

- Possibility of stray current causing interference damage to other metallic (foreign) structures.

7.5 IMPRESSED CURRENT TEST STATIONS. Test Stations for structures with impressed current cathodic protection systems normally are merely contact points for the positive connection of a voltmeter to allow for potential testing. Normally, there are two wires to the test station to permit test lead verification and redundancy. Also, impressed current systems require the same test stations as galvanically protected structures for casings, isolations, and bonding, with a higher likelihood for interference bonds. Any location where the structure is assessable could be considered a test station. These locations could be where a pipeline goes through a valve pit, low level drain pit, high level drain pit, exposed crossing a ditch, goes aboveground for a valve or meter, or enters a building or any other location where it is exposed. Test stations should be installed wherever the structure is inaccessible to allow the ability to test the cathodic protection system(s). Examples of such areas include paved areas and structures under concrete slabs. In these cases, the test stations provide a contact point for the reference electrode as well as test leads to the structure.

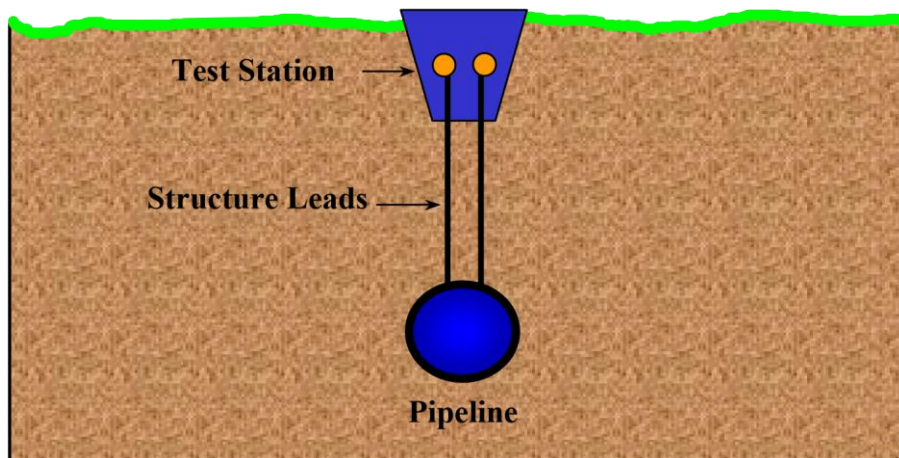


Figure 30
Flush Test Station

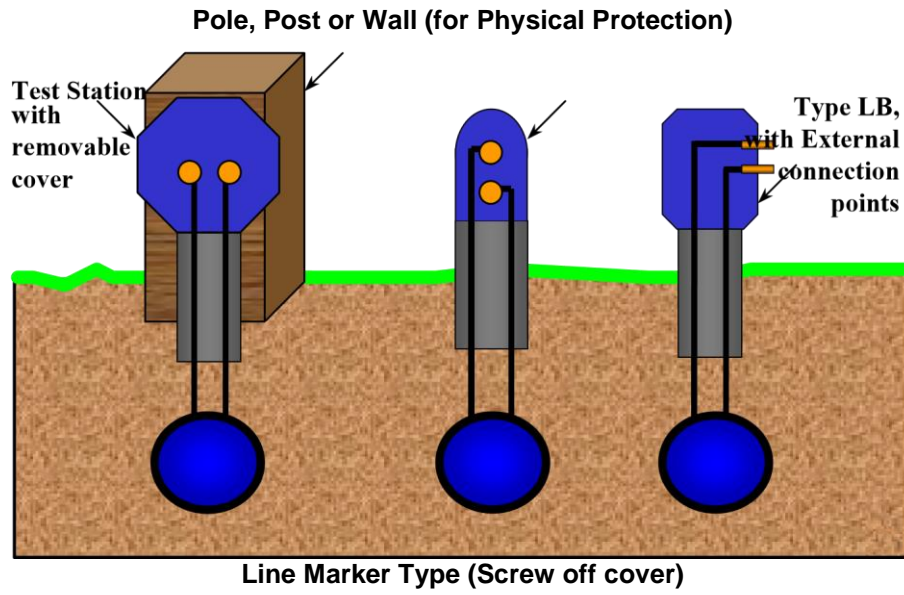


Figure 31
Abovegrade Test Station
Pole, Post or Wall (for Physical Protection)
Line Marker Type (Screw off cover)