

Engineering Encyclopedia

Saudi Aramco DeskTop Standards

Cathodic Protection Principles

Note: The source of the technical material in this volume is the Professional Engineering Development Program (PEDP) of Engineering Services.

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REASONS FOR CATHODIC PROTECTION

Corrosion Control Methods

A general definition of corrosion is the deterioration of a substance, or its properties, because of a reaction with its environment. Most materials corrode when they are exposed to certain environments. There are basically eight forms of corrosion listed below:

1. Uniform or general corrosion
2. Localized corrosion
3. Galvanic corrosion
4. Velocity effects
5. Intergranular corrosion
6. De-alloying attack
7. Cracking phenomena
8. High temperature corrosion

Regardless of what form it takes, corrosion is inevitable. However, it can be slowed or temporarily stopped. There are basically five forms of corrosion control listed below:

1. Change of materials
2. Change of environment
3. Barrier films
4. Improved design
5. Electrochemical techniques

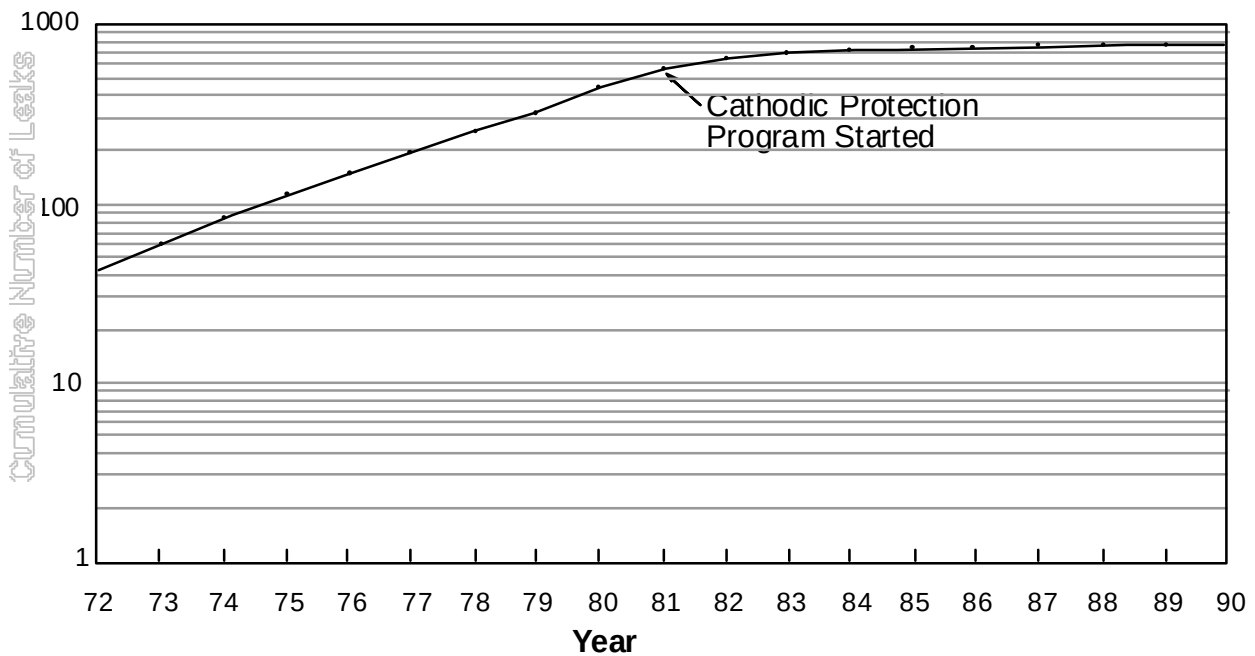
Many of the forms of corrosion can be controlled with treating chemicals. However, the use of treating chemicals is normally limited to internal systems. Paints and coating systems are the most widely used method to control corrosion. Coatings protect materials in conditions that range from atmospheric exposure to immersion in highly corrosive solutions.

Saudi Aramco uses an electrochemical technique called cathodic protection to control external corrosion of underground and marine structures. Cathodic protection is used to control internal corrosion of storage, production, and process vessels that contain water. In many cases, coatings are used with cathodic protection systems to reduce cathodic protection current requirements.

Economic Justification for Cathodic Protection

Cathodic protection (CP) is a proven method of corrosion control. However, CP must be economically justified because it can be expensive to install and maintain. If the life of the structure is not long enough to justify the expense of CP, it may be necessary to replace the structure. However, hazardous situations may make CP a necessity.

In many cases, CP is very advantageous. Its economic justification is determined by comparing leak repair costs with the cost to install and operate a CP system. Figure 1 shows how CP has decreased the number of leaks in Saudi Aramco's onshore oil well casings. The chart plots cumulative leaks versus time on semi-log paper. After a CP program was started in 1981, the number of leaks decreased significantly.



Reduction in Leak Frequency due to Saudi Aramco's Cathodic Protection Program

Figure 1

There are different types of CP systems. Therefore, a thorough economic analysis may be needed to consider the cost of more than one CP system. The cost of the CP systems evaluated should include the following costs:

1. The initial cost to design and install the system
2. The cost of power (if required)
3. The cost to maintain the system (i.e., inspection, repairs and component replacement)

Obviously, this economic analysis requires good records. Accurate data (e.g., cost per leak, power costs, and system installation costs) is not easy to obtain. However, the validity of the analysis depends on the accuracy of the cost figures.

Saudi Aramco's Cathodic Protection Organization

The responsibilities of agencies for the design, installation, operation, maintenance, and monitoring of CP systems is outlined in General Instruction 428.001. Figure 2 is a summary of the agencies and their responsibilities.

Agencies	Planning	Design	Installation	Commissioning	Operation & Maintenance	Monitoring*
Cathodic Protection Unit/CSD	●	●	●	●	○	●
Project Management Dept.	○	●	○	○	○	○
Construction Contractor	○	●	●	●	○	○
Inspection Division	○	○	●	○	○	○
Proponent Groups (i.e., Pipelines Department)	●	●	●	●	●	●

● = some responsibilities ○ = no responsibilities

* Monitoring responsibilities for various organizations are listed in G.I. 428.003

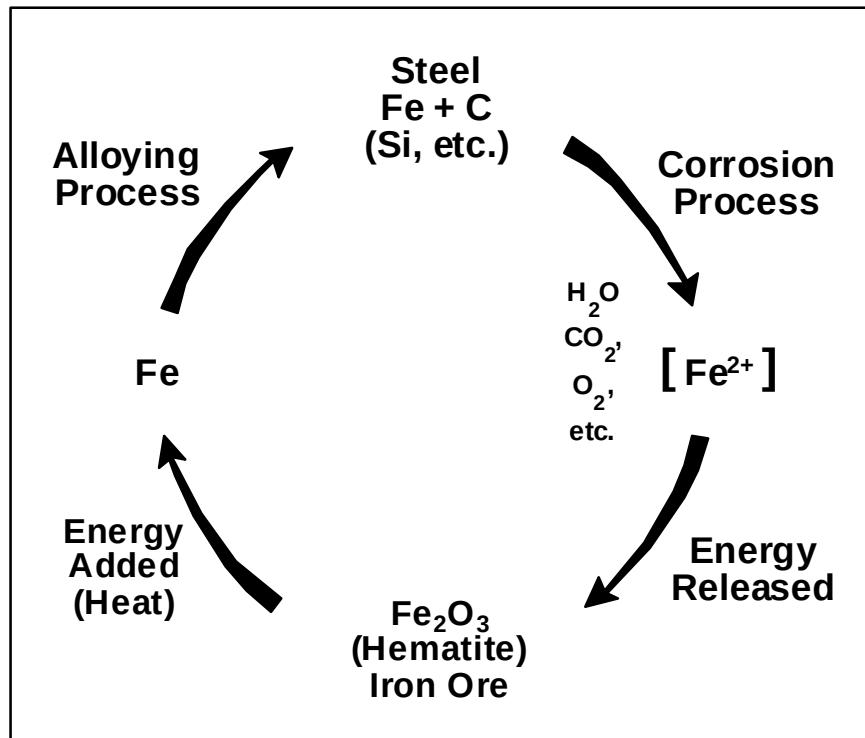
Saudi Aramco Cathodic Protection Organization
Figure 2

REASONS WHY METALS CORRODE

Electromotive Force Series for Metals

Most metals are made from natural compounds called ores. These ores contain metals that are combined with oxygen or sulfur. Metals are formed when ores are heated to remove oxygen and sulfur. Metals store this heat as chemical potential energy during the refining process. Metals corrode when they release stored energy through electrochemical reactions. Electrochemical reactions involve the transformation of chemical energy into electrical energy.

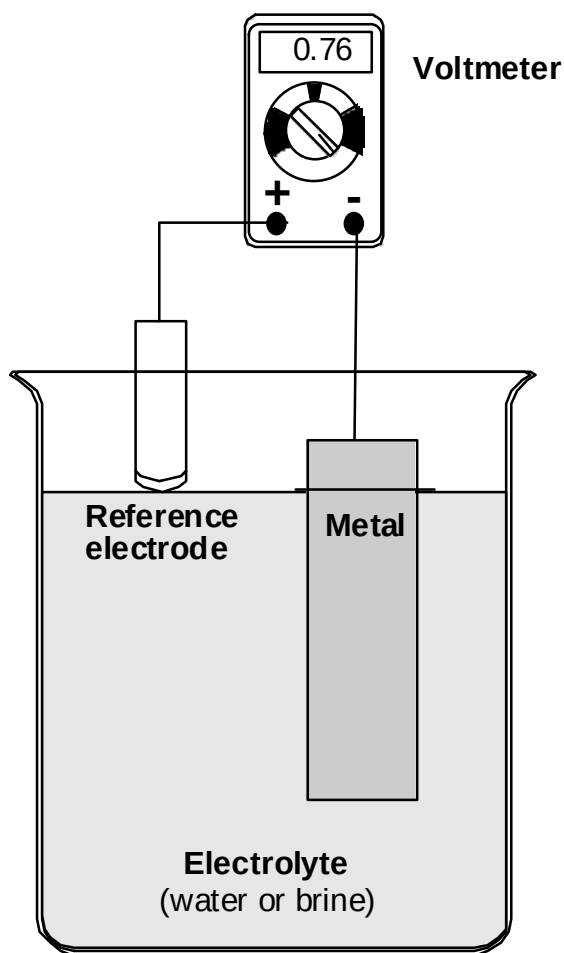
Figure 3 shows the refining and corrosion cycle for a common iron ore called hematite, Fe_2O_3 . Hematite changes to iron when energy is added during the refining process. Steel mills add carbon during the alloying process to change the iron to steel. The steel releases the stored energy when it changes to rust, Fe_2O_3 , during the corrosion process. Notice that hematite and rust have the same composition, Fe_2O_3 .



Refining-Corrosion Cycle
Figure 3

The driving force for electrochemical corrosion is related to the energy stored by metals during the refining process. Metals corrode at different rates because they store different amounts of energy. Magnesium, aluminum, and iron are metals that require and store a lot of energy during the refining process. Other metals require and store lower amounts of energy. Copper and silver are examples of these types of metals.

The *corrosion potential* of a metal can be measured with a *reference electrode* and a voltmeter. A piece of metal and a reference electrode are placed in a solution such as water or brine (Figure 4). Then, they are connected to the terminals of the voltmeter. The voltage reading from the voltmeter is called the reference electrode potential. The reference electrode potential is the difference in potential between the metal and the reference electrode .

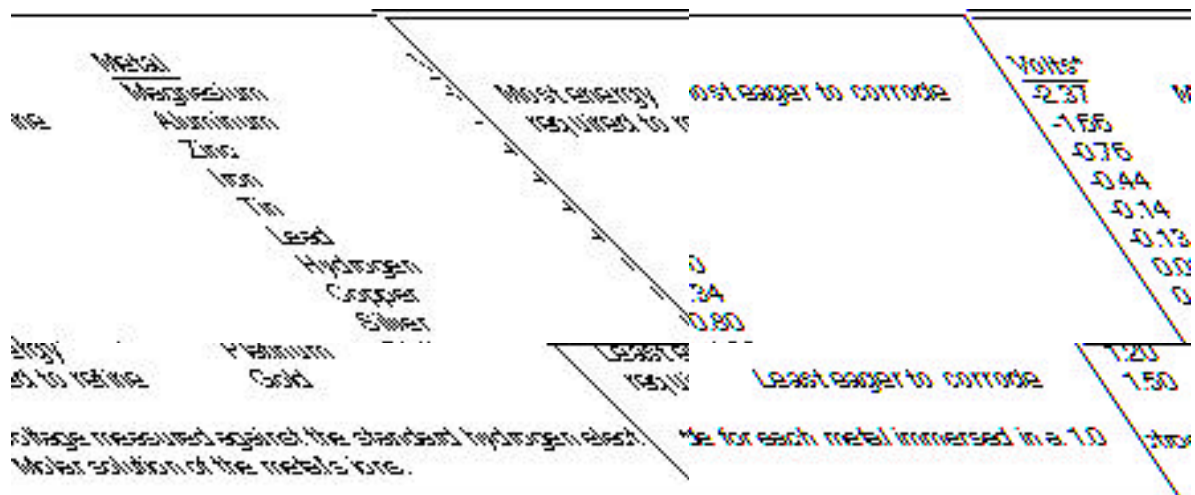


Reference electrode Potential Measurement

Figure 4

In all cells, the measured voltage arises from two sources—an electric potential at the anode and an electric potential at the cathode. It is impossible to measure the electrode potential of one electrode because a complete circuit requires two electrodes. The conventional procedure is to select one electrode as a reference electrode and assign it a zero value of electric potential. Then the other electrode's potential is referenced to this zero value. It is like saying that the reference electrode does not contribute to the voltage reading on the voltmeter. By international convention, the standard hydrogen electrode has been assigned a zero value at 25°C, 1 atm H₂ pressure, and 1 Molar H⁺ concentration. When the voltage of a metal is measured with respect to a standard hydrogen electrode, the entire voltage is attributed to the metal.

The potentials of various metals have been measured with respect to a standard hydrogen and arranged in the table shown in Figure 5. This table, the Electromotive Force Series for Metals, ranks metals according to their tendency to corrode. The metals with the most negative potentials appear at the top of the series. Metals near the top of the series will corrode easily in many environments. These metals require more energy to be refined from their ores. Metals near the bottom of the list will not corrode as easily. They require less energy to be refined from their ores.



Electromotive Force Series for Metals

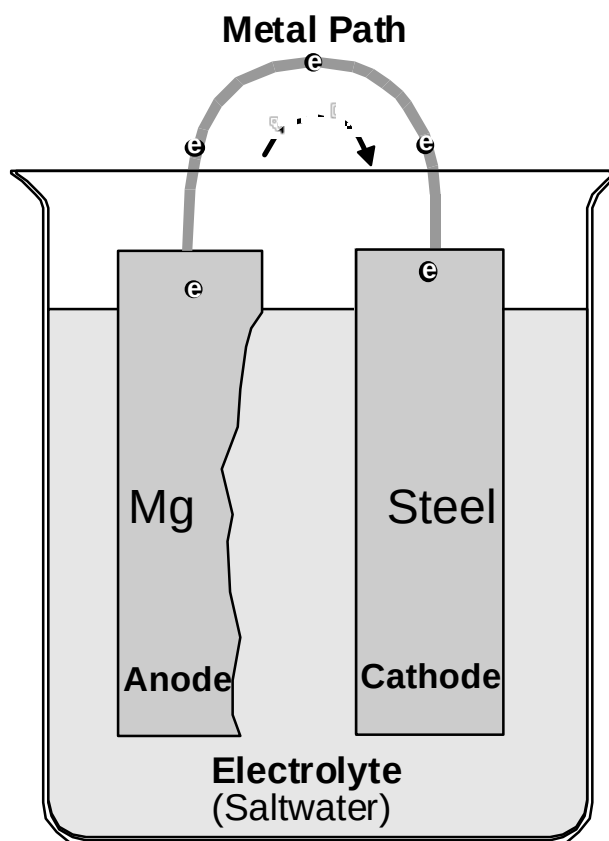
Figure 5

The Electrochemical Corrosion Cell

Electrochemical reactions cause most of the corrosion in the petroleum industry. Electrochemical reactions involve the transfer of electrons. Electrons and ions produced during the corrosion process migrate freely throughout the system. This transfer of electrons is directly associated with the creation of an electrical circuit. This electrical circuit and its associated chemical reactions are called an electrochemical corrosion cell. For a corrosion cell to exist, it must contain all of the following four components:

- an anode where corrosion (metal loss) occurs
- a cathode where electrons are consumed
- a metal path through which electrons move from the anode to the cathode
- an electrolyte in which oxidation and reduction reactions occur

An electrochemical corrosion cell can occur between two metals or on the surface of one metal. Figure 6 shows an electrochemical corrosion cell between two dissimilar metals, magnesium and steel. It is called a galvanic corrosion cell. The two dissimilar metals are connected with a copper wire (metal path) and placed in salt water. The magnesium has a more negative potential so it acts as an anode. The steel has a less negative (more positive) potential than magnesium. It acts as a cathode.

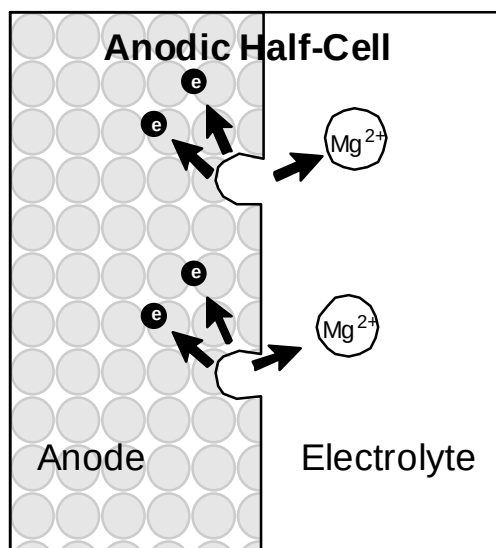
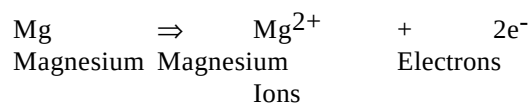


Laboratory Corrosion Cell

Figure 6

Anodic Half-Cell Reactions

The chemical reaction at the magnesium anode is called an anodic half-cell reaction. Figure 7 is a magnified view of the anodic half-cell reaction. When the metal corrodes, metal atoms lose electrons and go into the electrolyte as positively charged metal ions. This is shown in the following equation.

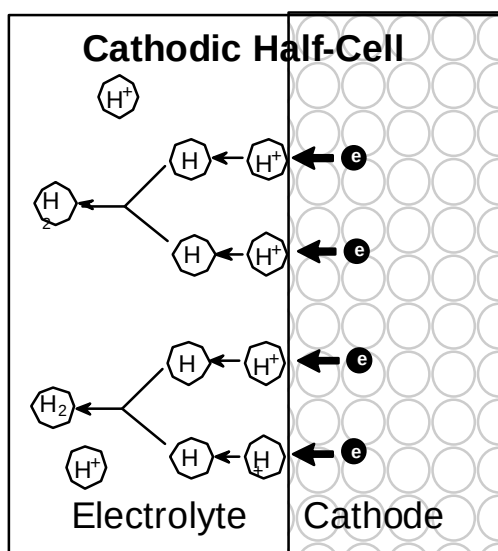


Anodic Half-Cell Reaction
Figure 7

The reaction above is an example of oxidation. Oxidation is a chemical reaction where electrons are lost. Two electrons are left behind in the metal when each magnesium ion goes into the electrolyte. The loss of metal into the electrolyte is characteristic of the electrochemical processes that occur at the anode.

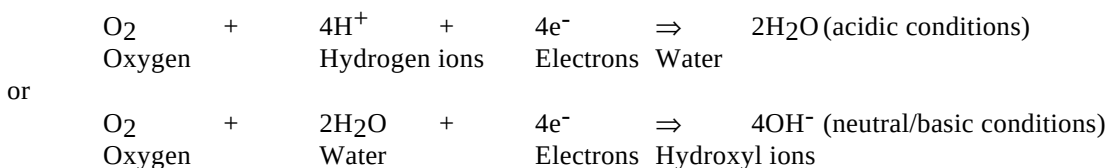
Cathodic Half-Cell Reactions

Electrons that are produced in the anodic half-cell reaction flow through the metal path to the cathode. At the cathode, the electrons are used in a chemical reaction. The chemical reaction at the cathode is called a *cathodic half-cell reaction*. Figure 8 shows reactions that occur at the cathode in acid solutions. Hydrogen ions from the acid solution use electrons from the cathode to form hydrogen atoms. Two hydrogen atoms usually combine to form a molecule of hydrogen gas as follows:



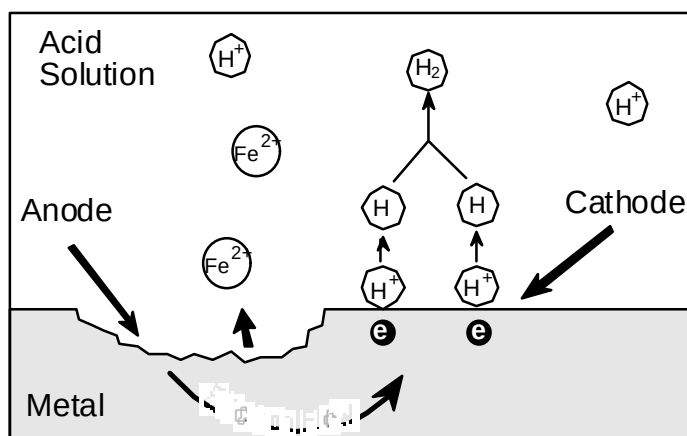
Cathodic Half-Cell Reaction
Figure 8

The cathodic half-cell reaction is an example of *reduction*. Reduction is a chemical reaction where electrons are consumed. No metal is lost at the cathode. All corrosion occurs at the anode. Two other reduction reactions that can occur at the cathode are:



Combined Anodic and Cathodic Reactions

Previously, we used two metals to represent an electrochemical corrosion cell. However, anodic and cathodic areas also occur on the surface of one metal. For example, Figure 9 is a magnified view of an iron surface corroding in an acid solution. The oxidation reactions at the anodic area generate electrons and release iron cations (Fe^{2+}) into the acid. The electrons travel through the metal to the cathode. At the cathode, the electrons reduce hydrogen ions from the acid solution to hydrogen atoms. Some of these hydrogen atoms combine to form molecular hydrogen gas. These oxidation and reduction reactions are characteristic of electrochemical corrosion reactions. As shown before, corrosion only occurs at the anodic areas of the metal surface.

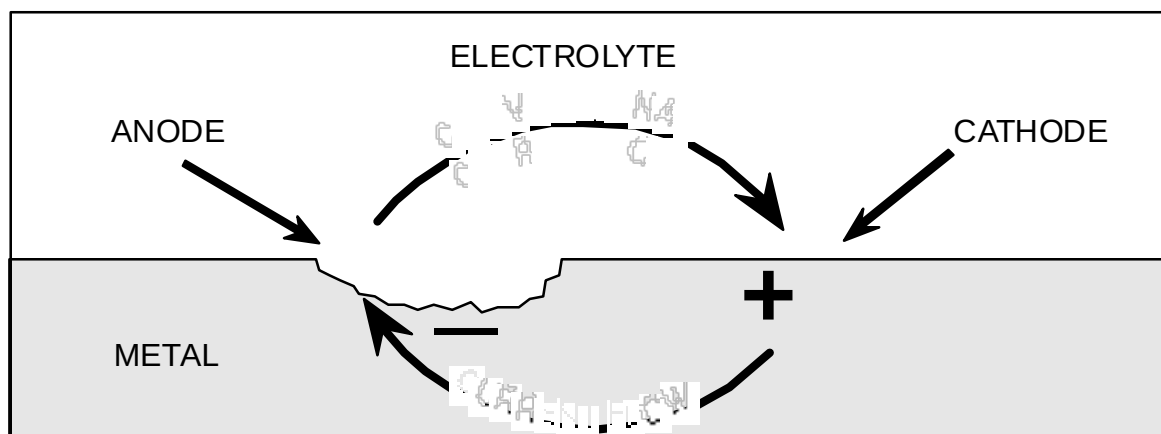


Corrosion Cell on a Metal Surface

Figure 9

Electrochemical Corrosion Current

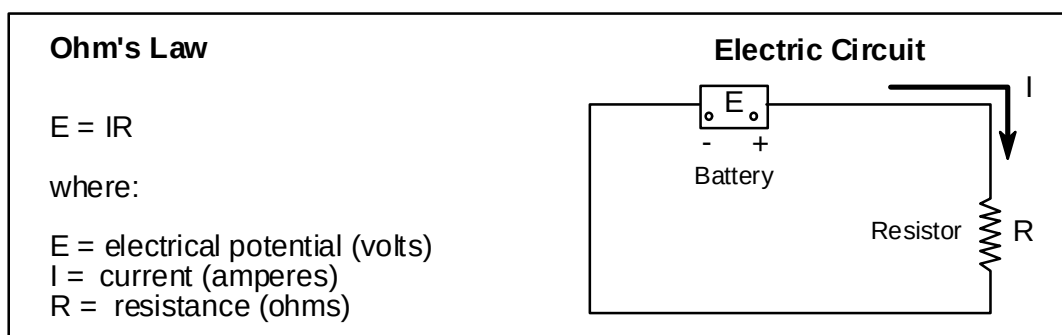
In nature, the flow of electrons creates electric current. The transfer of electrons during anodic and cathodic reactions creates an electric current in the corrosion cell. Electrons flow from the anode to the cathode through the metal path. Figure 10 shows the conventional current flow in a typical corrosion cell for iron. By custom, conventional electric current flows in the opposite direction from electrons in the metal path. In Figure 9, the electrons flowed from the anode to the cathode through the metal path. However, electric current flows from the anode, into the electrolyte, and toward the cathode. Notice that current flows through both the electrolyte and metal path. Electrons flow only through the metal path.



Conventional Current Flow in a Typical Corrosion Cell
Figure 10

FACTORS THAT AFFECT CORROSION RATE OF UNDERGROUND AND MARINE STRUCTURES

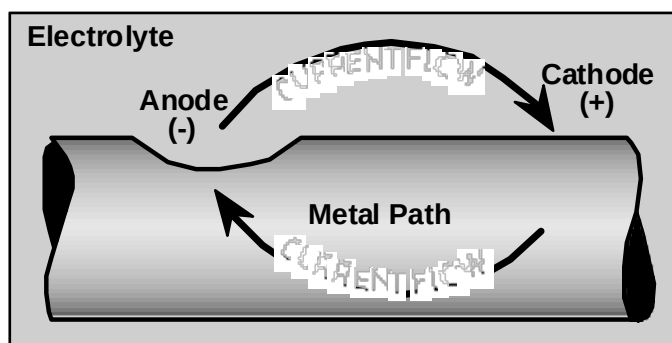
For a given surface area, the corrosion rate is directly proportional to the magnitude of the corrosion current. The greater the current, the faster the corrosion rate. Figure 11 shows the relationship between electric current, potential, and resistance as given by Ohm's Law.



Ohm's Law and the Electric Circuit

Figure 11

The diagram in Figure 12 is a corrosion cell on a section of buried pipeline. This corrosion cell contains an anode, cathode, metal path, and electrolyte. The corrosion cell is similar to the electric circuit. The “battery” in the corrosion cell is the potential difference between the anode and cathode. The resistance in the corrosion cell includes the resistance of both the electrolyte and the metal path.



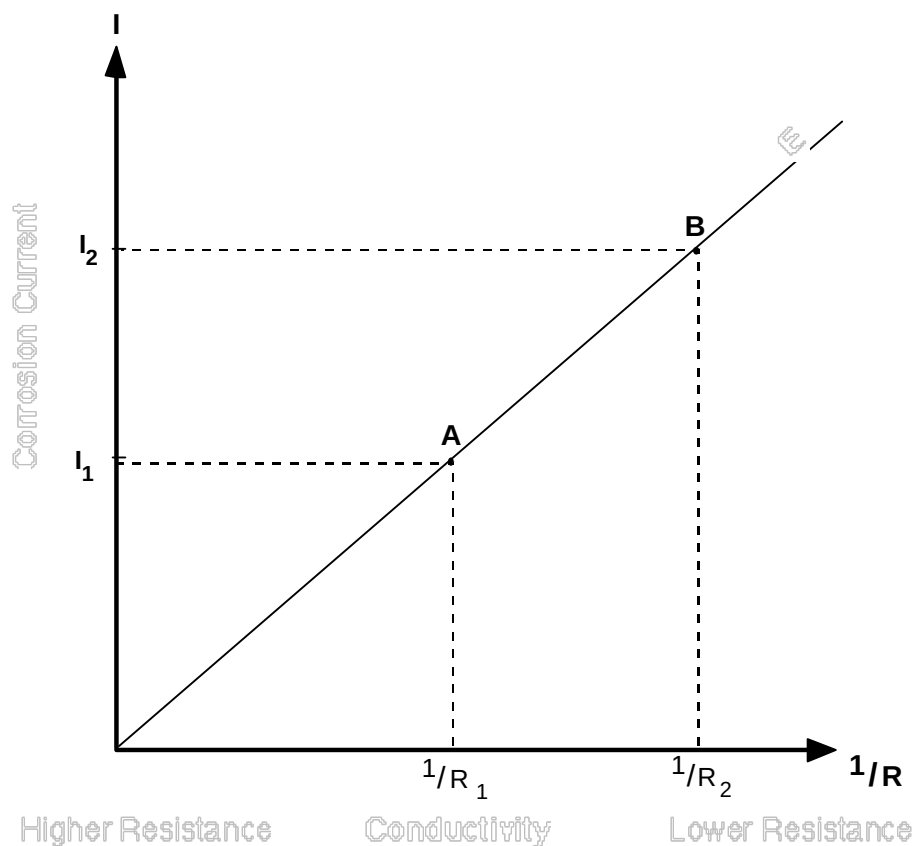
Corrosion Cell on the Surface of a Pipeline

Figure 12

According to Ohm's Law, the amount of current in both the circuit and the corrosion cell is equal to the electrical potential divided by the resistance, $I = E/R$. Corrosion current will increase with either an increase in potential or a decrease in resistance. The larger the current, the greater the corrosion rate.

Resistance

Ohm's Law states that if E remains constant, current flow increases as resistance decreases. This is shown graphically in Figure 13 where current is plotted as a function of conductivity, or the reciprocal of resistance. The difference in current between I_1 and I_2 represents the additional current generated by a decrease in resistance (increase in conductivity) from R_1 to R_2 .



Corrosion Current Increases with a Decrease in Resistance

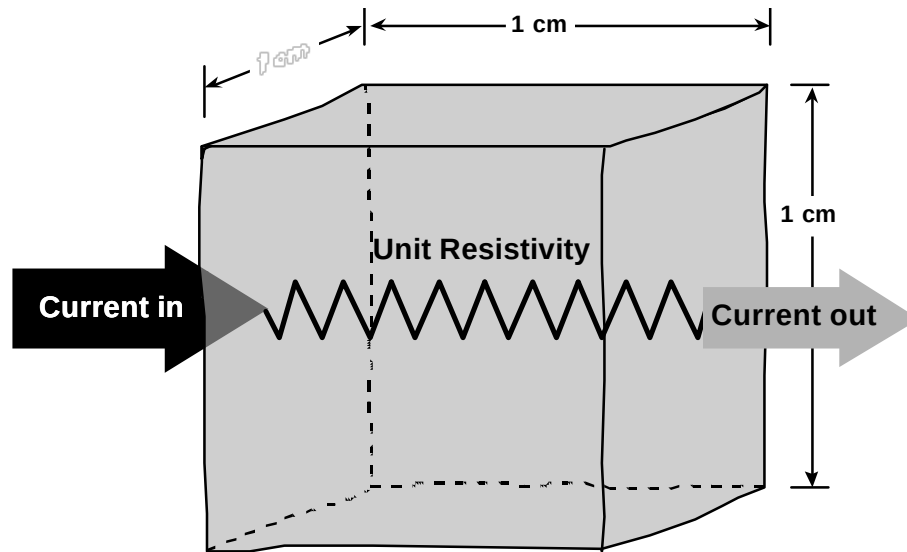
Figure 13

For pipelines and well casings, two factors that affect corrosion rates are soil resistivity and coating resistance. There is a difference between *resistivity* and *resistance*. Resistivity is a property of a material regardless of its shape.

Resistance is a fixed value for a specific element in the electric circuit. The resistance of a circuit element is determined by its resistivity and its size and shape. For example, a piece of No. 10 copper wire 100 meters long has a resistance of 1 ohm. A 10 meter long portion of the same wire has a resistance of 0.1 ohm.

Soil Resistivity

The ohm-centimeter is the unit of measurement of soil resistivity. The ohm-centimeter is the resistance between the opposite sides of one cubic centimeter of soil (Figure 14). To determine the unit resistivity, the resistivity of a larger mass of soil is measured and an average value is calculated.



Unit Resistivity (ohm-cm) Measured in One Cubic Centimeter of Soil

Figure 14

(Note: 1 ohm-m = 100 ohm-cm)

Resistivity varies for different electrolytes as shown below. The resistivities of substances such as water and soil vary with their compositions.

<u>Electrolyte</u>	<u>Resistivity</u>	
Seawater	20	ohm-cm
Raw water	40-80	ohm-cm
Drinking water	400-1,000	ohm-cm
Soil	1,000-5,000	ohm-cm
Sand	100,000-1,000,000	ohm-cm
Rock	500,000-5,000,000	ohm-cm

Soil resistivity is affected by the following:

- salt content
- oxygen content
- moisture content

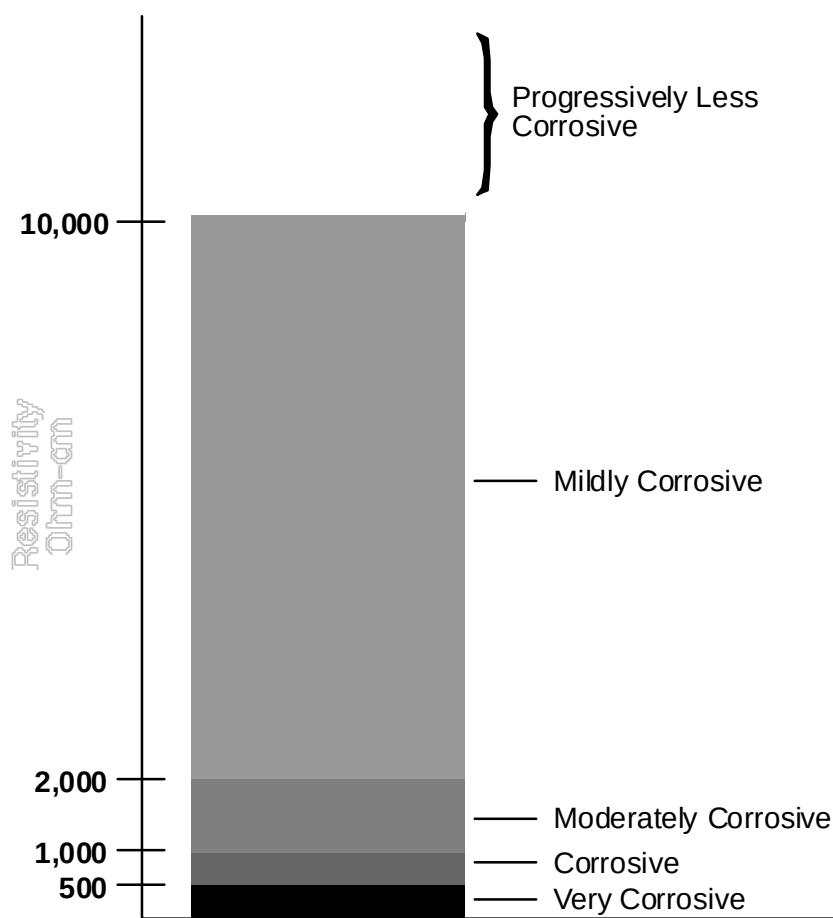
Soil resistivity is affected by the type and amount of salts in the soil. Salts that almost completely dissociate, or ionize, in water decrease soil resistivity. Sodium chloride and copper sulfate are examples of these types of salts. Soil resistivity decreases with increasing amounts of these salts.

Soils that contain oxygen are less conductive, or more resistant, to current flow than non-aerated soils. Soil resistivity also decreases with moisture content. The moisture content of soils in Saudi Arabia can range from almost 0% in inland desert sands to 100% in *subkha*. Soil moisture content changes due to precipitation, condensation at areas close to large bodies of water, and water table depth.

Soil resistivity can vary widely within a relatively short distance. Corrosion is likely to be more severe in low resistivity areas. Typical soil resistivities found in Saudi Arabia are listed below.

Soil Type	Resistivity Range (Ohm-cm)	Average (Ohm-cm)
Subkha	250-600	400
Dry sand	10,000-100,000	50,000
Rocky areas	50,000-2,000,000	100,000

All of these soil types are found along the East/West pipeline. Subkha has very low resistivity because it is high in moisture and salt content and low in aeration. Subkha is found throughout the Eastern Province of Saudi Arabia. Low soil resistivities can also be found at Wadi areas (dry river beds). Figure 15 can be used to classify the corrosivity of different soils based on resistivity. According to the figure, subkha is very corrosive while dry sand and rocky areas are much less corrosive.



General Classifications of Soil Resistivity Versus Corrosivity
Figure 15

Coating Resistance

Coatings are used to prevent direct contact between the metal surface and corrosive electrolytes. Most of the resistance between a structure and the earth is due to coatings. Coatings reduce the transfer of moisture, oxygen, air, and various ions (Figure 16). Coatings also resist the passage of electrons and electric current.

If coatings were perfect, they would completely prevent corrosion. However, coatings are not perfect. Corrosion occurs at any breaks, or holidays, in coatings. Breaks are caused by poor surface preparation, misapplications of coatings, and scratches prior to or during installation of the coated structure. Holidays also develop as coatings get older.

TOPCOAT	• Resistant to ion penetration • Alkali resistant • Insulator
INTERMEDIATE COAT	• Low moisture vapor transfer rate
PRIMER	• Adheres to substrate • Resists corrosion
METAL SURFACE	

Coating Components
Figure 16

Electrical Potential

According to Ohm's Law, the corrosion current increases as the potential difference between the anode and cathode increases. The following three factors influence this potential difference:

- dissimilar metals
- dissimilar electrolytes
- the amount of polarization

Dissimilar Metals

We stated earlier that each metal has a potential when it is exposed to an electrolyte. When two dissimilar metals are electrically connected in an electrolyte, the differences in their potentials will cause current to flow. The greater the difference in potential, the greater the current flow and rate of corrosion.

Figure 17 is called a galvanic series. A galvanic series is a list of metals arranged according to their potentials in a specific electrolyte. The galvanic series below is used to predict the galvanic behavior of metals that are electrically connected in neutral soils or water. Metals that are higher in the list are anodic to metals lower in the list. For example, if magnesium and steel are connected in soil or water, the magnesium would corrode and the steel would not corrode. Later we will apply this principle to cathodically protect steel with a magnesium anode.

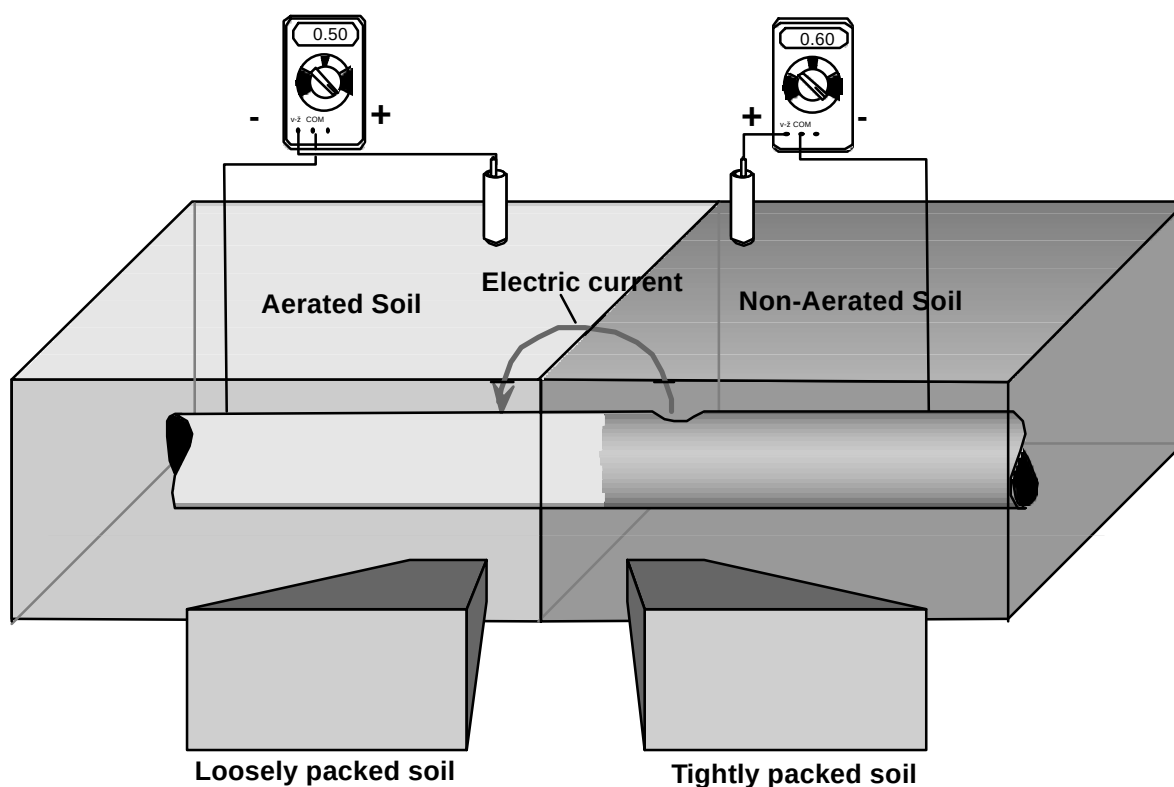
PRACTICAL GALVANIC SERIES (Neutral Soils and Water)	
Metal	Volts (Referenced to Cu/CuSO₄)
Commercially pure magnesium	-1.75
Magnesium alloy (6% Al, 3% Zn, 0.15% Mn)	-1.55
Zinc	-1.1
Aluminum alloy (5% Zn)	-1.0
Commercially pure aluminum	-0.8
Mild steel (clean and shiny)	-0.5 to -0.8
Mild steel (rusty)	-0.2 to -0.5
Cast iron	-0.5
Lead	-0.5
Mild steel in concrete	-0.2
Copper, brass, bronze	-0.2
High silicon cast iron	-0.2
Mil scale on steel	-0.2
Carbon, graphite, coke	+0.3

Figure 17

Dissimilar Electrolytes

The electrical potential of a particular metal varies in different electrolytes. If two identical pieces of metal are connected together and placed in different electrolytes, their potential difference creates a corrosion cell. Electric current flows from the metal with the more negative potential to the metal with the less negative potential. This type of corrosion cell is called a concentration cell.

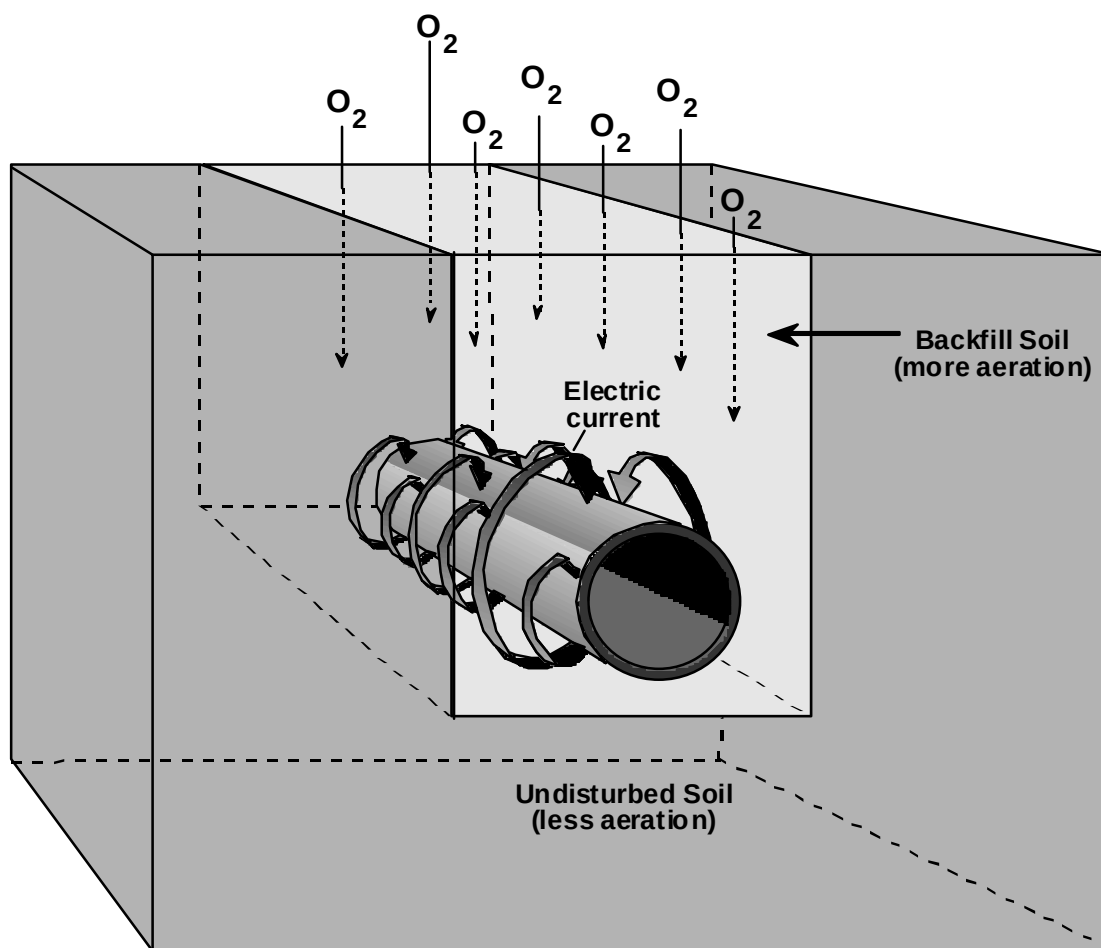
Concentration cells can be created when a structure lies in dissimilar electrolytes. For example, Figure 18 shows a pipeline which lies in two dissimilar soils. Part of the pipeline is in well-aerated soil. The other part is in non-aerated soil. The soil resistivity of the aerated soil is higher than the non-aerated soil. Therefore the part of the pipeline in the non-aerated soil will act as an anode. Electric current will flow from it to the section of pipeline in aerated soil. This is called an *oxygen concentration cell*.



Oxygen Concentration Cell Due to Dissimilar Electrolytes

Figure 18

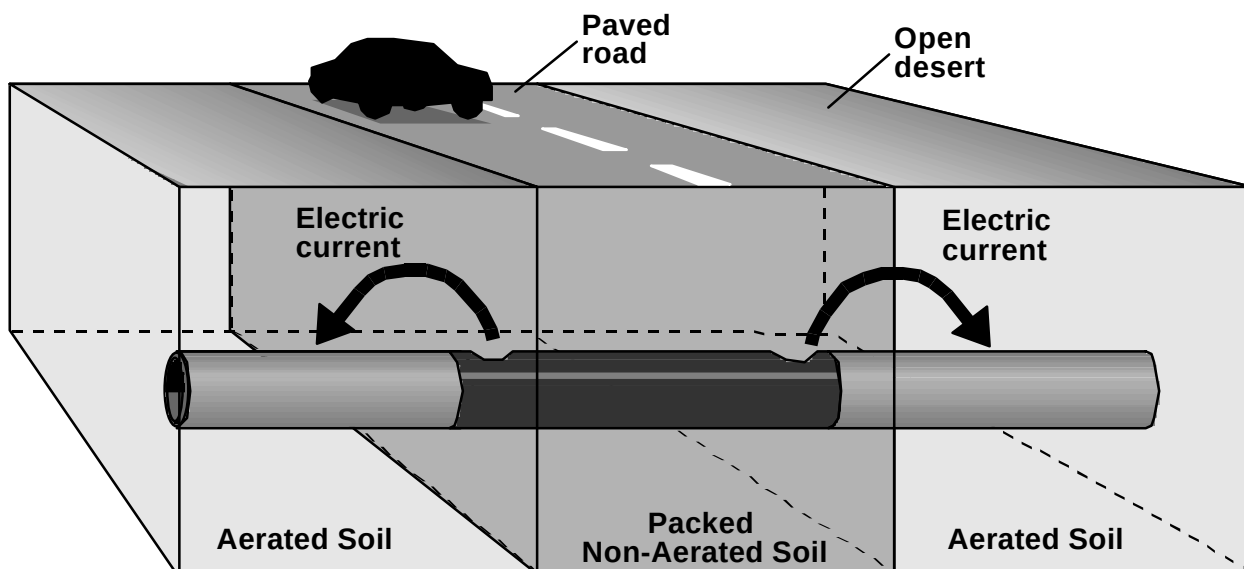
Oxygen concentration cells are very common on buried pipelines. Figure 19 shows how buried pipe usually rests on undisturbed soil at the bottom of the ditch. The pipe is surrounded on the top and sides by backfill soil that is more permeable to oxygen. Oxygen diffuses from the surface through the backfill. The undisturbed soil contains less oxygen than the backfill. This creates an oxygen concentration cell around the pipeline. Because the undisturbed soil is a better electrical conductor, the bottom surface of the pipeline becomes the anode and corrodes. The rest of the pipeline, primarily the upper surface, is less likely to corrode.



Oxygen Concentration Cell Created by Backfill and Undisturbed Soil

Figure 19

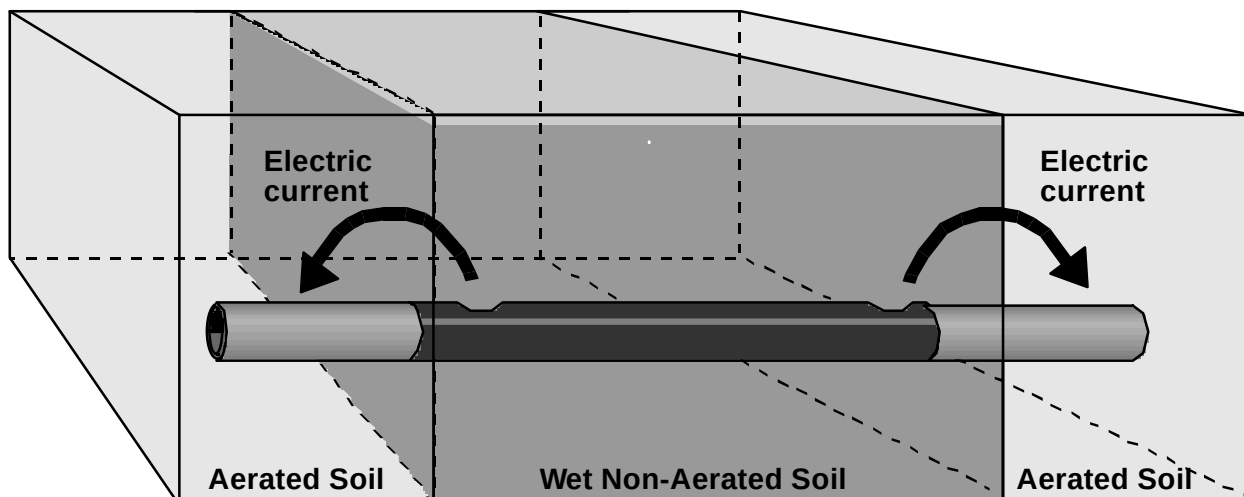
Roads and camel crossings are the most common causes of oxygen concentration cells in Saudi Aramco's pipelines (Figure 20). Roads and traffic pack soil down so it is less permeable to oxygen. Also, asphalt prevents oxygen from reaching the soil underneath it.



Oxygen Concentration Cell Created by Paved Roads

Figure 20

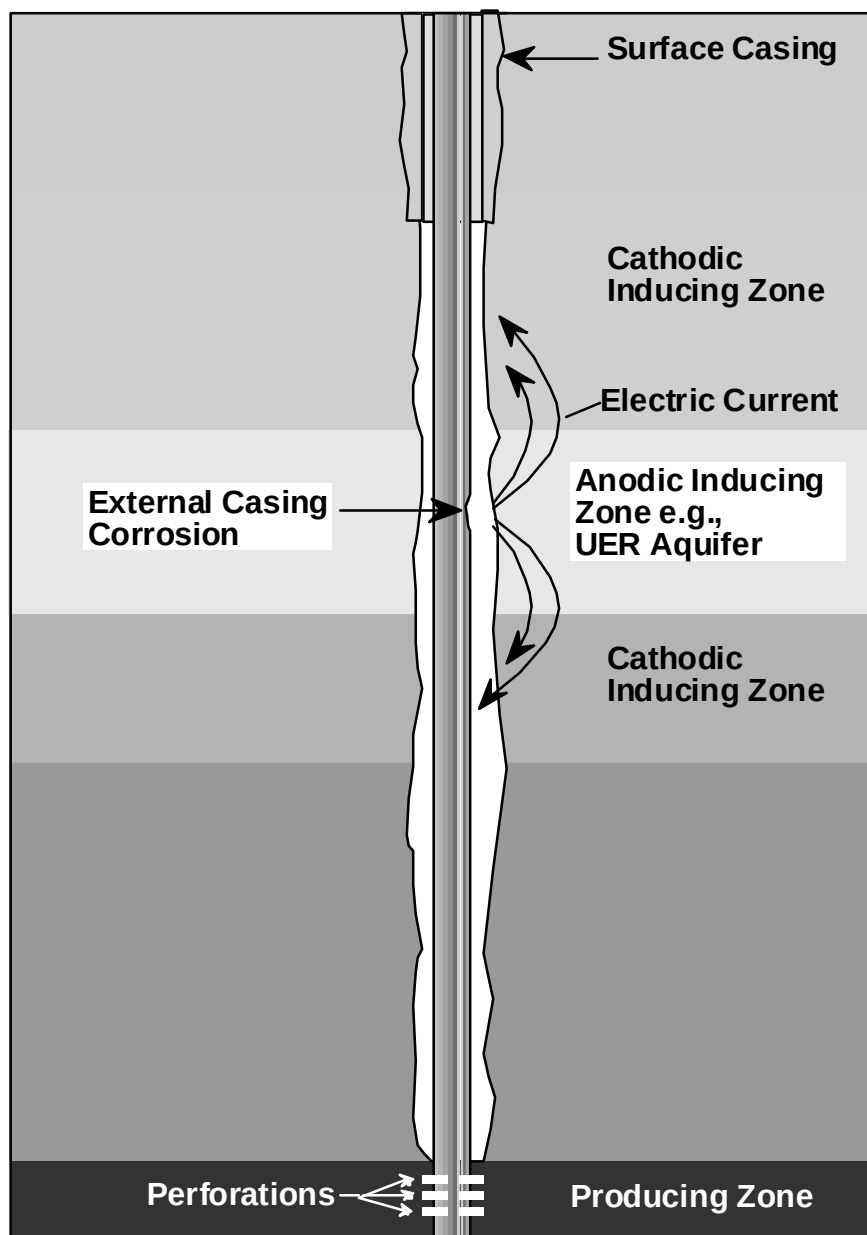
A concentration cell also forms where a pipeline goes through any wet soil (Figure 21).



Oxygen Concentration Cell Created by Wet Soil

Figure 21

Casing is set in several formations with different compositions (e.g., sand, shale, and limestone). Formation fluids also vary in composition from fresh to salt water. These zones of varying composition create areas with different electrical conductivity and potential (Figure 22). Corrosion occurs as current leaves the casing surface in the anodic areas. The current eventually reenters the casing at the cathodic areas. The current flows through the casing and returns to the anodic areas to complete the circuit.



Potential Differences of Zones Cause External Casing Corrosion

Figure 22

Polarization

Electrochemical reactions tend to slow down due to the effects of anodic and cathodic corrosion products. This causes a decrease in the potential difference between the anode and cathode. It is possible to measure this effect by measuring the potential of the metal. A change in potential due to a decrease in electrochemical reactions is called polarization. Two forms of polarization are possible—concentration polarization and activation polarization.

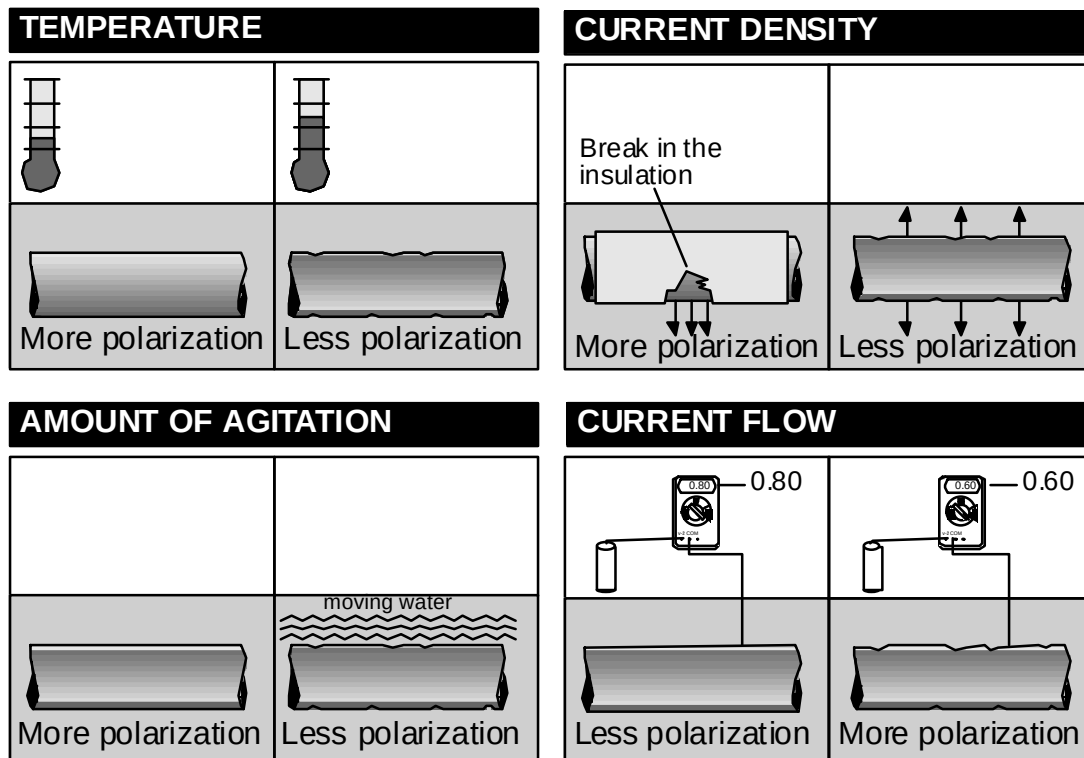
Concentration polarization occurs when an electrochemical reaction slows down because there are not enough reactants available. For example, in a cathodic half cell reaction, hydrogen ions use electrons to form hydrogen atoms. Therefore, the diffusion rate of hydrogen ions to the cathode controls the corrosion rate in dilute acids. This occurs because there are fewer hydrogen ions present in a dilute acid than in a concentrated acid solution. Any change which increases the diffusion of hydrogen ions to the cathode will increase the corrosion rate.

In *activation polarization*, factors that are characteristic of the reaction control the corrosion rate. For example, electrons reduce hydrogen ions to hydrogen atoms at the cathode. The rate of reduction depends on the metal, the hydrogen ion concentration, and the temperature of the system. Some metals transfer electrons to hydrogen ions at the metal surface quicker than other metals. An increase in the hydrogen ion concentration at the cathode will not increase the corrosion rate in this case. The metal determines the rate of electron transfer. If the cathodic reaction is activation controlled, agitation or movement of the electrolyte will have no effect on the corrosion rate.

Cathode polarization at a pipe/soil interface will often cause a gradual change in the pipe potential. This occurs when a resistive film forms on the pipe surface. The film contains calcium salts which are plated out from the ground.

Changes in polarization potential (Figure 23) are caused by the following conditions:

- a change in temperature
- a change in the amount of current density
- agitation in the cell, such as the movement of water in soil
- an increase or decrease in current flow



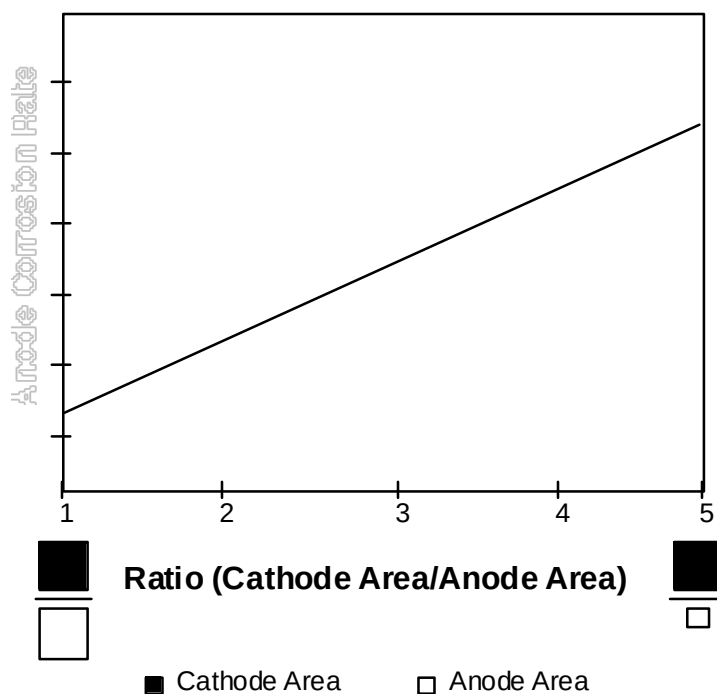
Changes in Polarization Potential in Different Conditions

Figure 23

The Area Effect

Corrosion rate is not only related to the total amount of current flow. It is also related to the density of the current. The area effect involves the current density of each metal. It controls the rate of corrosion in a galvanic (bi-metallic) couple. In a galvanic couple, a given amount of current flows between the anode and cathode. The current density of the anode is the current divided by the surface area of the anode. The current density of the cathode is the current divided by the surface area of the cathode.

For a given amount of current, the metal with the smallest area has the largest current density. For example, the current density of a small anode is very large. The current density of a relatively large cathode is very small. If you use a small anode with a large cathode, the anode will corrode very rapidly (e.g., steel rivets in a copper plate). The area effect is shown graphically in Figure 24. The principle of the area effect is that the corrosion rate increases with the ratio of the cathodic to anodic areas.

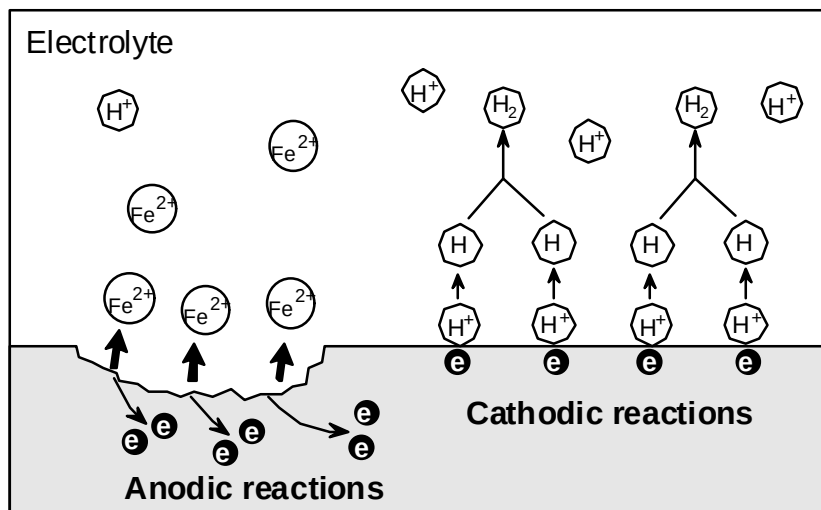


Graphical Representation of the Area Effect

Figure 24

HOW CATHODIC PROTECTION WORKS

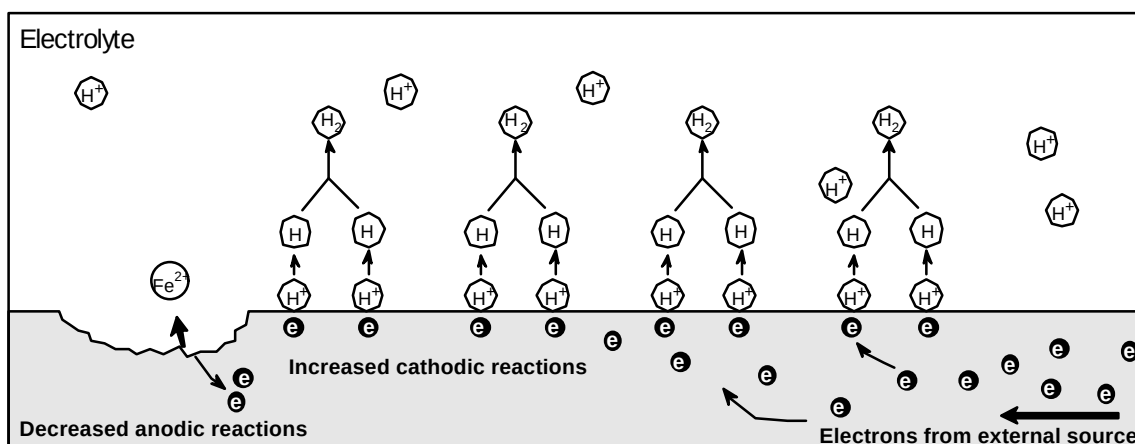
To understand how cathodic protection works, consider the electrochemical reactions that occur in a corrosion cell (Figure 25). As corrosion occurs, the electrons that are released in anodic reactions are consumed in cathodic reactions.



An Electrochemical Corrosion Cell on the Surface of a Metal

Figure 25

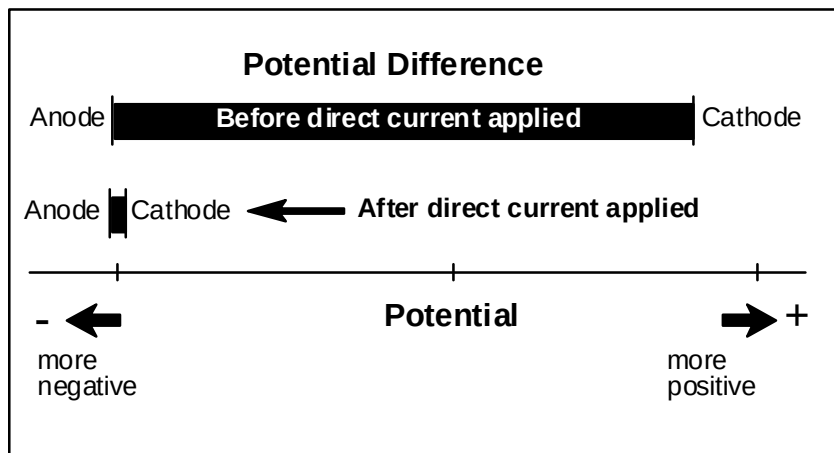
Assume that we supply additional electrons to the metal from an external source (Figure 26). More electrons will be available for cathodic reactions so the cathodic reaction rate and the evolution of hydrogen gas will increase. However, the demand for electrons at the cathode will decrease and the anodic reaction rate will decrease to produce fewer electrons. This is the basic principle of cathodic protection.



Electrons Introduced from an External Source

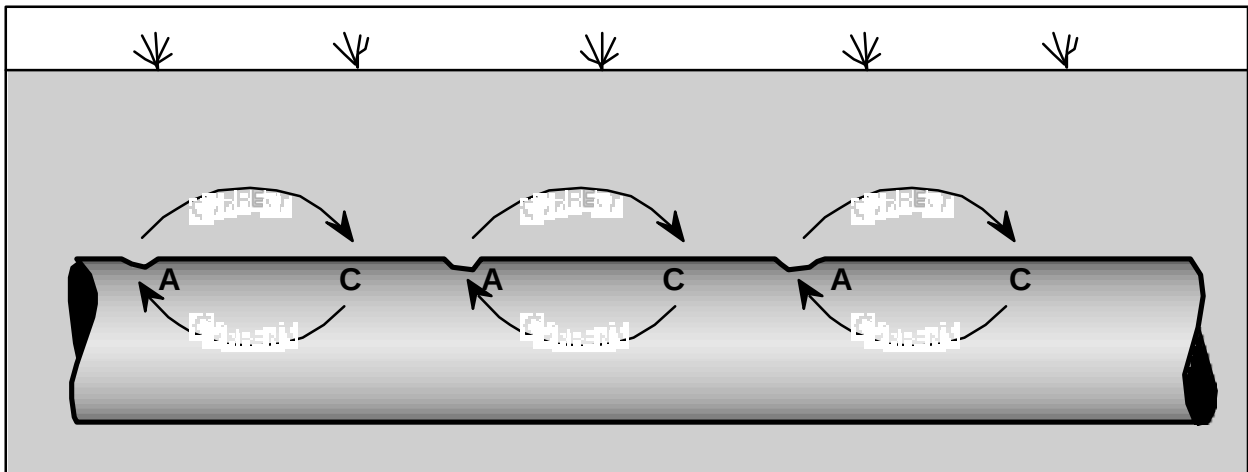
Figure 26

These additional electrons are supplied by direct electric current. As direct current is applied, the potential of a cathodic area shifts toward to the potential of an anodic area. This is shown graphically in Figure 27.



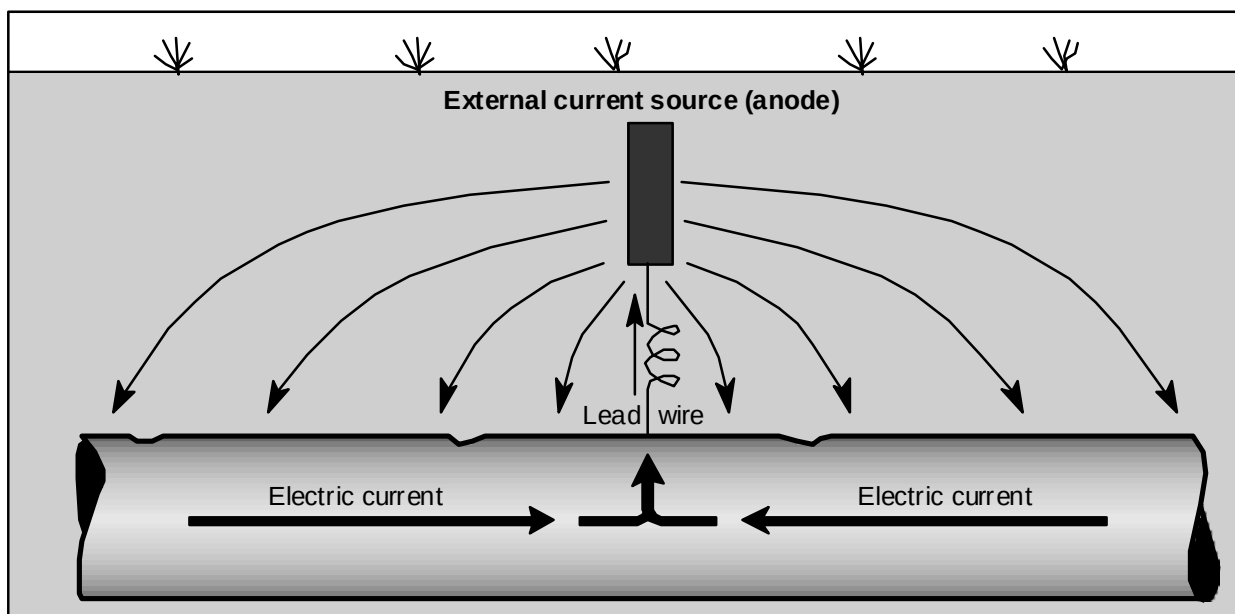
Cathodic Polarization Caused by Direct Current
Figure 27

If enough direct current is applied, the potential difference between an anode and cathode will be eliminated and corrosion will cease. For example, Figure 28 shows corrosion cells on a buried section of pipeline. Corrosion currents flow between local anodic areas (A) and cathodic areas (C) in the corrosion cells.



Before Cathodic Protection Current is Applied
Figure 28

In Figure 29, direct current is forced to flow from an external current source onto the buried pipeline. This current flow causes the potential of the cathodic areas to shift in a more negative direction. If enough current flows onto the metal surface, the potential of all the cathodic areas will reach the potential of the most anodic area on the pipeline. Corrosion will stop. To complete the circuit, a lead wire returns current to the current source. It is important to note that CP does not eliminate corrosion. It transfers corrosion from the protected structure to the expendable external current source or anode.



After Cathodic Protection Current is Applied

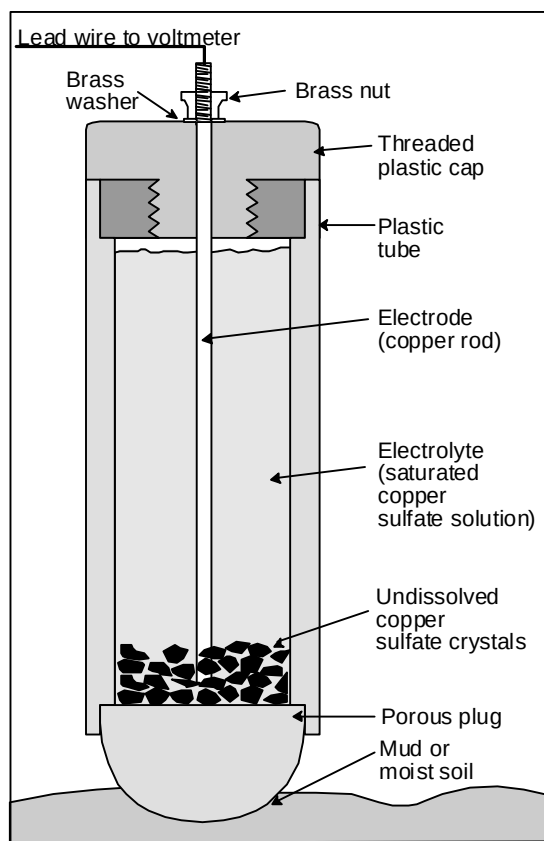
Figure 29

NOTE: Cathodic protection current will only protect external surfaces on buried structures. Above ground, structures cannot be protected by cathodic protection because the current discharged from the current source will not travel through the atmosphere. Internal surfaces of pipelines can only be protected by either corrosion inhibitors or coatings, or by using a corrosion resistant alloy for the pipeline.

Measuring Electrical Potential

When direct current is applied to a metal surface, its potential becomes more negative. This shift in electrical potential can be measured and used as a criterion of cathodic protection. Electrical potentials are always measured with respect to a reference electrode or half-cell. The copper-copper sulfate (Cu-CuSO_4) reference electrode is the most common reference electrode used for buried structures. The Cu-CuSO_4 reference electrode is durable, easy to make, and easy to maintain. Also, the potential of a Cu-CuSO_4 reference electrode changes very little with temperature.

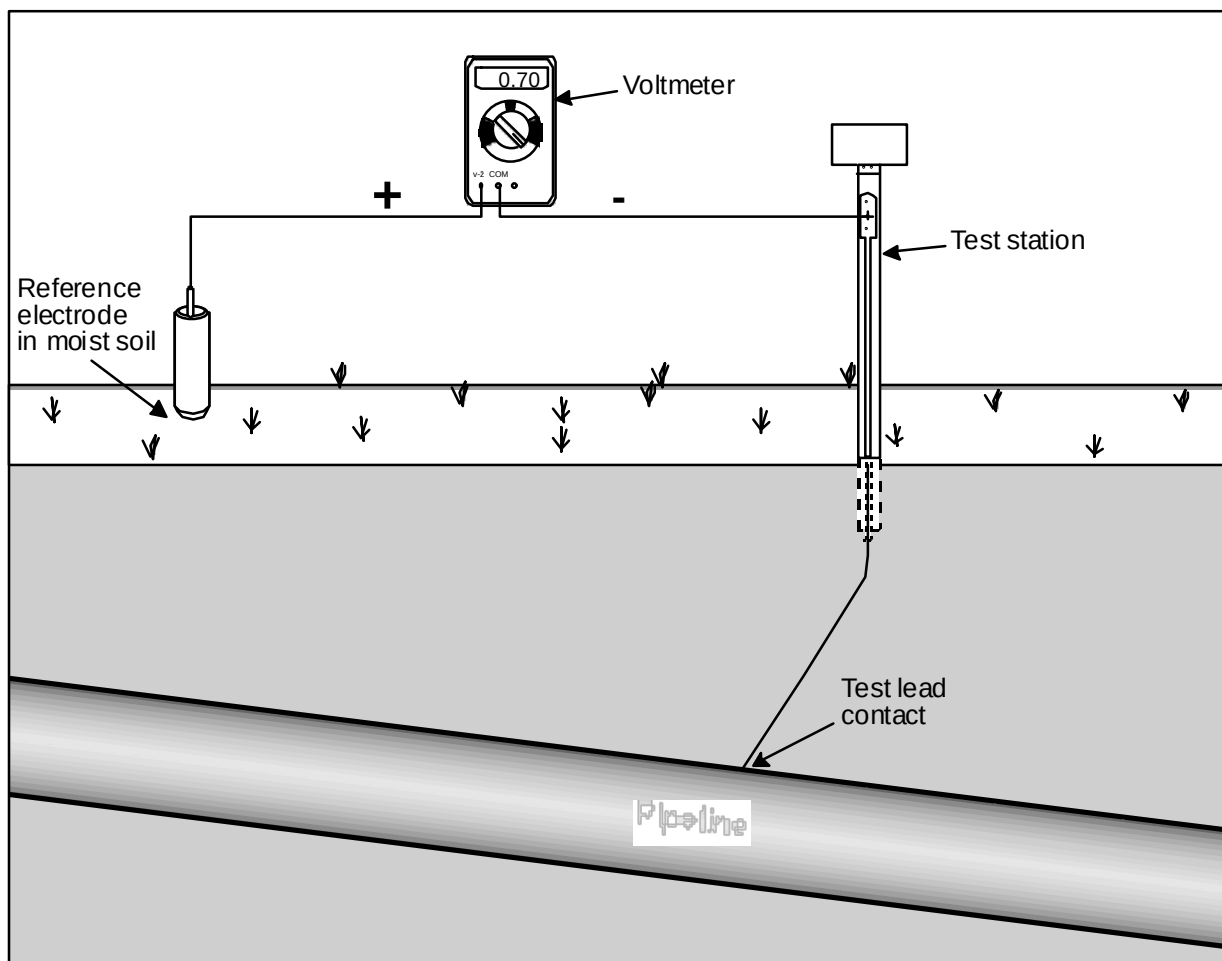
Figure 30 is a diagram of a Cu-CuSO_4 reference electrode. The voltage of a Cu-CuSO_4 reference electrode depends on the concentration of copper sulfate in the electrolyte. Saturated solutions are easiest to make and they provide consistent measurements. To make a saturated solution, copper sulfate crystals are added to water until some of the crystals do not dissolve. The solution remains stable as long as some copper sulfate crystals are undissolved. The plug at the bottom of the reference electrode is made of porous material. The porous plug provides a conductive path between the reference electrode and the electrolyte around a structure.



Copper-Copper Sulfate Reference Electrode

Figure 30

Figure 31 shows how to measure the potential difference between a pipeline and the Cu-CuSO₄ reference electrode. The reference electrode is connected to the positive lead of a high impedance (high internal resistance) voltmeter. The common (negative) terminal of the voltmeter is connected to the pipeline test lead. The voltmeter reading is a combination of the potential between the reference electrode and the soil and the potential between the pipeline and the soil. The potential between the reference electrode and the soil is constant. The potential between the pipeline and the soil can vary. When connected as shown, the potential reading will normally be positive. By convention, voltage readings are reported as negative numbers.



Measuring Structure-to-Reference Electrode Potential

Figure 31

Saudi Aramco's Potential Requirements

Experts have determined that the most anodic areas on a corroding steel structure will have a structure-to-soil potential of about -0.80 volts versus Cu-CuSO₄. The reference electrode is usually placed on the ground directly over the buried structure (e.g., a pipeline). When the entire structure has a potential of -0.80 volts or more negative, the flow of corrosion current between the anodic and cathodic areas will cease.

CP experts have generally accepted a potential of -0.85 or more negative as a criterion for adequate corrosion protection. For cross-country pipelines, Saudi Aramco has established a criterion of -1.20 volts. The stricter criterion compensates for special local conditions such as high reference cell *contact resistance* and large "IR" drops in dry soils.

Figure 32 shows Saudi Aramco's electrical potential requirements for cathodic protection of onshore and offshore structures. To measure the potential of a structure in water, a silver-silver chloride reference electrode is used.

Structure	Required Potential
Current On	
Buried cross-country pipeline	-1.20 volts or more negative versus CuSO ₄
Buried plant piping	-0.85 volt or more negative versus CuSO ₄ electrode +0.25 volt or less positive versus Zn
Tank bottom external	-1.00 volt or more negative versus CuSO ₄ at periphery -0.85 volt or more negative versus permanent CuSO ₄ +0.20 volt or less positive versus permanent Zn -0.35 volt change in structure potential vs CuSO ₄
Tank interior	-0.90 volt or more negative versus AgCl electrode +0.15 volt or less positive versus Zn
Marine structures	-0.90 volt or more negative versus AgCl electrode
Current Off	
Well casings	-1.00 volt or more negative versus CuSO ₄ (G.I. 428.003)

Saudi Aramco's Potential Requirements

Figure 32

CALCULATING CURRENT REQUIREMENTS

Current Requirement Calculation Procedures

Saudi Aramco has established an electrical potential criterion of -1.20 volts for cross-country pipelines. Enough CP current must be applied to a pipeline to reach this protective potential. Saudi Aramco has determined the design current densities needed for pipelines. The design current density is given in milliamperes per square meter, ma/m^2 . Current density is the current (in milliamperes) divided by the surface area of the structure (in square meters).

To calculate the amount of CP current, multiply the minimum required current density by the surface area of the structure exposed to the electrolyte. For example, Saudi Aramco has determined that a current density of 0.75 ma/m^2 is needed to adequately protect a pipeline coated with coaltar epoxy. The amount of current needed to protect a similar pipeline with a surface area of $1,000 \text{ m}^2$ is calculated as follows:

$$(1,000 \text{ m}^2)(0.75 \text{ ma/m}^2) = 750 \text{ ma} = 0.75 \text{ amperes}$$

This calculation procedure only considers the apparent surface area of a structure. However, the surface roughness of a corroded structure can increase the effective surface area by 25% or more. Similarly, most metal surfaces are covered with a thin layer of corrosion products. Surface roughness and corrosion films can significantly change CP current demand. Actual CP current demand also depends on the effectiveness of any coatings and the resistivity of the electrolyte. Therefore, current requirement tests may still be needed to determine the actual amount of current required.

For design purposes in this Module, we will use the minimum required current densities found in Saudi Aramco Engineering Standards SAES-X for the following structures.

Buried Pipelines

Current density requirements for cathodic protection of buried pipelines are given in Saudi Aramco Engineering Standard SAES-X-400. The standard includes a table of design current densities for coated and uncoated pipelines. This table and a procedure for calculating the amount of current are shown in Work Aid 1A.

Tanks and Vessels

Tank bottoms in contact with moist soil are susceptible to corrosion. Current density requirements for tank bottoms are provided in SAES-X-600, Cathodic Protection for In-Plant Facilities. Anodes are often distributed around tanks to provide protective current to external tank bottoms.

Impressed current systems are designed and operated so that the outside bottom of each tank has a structure-to-soil potential of -1.0 volt. The center of a tank is the most difficult part to cathodically protect. A zinc reference electrode is permanently installed in the soil under the center of a tank bottom. If a permanent reference electrode is present, a minimum structure-to-soil potential of -0.85 volt with respect to a Cu-CuSO₄ reference electrode (or equivalent) is needed.

Cathodic protection is also used to protect the water-wet internal areas of production and process vessels. SAES-X-500, Cathodic Protection Vessel and Tank Internals, requires coatings and CP for the interior of a water tank if the resistivity of its contents is 15 ohm-meter or less. Cathodic protection is required to protect the bottom interiors of hydrocarbon product storage tanks. Coatings reduce current requirements and help to distribute protective current. To calculate the amount of CP current, the current density is multiplied by the surface area of the vessel in the electrolyte. When you calculate the current requirements for vessel interiors, only use the surface area of the water-wetted areas. Cathodic protection cannot protect the hydrocarbon or gaseous areas of vessels. These current density requirements and a procedure for calculating the amount of current are shown in Work Aid 1B.

External Well Casings

Cathodic protection is the most effective method to control external corrosion of well casings. Current requirements for external well casings are provided in SAES-X-700, Cathodic Protection of Onshore Well Casings. The standard specifies that CP systems shall have capacities of 50 amperes for each uncoated well casing and 10 amperes for each coated well casing. Systems with lower current capacities are justified if supporting data is available.

Marine Structures

Saudi Aramco cathodically protects offshore platforms, marine pipelines, breasting dolphins, and loading/mooring buoys. Saudi Aramco's objective is to quickly polarize offshore platforms to a minimum of -0.90 volts versus a silver/silver chloride reference electrode. Polarization has two advantages. First, little corrosion occurs. Second, chemical reactions at the cathode form a protective deposit. Scale reduces current requirements and allows current to reach metal surfaces further from the anode. Galvanic anodes are used most often to protect marine structures. The galvanic anodes are sized to provide current for 25 years. Impressed current systems are used when an economical power source is available. Saudi Aramco requires a 15-year design life for impressed current systems.

Current density requirements for marine structures are provided in Saudi Aramco Engineering Standard SAES-X-300, Cathodic Protection Marine Structures. Saudi Aramco's current requirements and a procedure for calculating the amount of current are shown in Work Aid 1C.

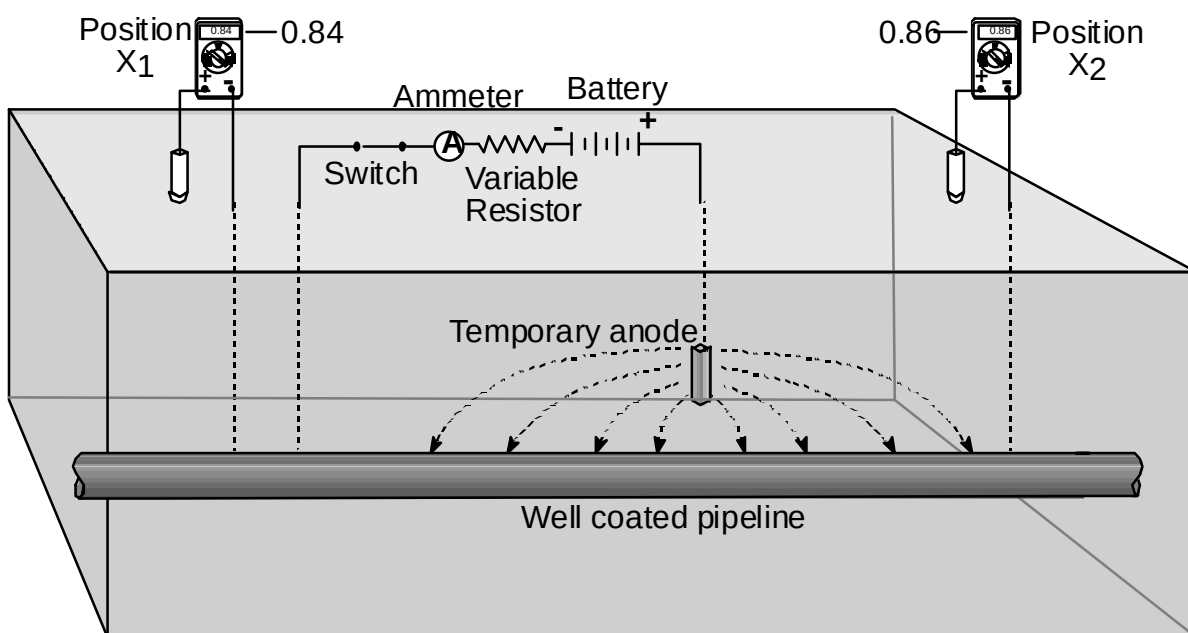
Current Requirement Tests

An adequate amount of CP current must be applied to buried and immersed structures to control corrosion. Bare structures require more current than coated structures. For example, 0.75 amperes of current is needed to protect a coated pipeline with a surface area of 1,000 m². If the same structure were bare, it would require 20 amperes. This is more than 26 times the current required by the coated structure. It is sometimes desirable to make specific tests to determine the current requirements for CP. The type of current requirement test depends on whether the structure is well coated, poorly coated, or bare.

Current Requirement Tests for Coated Structures

The current requirement test setup for a coated pipeline is shown in Figure 33. A power supply and a temporary anode are used to produce current. The power supply may be automobile batteries or heavy duty dry batteries. The amount of current is controlled with adjustable resistors. Current flows onto the pipeline and causes its potential to shift in a more negative direction. Voltage readings are taken using two voltmeters at positions X_1 and X_2 . The current is gradually increased until the average of the voltmeter readings reaches -1.2 volts versus a

Cu-CuSO₄ electrode. Most of the resistance between the earth and a well coated structure is due to the coating. Therefore, a measurement between a coated pipeline and the closest soil (directly above it) is usually sufficient. A reference electrode placed directly over a structure is called a “close electrode.”

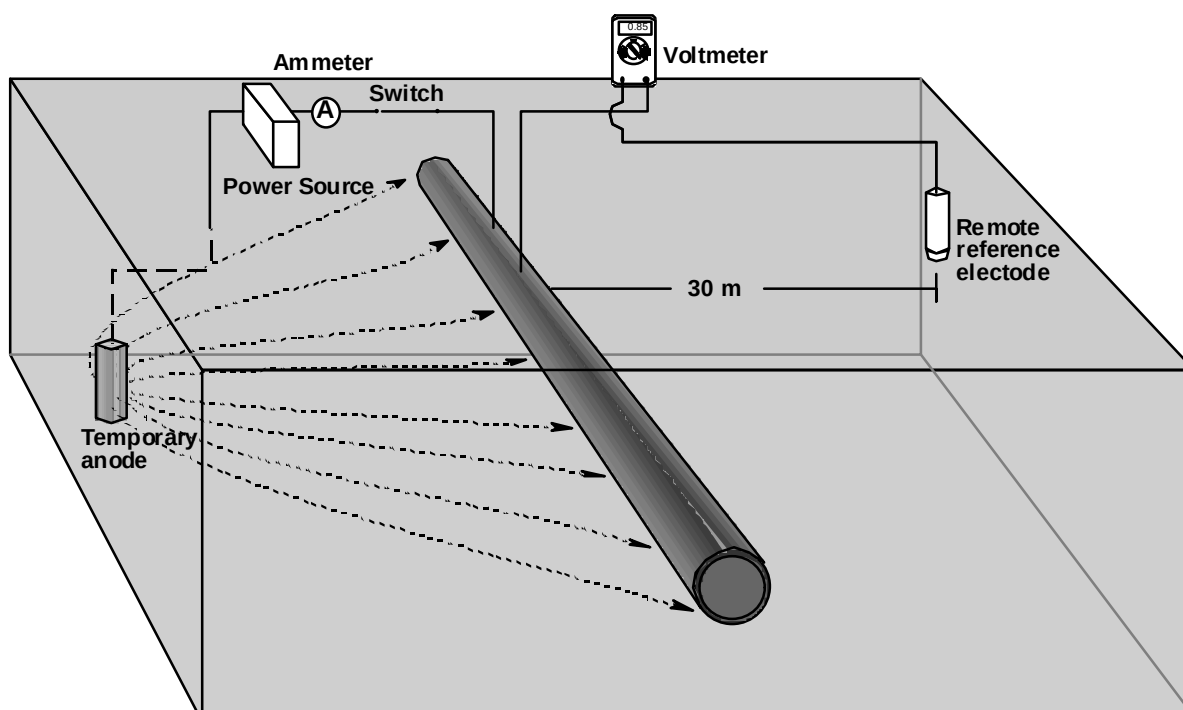


Current Requirement Test for a Coated Pipeline Using Close Cu-CuSO₄ Electrodes

Figure 33

Current Requirement Tests for Bare or Poorly Coated Structures

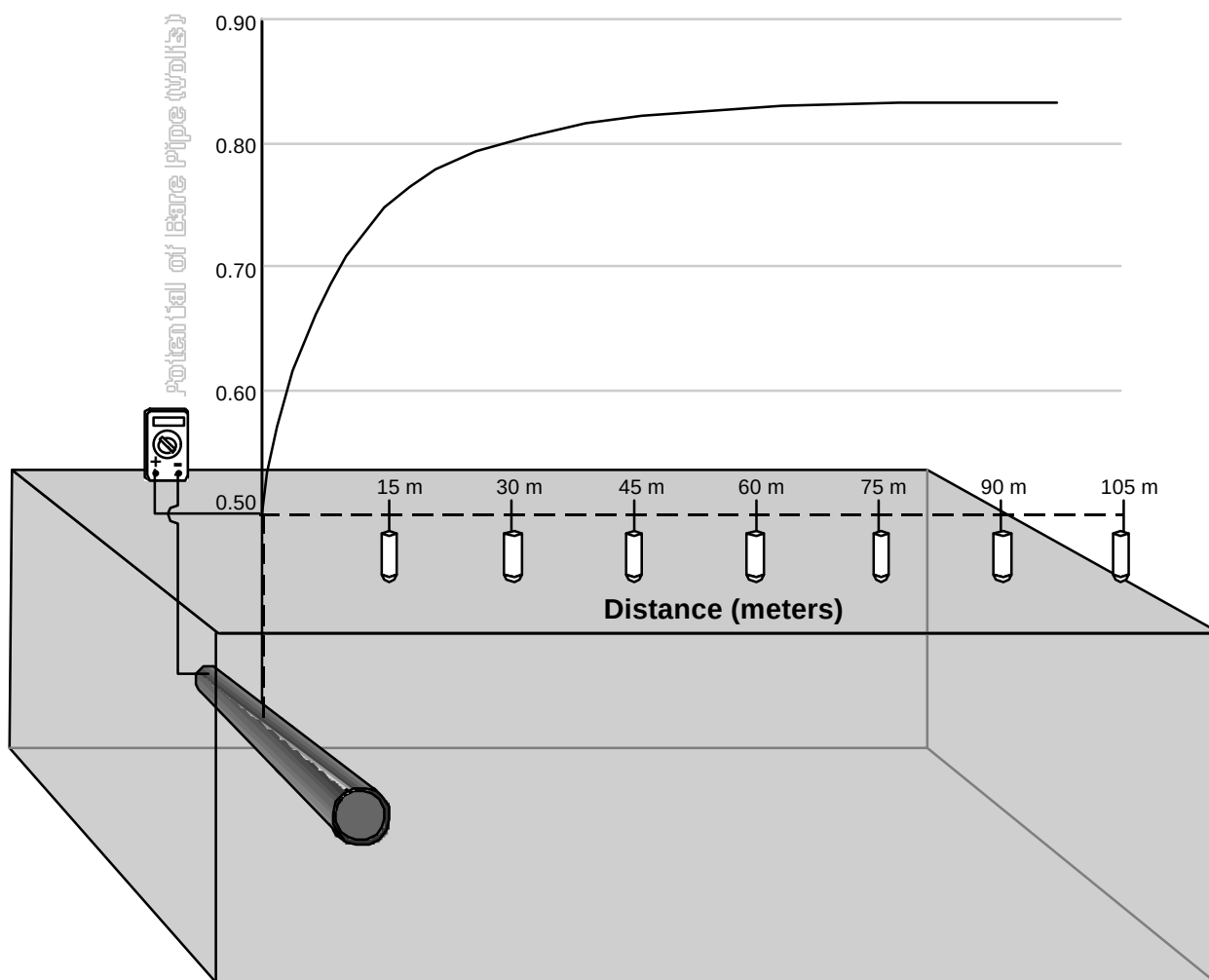
Current requirements are greater for bare or poorly coated structures. Therefore, a welding machine or portable generator is used to provide adequate current and voltage. A temporary anode is also used. A typical test setup is shown in Figure 34.



Current Requirement Test for a Bare Pipeline Using a Remote Cu-CuSO₄ Electrode
Figure 34

In the test for well coated structures (Figure 33), the reference electrode was placed directly over the structure. For bare or poorly coated structures, the resistance between the structure and the earth mainly consists of (1) the contact resistance between the structure and the earth, and (2) the resistance of the earth surrounding the structure. To read the maximum potential between the structure and the earth, the reference electrode must be placed far enough away from the structure to include the major part of the resistance. A distance of 30 meters (100 feet) is usually adequate.

Figure 34 showed the distance from the pipeline to the electrode as 30 meters. The suitability of this distance can be tested. With a constant current flow, the reference electrode is moved at intervals of about 15 meters (50 feet) beyond the 30 meter mark (Figure 35). Measurements are taken at each position until there is no significant change in the potential readings. The reference electrode is then said to be in “remote earth.” If the data is plotted, it would appear as shown in Figure 35.



Determination of Remote Earth

Figure 35

The bare pipeline potential of -1.2 volts achieves a practical amount of protection when the current is on. However, complete protection of a bare or poorly coated structure is not achieved until the structure is fully polarized. A structure becomes polarized as a protective film of corrosion products forms on its surface. Full polarization may not occur for some time because the polarization film takes time to form.

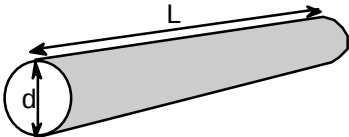
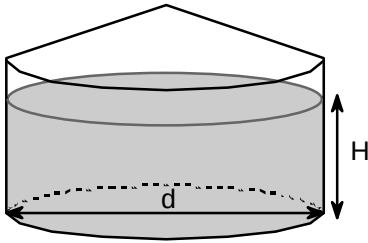
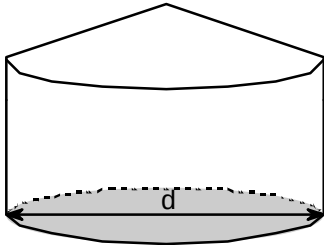
Full polarization occurs when the remote structure to earth potential is -0.85 volts immediately after turning the current off. This is called the “instant off” voltage. The reading must be taken within one second after turning the current off because depolarization occurs rapidly. As the film forms, the “instant off” voltage readings become more negative with time. Several readings may be required. However, the procedure can be shortened by extrapolating the data to give a final test value.

Note that instant off potentials are very difficult to obtain because various structures (plants, pipelines, well casings, etc.) are bonded together.

Work Aid 1: Formulas, Data Bases, And Procedures For Calculating Current Requirements

This Work Aid provides surface area formulas, Saudi Aramco's required current densities, and procedures to calculate the current required to cathodically protect onshore and offshore structures.

Formulas**Surface Areas of Various Structures**

<u>Structure</u>		<u>Exposed Surface Area</u>
Pipelines		πdL
Tank Interiors		$\pi \frac{d^2}{4} + \pi dH$
Tank Bottom Exteriors		$\pi \frac{d^2}{4}$

Work Aid 1A: Design Current Densities and Procedure for Calculating Current Requirements for Buried Pipelines

This Work Aid is designed to assist the Participant in calculating current requirements for buried pipelines.

Saudi Aramco Design Current Densities

Saudi Aramco's design current densities for coated and uncoated pipelines, shown in the table below, are listed in Section 4.4 of SAES-X-400.

<u>Pipeline Surface</u>	<u>Current Density (ma/m²)</u>
Uncoated	20.00
Tape or P-2 wrap	1.25
Coaltar epoxy	0.75
Fusion bonded epoxy	0.10
Polyethylene	0.10

Procedure

1. Locate the required current density for the structure in the table above.
2. If the surface area is not provided, calculate the exposed surface area of the section of pipeline using the formula provided in Work Aid 1.
3. Multiply the required current density by the surface area of the pipeline.

Work Aid 1B: Design Current Densities and Procedure for Calculating Current Requirements for Tanks and Vessels

This Work Aid is designed to assist the Participant in calculating current requirements for tanks and vessels.

Saudi Aramco Design Current Densities

Saudi Aramco's design current density requirements for tanks and vessels, shown in the table below, are listed in Section 4.4 of SAES-X-500 and Section 4.4 of SAES-X-600.

<u>Surface</u>	<u>Current Density (ma/m²)</u>
External tank bottoms (uncoated)	20.0
Coated tanks (internal)	0.5
Coated vessels (internal)	3.0
Uncoated tanks & vessels (internal)	30.0

Procedure

1. Locate the required current density for the structure in the table above.
2. If the surface area is not provided, calculate the exposed surface area of the tank or vessel using the formula provided Work Aid 1.
3. Multiply the required current density by the exposed surface area of the tank or vessel.

Work Aid 1C: Design Current Densities and Procedure for Calculating Current Requirements for Marine Structures

This Work Aid is designed to assist the Participant in calculating current requirements for marine structures.

Saudi Aramco Design Current Densities

The design current density requirements for marine structures, shown in the table below, are listed in Section 4.4 of SAES-X-300.

<u>Environment</u>	Current Density (ma/m ²)	
	<u>Coated</u>	<u>Uncoated</u>
Seawater structures	10.0*	50.0*
Structures in mud or soil	10.0	20.0
Marine pipelines	2.5	--

* Higher current density may be required depending on turbulence and/or velocity.

Procedure

1. Locate the required current density for the structure in the table above.
2. If the surface area is not provided, calculate the immersed surface area of the marine structure.
3. Multiply the required current density by the total immersed surface area of the marine structure.

GLOSSARY

activation polarization	The characteristics of the reaction that control the corrosion rate. Examples of characteristics are the type of metal, the hydrogen ion concentration, and the temperature of the system.
anode	The electrode or area at which oxidation occurs.
anodic half-cell reaction	A chemical reaction that occurs at the anode.
area effect	The effect on corrosion rate of the ratio of the cathodic to anodic area in a galvanic couple.
cathode	The electrode or area where practically no corrosion occurs. Reduction reactions take place at the cathode.
cathodic half-cell reaction	A chemical reaction that occurs at the cathode.
cation	A positively charged ion.
close electrode	An electrode placed on the surface directly above a coated structure.
concentration cell	A cell that consists of an electrolyte and two identical electrodes. The potential in the cell results from differences in the chemistry of the environment near the metal surface.
concentration polarization	Polarization of an electrode caused by concentration changes in the environment near the metal surface.
contact resistance	Resistance at the interface between two materials.
corrosion potential	The potential that a corroding metal exhibits under specific conditions of concentration, time, temperature, aeration, velocity, etc.
electrochemical reaction	A chemical reaction that involves the transfer of electrons and electric current.
electrolyte	An ionic conductor. Examples are soil and seawater.

ion	An atom, or group of atoms, that has gained or lost one or more outer electrons and thus carries an electric charge.
metal path	The contact between the anode and cathode that allows the flow of electrons and electric current.
oxidation	A chemical reaction where electrons are lost (e.g., when a metal goes from the metallic state to the corroded state).
oxygen concentration cell	A galvanic cell caused by a difference in oxygen concentration at two points on a metal surface.
polarization	A shift in the electrode potential due to the effects of current flow, measured with respect to the zero-flow (reversible) potential.
reduction	A chemical reaction that results in a gain of electrons.
reference electrode	A pure metal in contact with a solution of known concentration of its own ions. When two reference electrodes are coupled together, an overall potential develops which is the sum of the reference electrode potentials.
remote electrode	An electrode which is electrically remote from a structure at a point where there is no significant increase in negative potential readings.
resistance	A property of a conductor based on its resistivity, size, and shape.
resistivity	The resistance between opposite sides of a one-centimeter cube of a given material. The unit of measurement of resistivity is the ohm-centimeter.
subkha	A low resistivity soil found near the Arabian Gulf. Subkha is high in moisture and salt content and low in oxygen content.
