

Corrosion and Corrosion Control

by

David H. Kroon, P.E.
Vice President, Engineering
Corrpro Companies, Inc.
Houston, Texas

and

N. Dennis Burke, P.E.

corrpro[®]

Corrpro Companies, Inc.
1090 Enterprise Drive
Medina, OH 44256
330.723.5082
WWW.CORRPRO.COM

Corrosion and Corrosion Control

by

N. Dennis Burke, P.E.

and

David H. Kroon, P.E.

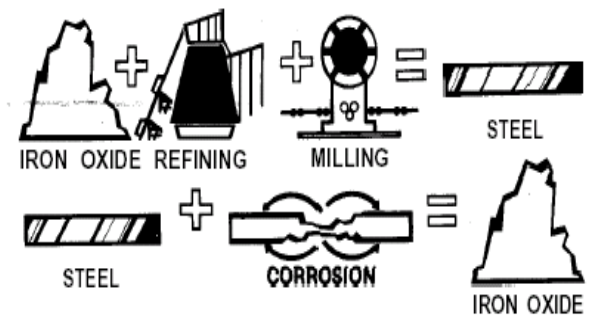
CORRPRO Companies, Inc..

Introduction

Corrosion is a natural phenomenon which follows the laws of science. With an understanding of the basic principles, the causes of corrosion and the preventive measures for controlling corrosion are greatly simplified. The purpose of this paper is to present the fundamental theories of corrosion and corrosion control.

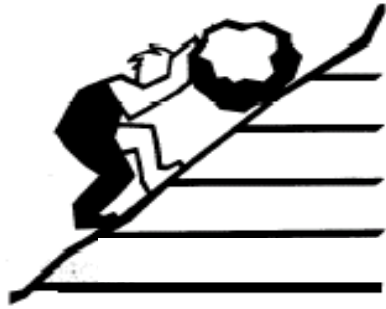
Corrosion

The manufacture of metal products is a prime example of how man has changed the balance of nature. Most metals are not found in nature as pure materials. They are combined with other elements such as oxygen, forming compounds called ores. To obtain metals from ores, the compounds are subjected to extreme heat to break the chemical attractions between the elements. Once the pure metal is isolated, it undergoes rolling, bending, and other shaping operations to obtain the desired finished product. All of the refining and production steps for the transformation of an ore to a final product have one thing in common: they add ENERGY to the metal. Energy is added to force the metal to break free of the ore, and more energy is added to shape the end product. An imbalance of energy exists. Nature does not ignore this imbalance and fights back. As soon as the addition of energy ceases, the metals begin to reform their ores.



A common example of this involves the manufacture of steel from iron oxides. The iron ore is smelted and refined to make steel ingots which are folded into sheets or billets for the making of various items such as piping, tanks and pilings. Common experience shows that products made from iron ore do not remain in the same condition as originally intended. The steel begins to revert to iron oxides (rust) immediately after it is formed. This results in a deterioration of the steel product.

To help understand why the reforming of natural ores occurs, consider the process of rolling a round stone up a hill. The higher up the side of the hill the stone is pushed, the greater the energy expended to get to that height. The hill can be thought of as an energy hill, and the different heights obtained as energy levels. Once the addition of energy to the stone ceases, the stone will roll down the energy hill and lose the energy that had been expended to place it in the elevated position.



The same downhill process applies to steel. The metal “rolls” down the energy hill to return to its natural energy level. The process of a metal releasing energy to reform its natural ores is called corrosion. Corrosion is a normal occurrence common to all metals not in their natural states.

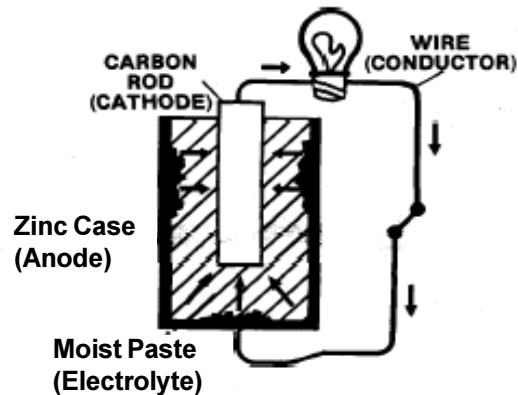
As steel corrodes in either soil or water, electrical energy is released. When metals form ores in these environments an electric current is generated. Corrosion is a process that has two primary aspects. A physical change in the metal occurs and direct electric current is generated.

A corroding metal releases electrical energy, but nature requires that this energy be balanced. To achieve balance, some other metal receives the energy. By receiving energy, the second metal can maintain its level on the energy hill and remain stable. In order for electric current to flow, a metallic connection between the two metals must exist. The two metals involved in the corrosion process are electrodes. More specifically, the electrode releasing electric energy to the environment is an anode, and the one receiving the electrical energy is a cathode.

One other basic requirement is that the metal be placed in soil or water. These are solutions that surround the electrodes and which contain the necessary elements to react with the metal to form an ore. The solution also conducts the electric current flow between the anode and cathode, serving as an electrolyte. The anode releases electrical energy and metal ions into the electrolyte. The metal ions combine with the chemicals adjacent to the anode to form ores and the electric current flows through a conductor to the cathode. At the cathode, the current causes other ions in solution to react

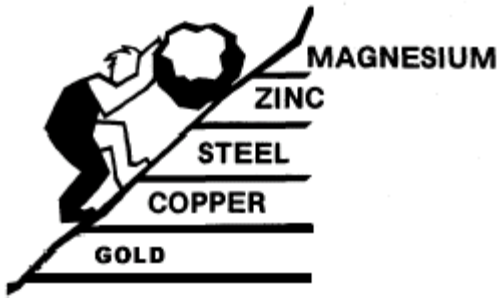
and form films on the surface of the cathode. The balance of energy is maintained. The anode releases energy and loses part of its physical form. The cathode gains an equal amount of energy and a physical change occurs.

For corrosion to occur, four items must be present. There must be at least two metals at different energy levels, an electrolyte, and a conductor. When such a combination is present, a galvanic cell is formed. A familiar type of galvanic cell is the flashlight battery. The corrosion process involving the zinc case, carbon center post, electrolyte, and conductor produces the electric energy required to light a bulb or ring a bell. All of the conditions for a galvanic cell are present.



In a galvanic cell, which is also called a corrosion cell, electrical energy is present. It is the energy difference between the anode and cathode which provides the force to make the current flow. When analyzing a corrosion cell it is necessary to determine which of the metals is the anode and which is the cathode. If the current flow in the electrolyte or the conductor were monitored, the identification would be simple, but in many situations this is impractical. Another means of distinguishing anodes from cathodes must be used.

Consider again the energy hill. Every metal contains a certain amount of energy and has its own position on the energy hill. The position of the metal reflects its energy potential. The more potential that a metal has, the higher up the energy hill it is found. By measuring the energy or potential of a metal, its position on the energy hill relative to other metals can be determined.



In electrical terms, the force that pushes electric current is voltage. Under similar conditions, the greater the voltage, the greater the current flow. Often a reference electrode is used to measure voltage, and the metals are listed according to this reference. In the corrosion control industry, the copper-copper sulfate electrode is used as the common reference for soils and fresh water and the silver-silver chloride electrode is used for salt water applications.

Once the positions of the metals on the energy hill are known, the anode and the cathode of a cell can be. Any metal on the energy hill will release energy to any one below it and conversely receive energy from any metal above it. Scientists have measured the potential of many different metals and have compiled a list which places these metals on the energy hill. One of the names for this list is the GALVANIC SERIES OF METALS. Some of the common metals are listed in **Table 1**.

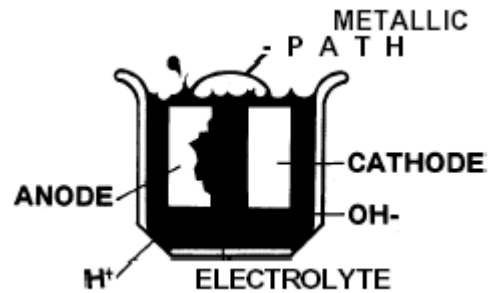
(highest)	Magnesium (Mg)
	zinc (Zn)
	Aluminum (Al)
	Iron (Fe)
	Lead (Pb)
	Copper (Cu)
	Nickel (Ni)
	Silver (Ag)
	Carbon (C)
	Platinum (Pt)
(lowest)	Gold (Au)

TABLE 1

Consider a piece of zinc and one of copper connected with a wire and buried in the earth. From Table 1, the zinc is the anode because it will release electrical en-

ergy to copper, and copper is the cathode because it will receive the energy.

Since everything in nature is balanced, a chemical reaction at the anode requires that one occurs at the cathode. The cathode reaction is dependent upon electrolyte chemistry. The formation of hydrogen is the simplest of the possible reactions. Hydrogen ions are naturally present in water. As the metal releases energy into the electrolyte, the electrolyte around the cathode absorbs an equal amount of electrical energy. The hydrogen ions in the water absorb the energy and form hydrogen atoms. The phenomenon caused by reactions at the cathode is commonly referred to as polarization.



The basic galvanic corrosion process can be summarized as follows:

- * All metals formed from ores will corrode in order to achieve a balance of energy.
- * To maintain balance, a second metal must receive the released energy.
- * The corroding metal is called an anode and the noncorroding metal a cathode.
- * A suitable environment must exist for the energy to transfer. This environment consists of an electrolyte and a metallic connection between the anode and cathode.

The electrical connection between the anode and cathode as illustrated above is a wire connection non-submerged in the electrolyte. In actual practice, this may be any direct connection. Commonly, metals are joined by mechanical couplings, brazing, welding, and physical contact.

A few examples of galvanic cells resulting from two different metals buried or submerged together are:

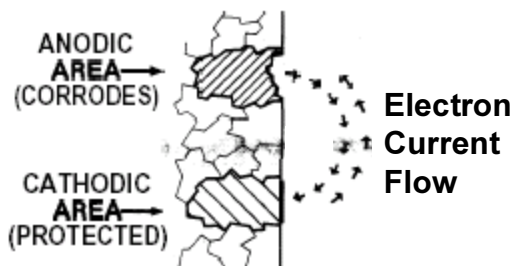
- * Steel tanks interconnected with copper piping or copper grounding systems.
- * Brass valves inserted in steel piping.
- * Rivets in any vessel which are of different alloys than the vessel.
- * Tube sheets and tubes of different alloys in heat exchangers or surface condensers.

The list can be easily expanded.

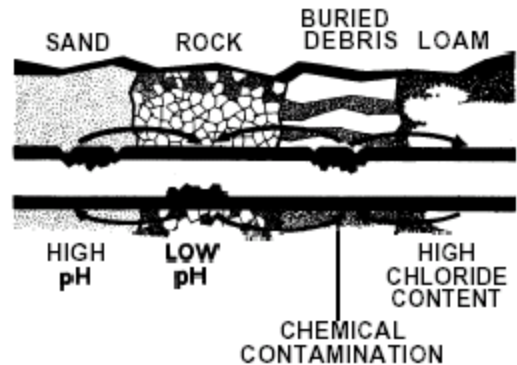
Often corrosion occurs without an obvious anode and cathode. Why does a steel fuel tank buried alone develop corrosion pits and penetrations? Why do the copper strands of the copper concentric neutral spiraled along the buried power cable corrode? The answers are the same: different energy levels exist. These differences are more subtle than previously discussed and are caused by differences within the metal or by differences within the electrolyte.

The corrosion of fuel tanks or copper neutrals is caused by galvanic cells. What causes the energy level differences are areas of imbalance within the material or environment. For example, a steel tank is formed by bending a piece of steel to a specified shape and welding the sections to form a containment vessel. The bending imparts work or energy into some portion of the plate.

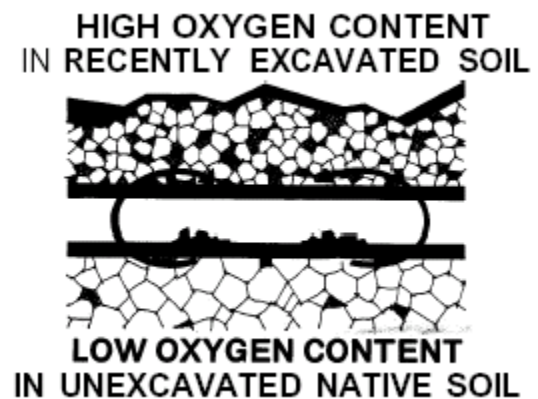
The welding process heats the plate and changes the energy levels in the heated zone. Although made of one material, the tank has many separate levels of energy. These are ideal for generating galvanic cells.



The cable with copper neutrals transverses many types of soil. The chemical content of these soils vary and the energy levels of copper will vary accordingly. The differences in concentration result in energy imbalances, and a galvanic cell.



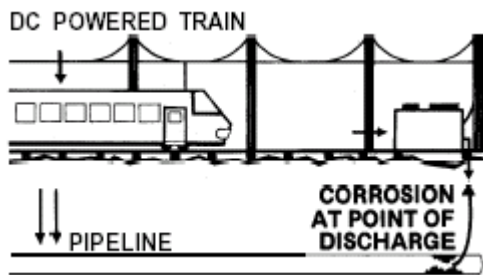
Another example of a galvanic cell is evidenced on piling systems along the sea coast. Typically, the most severe corrosion rates are found just below that mean low water mark and at the mud. These are two areas in which the oxygen concentration differs greatly from the remainder of the electrolyte. The surface wave movement at the mean low water to high water area increases the oxygen level. The zone immediately below has an energy imbalance due to the difference in oxygen concentration. At the mud line, an oxygen concentration differential exists and a galvanic cell forms. The difference in oxygen concentration is also responsible for the bottom of the pipe being anodic to the top of the pipe in underground applications. Such oxygen differentials are frequently the cause of corrosion.



In all examples, the metallic connection between the anodes and cathodes is the structure itself. A separate connection is not necessary.

Galvanic cells are the most commonly encountered causes of corrosion. A second general category of corrosion is caused by electrolytic cells. Electrolytic corrosion results from an external source of DC current being received on one portion of a metallic structure and discharged on another. Although not as prevalent, electrolytic corrosion often leads to rapid failures in concentrated areas.

The operation of DC transit systems often causes electrolytic corrosion on neighboring structures. A portion of the DC traction power current leaves the rails of the transit system. This current flows through the earth to a structure where it is received onto the surface. The current flows along the structure to an area where it is discharged to return to the electrical ground of the DC traction power system. In the area of current discharge, concentrated corrosion occurs. One ampere of current flowing from steel carries approximately twenty pounds of metal into solution in one year. Often, only a few grams of metal need to be lost in a concentrated area to penetrate the wall of a containment vessel, which can result in catastrophic corrosion failures.



When trolley car systems were present in many of the major cities, this type of corrosion occurred throughout metropolitan areas. Early recognition of the severe consequences of electrolytic corrosion resulted in many people referring to corrosion as electrolysis. Electrolytic action is, however, only one of the major causes of corrosion. In addition to transit systems, common sources of DC current that cause electrolytic corrosion include welding machines, DC motors, HVDC transmission and cathodic protection systems.

The four requirements for corrosion are also present in electrolytic cells: the cathode is the area where the current is received; the anode is the area where the current is discharged, the soil is the electrolyte; and the metal

structure is the conductor between the anode and cathode. In electrolytic corrosion, the energy imbalance is created by an outside source of current flowing through the electrolyte.

In practice, the corrosion process usually involves more than one of the many possible combinations of corrosion cells. When analyzing corrosion, each of the four components in the cell must be defined. Within those components, the possible variations are then identified. With all of the factors at hand, a systematic corrosion control solution can be outlined.

Corrosion Control

The most common methods of corrosion control involve material selection, coatings, electrical insulation and cathodic protection. Each of these measures has distinct advantages and disadvantages. All should be considered when planning a comprehensive corrosion control program.

Material selection needs to be addressed during project design. Through the use of non-metallic components corrosion can be avoided. Most often, however, non-metallic materials have operating limitations that necessitate the use of metals. Under these circumstances, similar metals should be incorporated in the design to avoid the interconnection of materials that are not close to each other on the energy hill. This serves to reduce the driving force between the anode and cathode in the corrosion cell and thereby decreases the rate of corrosion.

The proper selection of materials for the environment is very important. Many materials perform well in one environment but corrode very rapidly in another. Aluminum, for example, is extremely resistant to corrosion in the atmosphere because it forms a protective oxide layer that inhibits further corrosion. In salt water or soil environments, aluminum rapidly corrodes because the oxide layer that forms does not have the same protective properties. Stainless steel performs similarly. When stainless steel is placed in an oxidizing environment, a very thin oxide forms which passivates the metal surface. If this film is damaged by such things as abrasion or the presence of chloride ions, the stainless steel will

corrode at approximately the same rate as mild steel.

The careful selection of materials can reduce but cannot prevent corrosion. Differences in the electrolyte and differences along the surface of the metal will still create an energy imbalance which results in corrosion. This cannot be entirely avoided.

Coatings are often used for corrosion control. The purpose of a barrier coating is to insulate the anode and cathode of the corrosion cell from the environment. By insulating the metallic surface from the electrolyte, coatings prevent the corrosion reaction from occurring.

Many types of coatings have been developed over the years. Vinyls and epoxies are often used for submersion service. Coal tar enamel, extruded polyethylene and epoxies are all used underground. Whatever the material, a good barrier coating should have certain important characteristics. The coating should have a high dielectric strength to effectively insulate the structure from the electrolyte; it should be relatively inert with respect to the environment to ensure a long life; it should have high impact resistance to avoid damage during shipping, handling and installation; it should have good bonding characteristics to ensure permanent contact to the structure; and it should have low water absorption properties to maintain the dielectric strength.

Selection of a coating for a particular application requires detailed knowledge of the environment and the type of service. After a coating is selected, great care must be exercised to make certain the coating is properly applied. A coating failure usually occurs due to improper application and not to a break down of the coating material. Surface preparation is critical to coating performance.

Whatever the material selected and no matter how well the coating is applied, coatings are not perfect. Voids or holidays will exist; These may be large enough to be seen or may be tiny microscopic pinholes that cannot even be detected with a flaw detector (jeoper, holiday detector). Attempts have been made to achieve perfect coatings. These are both unsuccessful and prohibitively expensive. Coatings will also deteriorate with time. As

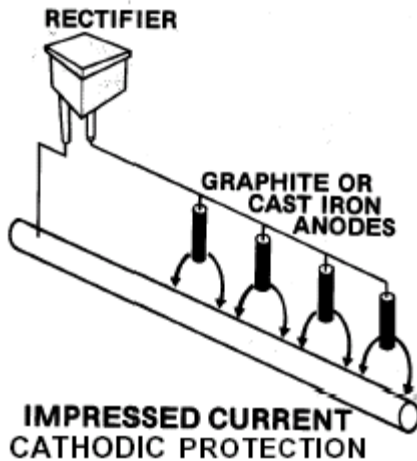
with all things, coatings suffer from both imperfection and aging.

The proper selection and application of a coating system will reduce the total metal loss but will not prevent corrosion. Unfortunately, coatings concentrate the corrosion activity at the imperfections. This intensifies the corrosion and results in penetrations more rapidly than if the structure were uncoated.

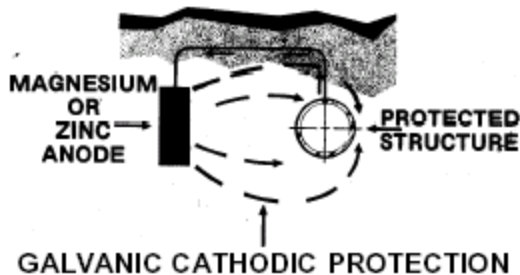
Electrical insulation is another method of corrosion control that can be used to break the conductor which connects the anode and cathode in the corrosion cell. Insulating fittings come in many forms which include unions, couplings, flanges and spools. These are most often used to electrically separate dissimilar metals. Common applications include the installation of an insulating fitting at a gas service meter to insulate the steel gas line from a copper water service which is electrically connected at the water heater. Insulating flanges are often used at well heads to break the electrical connection between bare steel well casings and coated steel flow lines. Pipelines are sometimes insulated at station locations to electrically isolate the steel pipeline from the copper grounding system. In all cases, the insulator is used to break the electrical continuity between the anode and the cathode.

Insulation only serves to break apart obvious corrosion cells. It will not prevent local corrosion activity resulting from such things as different oxygen concentrations. Insulating fittings must not be used indiscriminately, because, at times, electrical continuity is desired for other reasons including electrical grounding and cathodic protection.

The principles of cathodic protection can be best understood by examining the corrosion cell. At the anode metal is consumed, but at the cathode, the energy level is maintained. By making the entire structure a cathode, all surfaces that receive sufficient current can maintain their position on the energy hill. This is cathodic protection.



Cathodic protection requires an outside source of direct current that flows through the electrolyte onto the surface of the metal. One source for this current may be a DC power supply connected to a relatively inert electrode that is placed in the soil or water. Current is forced to flow from the electrode, through the electrolyte, to the metal surface. This is impressed current cathodic protection.



Another source of current may be obtained by connecting a metal that is higher on the energy hill to a metal that requires protection. The higher energy material becomes the anode in an intentionally designed corrosion cell and sacrifices itself to protect the structure. This is galvanic anode cathodic protection.

Both impressed current and galvanic anode cathodic protection require that current flows from the cathodic protection anode, through the electrolyte, onto the cathode surface. Through the addition of energy, the cathode, or protected structure, maintains the energy level

of the refined metal. A familiar application of cathodic protection is household hot water heaters. Small magnesium rods are installed inside the tank to provide cathodic protection to the submerged metallic components.

Because cathodic protection current must flow onto the metal surface, cathodic protection can only be applied when the structure is buried, submerged or embedded in an electrolyte. Unfortunately, cathodic protection is not applicable for controlling atmospheric corrosion. It cannot be used in the form described to protect automobiles from corroding. Galvanizing, which is essentially the deposition of zinc on a steel surface, is a form of cathodic protection. The zinc is the anode and the steel is the cathode. In this case, the cathodic protection anode is directly applied to the surface of the cathode.

Material selection, coatings, electrical insulation and cathodic protection have been briefly introduced. All of the corrosion control techniques should be considered during project design or development of a corrosion control program. In almost all cases, a combination of the techniques results in the most effective and economical system for controlling corrosion. For example, coatings and cathodic protection are most effective in combination. The coating reduces the current requirements for cathodic protection and cathodic protection effectively overcomes the limitations of the coating.

The best approach to corrosion control is to have knowledgeable engineers develop a complete program for design, construction, monitoring and maintenance. Responsible engineering will assure economy of operation, safe conditions and environmental protection.