

Corrosion of Steel, Aluminum and Copper in Electrical Applications



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Executive Summary

Corrosion, typically defined as the deterioration of metals through the combined actions of oxygen, other metals and salts, has a major impact on industrial economies. But despite the damage it does, and the seriousness of the issue in economic terms, awareness of ways corrosion can be controlled is in surprisingly short supply.

In the United States, Japan, Great Britain and Australia, studies of the economics of corrosion have indicated that its cost to the economy runs in the vicinity of 3-4 per cent of Gross National Product.

Further, in a world where businesses are looking for ways to simultaneously stretch budgets and address concerns about the sustainability of their processes, corrosion presents another problem. Of the new steel consumed every year around the world, it is estimated that roughly 20 per cent is used to replace metal lost to corrosion¹.

As is often the case, the reality on the ground is a lot messier than the scientific explanation. In theory, corrosion processes are easy to describe, but the truth of the matter is that corrosion is a multi-phased process that can sometimes result in secondary chemical agents that are as damaging as the corrosion itself. Hydrogen evolution is a good example of this. While corrosion is the main culprit, the resultant processes further weaken metallic components.

Likewise, the corrosion resistance properties of various metals – often thought of as a cut-and-dry matter – are much more complex than they appear at first glance.

Considering the cost it exacts on our economy, it is surprising that corrosion is such a misunderstood process, and that it is often treated as an uncontrollable cost of doing business. By acquiring knowledge of the corrosion process, we can better understand how to limit its negative effects.

This paper provides a brief overview of corrosion and explores how best to control it by examining its impact on the three most commonly used metals in electrical installations: copper, steel and aluminum.

Why Metals Corrode

To reduce it to simplest possible terms, corrosion is really nothing more than the inherent tendency of metals to revert from a processed, metallic state to their more natural state, which we commonly call “ore”.

Most metals, with the exception of precious metals, such as gold and platinum, do not occur in metal form in nature – they exist as ore. When ore is processed into metal, the refining process transfers its latent energy to the ore. It is the taking on of this latent energy that transforms ore into metal, but by taking on this energy, the metal elevates to a higher energy state, which means it also becomes less thermodynamically stable.

Corrosion is really nothing more than the inherent tendency of metals to revert from a processed, “metallic” state to their more natural “ore” state.

The process of metal, in its new high-energy state, reverting to its lower energy (ore) state is what we call corrosion. It is, quite simply, the means by which metal returns to its more stable, lower energy mineral state through the release of the latent energy acquired in refinement.

Precious metals such as gold and platinum exist naturally in their metal state and have intrinsic thermodynamic stability. All other metals are prone to corrosion. In some cases, metals can form oxide films as part of the corrosion process. Some metals form oxide films that are porous while other metals form oxide films that buckle and flake off. In both cases, the underlying metal is subject to continued oxidation process and results in metal loss. But there can be an upside to oxide films as well.

Metals that form a tightly adhering layer of surface oxides are much more corrosion resistant because the adhering layer – known as the passivation layer - offers significant protection by isolating the metal from the corrosive environment.

How Corrosion Works

Four conditions must exist for corrosion to occur:

- There must be an anode (corroding) and a cathode

¹Vander Velde, H. 1994. Corrosion Testing and Rehabilitation of Unbonded post tensioned cables in “Push-Through” or “Heat Sealed Sheaths”, In Seminar on Parking Garages, Toronto, Edited 2002.

(protected) component

- There must be an electrical potential between the anode and the cathode
- The anode and cathode must be immersed in an electrolyte, which is an electrically conductive fluid
- The anode and cathode must be connected by a metal path of low resistance

In other words, corrosion is essentially an electrical circuit wherein electrons flow from the anode to the cathode. When electrons flow from the anode, the anode oxidizes to form metallic ions. These metallic ions then detach from the metal surface to flow toward the cathode through the electrolyte.

Throughout this process the metallic ions may also react with elements in the electrolyte to form other compounds. Rust is a good example. Rust (also known as FeOOH) is created when iron ions react with various elements in the water.

As the electrons flow across the low-resistance metallic path to the cathode, the cathode is reduced and the formation of metal ions is halted. When the metal is not in a positively charged ionized form, it is much less reactive. This is why the cathode develops an inherent protection from metal loss to corrosion. Below is an example (Figure 1) showing how iron is oxidated (loses electrons and becomes a metallic ion) and reacts with the hydroxide ions present in the electrolyte, thus forming FeOOH (rust).

Oxygen is frequently involved in the corrosion process because most metals in ore form are typically oxides. For example, iron and aluminum exist in nature as an oxide (Al_2O_3 and Fe_2O_3 respectively). Copper, on the other hand, is typically found as copper sulfate. This means that in the presence of sulfur, copper will readily react with sulfur to return back to its natural state of copper sulfate.

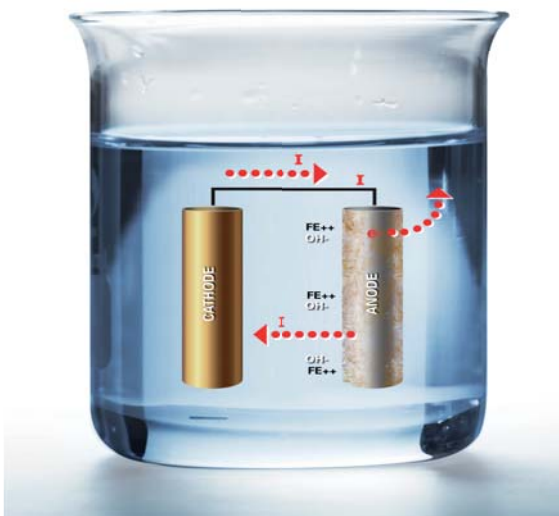


Figure 1

The Electrical Metals: Steel, Aluminum and Copper

Steel, aluminum and copper are the three main metals used in electrical applications. Steel is typically used in housing, enclosure and support systems (struts and cable trays). Copper is often used in conductors. And aluminum can be found most often in conductors, conduits, armor and supports (cable trays). Each of these metals is susceptible to corrosion and there are many misconceptions about the corrosion resistance of each.

The electrical industry generally considers copper to be corrosion resistant in virtually all environments while regarding steel and aluminum as non-resistant. However, this is an over-generalization.

Of the three metals copper is the most cathodic, or noble, and is typically less affected by galvanic reactions. As a result, the electrical industry generally considers copper to be corrosion resistant in virtually all environments while regarding steel and aluminum as non-resistant. However, this is an over-generalization in what should be thought of in more relative terms. The truth of the matter is that copper tends to get a “free ride at the expense of other metals”. Were it to be used in contact with more noble metals such as passive nickel, passive stainless 316 and 304 stainless steel or titanium, copper would galvanically deplete just as readily as steel or aluminum do.

Atmospheric, Soil and Galvanic Corrosion

In general, atmospheric, soil and galvanic corrosion represent the major types of corrosion metals are exposed to in the electrical industry.

Atmospheric Corrosion of Steel

Steel typically corrodes or rusts rapidly in moist environments, and the rate of corrosion accelerates with exposure to salt water.

As mentioned previously, Fe_2O_3 forms on the surface of iron or steel to act as a passivating layer. However, in the presence of water, oxygen, and sulfur dioxide and carbon dioxide solutions, the protective Fe_2O_3 layer becomes non-protective rust (FeOOH) due to the formation of Fe_3O_4 .

This layer is continually flaking off at the surface to expose fresh metal to corrosion. This process carries on until either all of the iron or all of the oxygen, water, carbon dioxide, or sulfur dioxide in the system is removed or consumed. In electrical applications where steel is usually used as the housing, enclosure or support system material, corrosion needs to be controlled by measures such as galvanizing, alloying, or painting. Galvanizing steel with zinc provides steel with a sacrificial anode that will continually deplete to protect the

more cathodic steel. Alloying steel with chromium allows for the formation of a tightly adhering surface oxide layer, thus turning steel into stainless steel. Painting prevents corrosion by sealing out the agents of corrosion listed above.

Atmospheric Corrosion of Copper

Copper can sometimes be found naturally in a metal state and is therefore thermodynamically stable in most atmospheric conditions. As a result, copper is widely used for roofing and other applications where it will come into contact with water.

Copper develops a strongly adhering oxide layer, which thickens to acquire the familiar green patina we see on copper roofs. In the presence of atmospheric sulfur dioxide (SO₂) the transition from oxide layer to patina is accelerated. In applications such as roofing where the green patina has aesthetic value, the increase in formation of patina is desirable. This is definitely not the case in electrical system applications where the formation of this thick non-conductive patina is undesirable. Where the greenish corrosion product is found on a copper conductor, this corrosion product must be removed by means of a wire brush or emery cloth to ensure low resistance contact between conductor and connector.

Atmospheric Corrosion of Aluminum

Only beryllium, potassium, sodium and magnesium are more thermodynamically reactive than aluminum. However, a signature property of aluminum is its tendency to form a strongly bonded passivating oxide film on its surface. For this reason, it offers excellent resistance to corrosion and provides years of maintenance-free service in natural atmospheres. At an ambient temperature of 25 degrees C, the normal surface film formation is only about 2-50nm thick. If damaged – by a fresh abrasion for example – this corrosion-protective film re-forms immediately in most environments and ensures continued protection. As a result, aluminum and its alloys are used in a wide range of applications that include buildings, power lines, large ship superstructures, truck transports, railroad and subway cars, water pipelines, beverage containers (soft drink and beer cans), and chemical industry tanks, piping, barges, reaction vessels, and distillation columns². In applications where exposure to the elements – particularly water – is a factor, you can be sure you will find aluminum being used.

For an excellent example of aluminum's time-proven resistance to corrosion at work in the electrical industry, look no further than bare aluminum transmission conductors, which have been hard at work and resisting corrosion now for over 100 years.

Soil Corrosion of Steel

The reaction of carbon steel to soil corrosion depends primarily on the composition of the soil and other environmental factors, including the presence and abundance of moisture and oxygen. The extreme variability of these factors amounts to extreme variation in the rate of attack by corrosion.

Consider, for instance, that a buried iron vessel in the worst possible soil conditions may perforate in less than a year, and yet iron tools hundreds of years old have been unearthed by archeologists in arid desert regions. As a rule, soils with high moisture content, high electrical conductivity, high acidity, and high dissolved-salt content will be most corrosive³. For this reason, exposed steel is not often buried in the ground in electrical applications, and as a result, soil corrosion of steel is rarely a concern.

Soil Corrosion of Copper

A relatively noble metal, copper forms the passivating protective layer that has been referenced previously. In this case the layer is a reddish-brown film, otherwise known as cuprous oxide (Cu₂O). In most cases, the protective film on copper remains intact or is readily repaired under most soil conditions. But there are situations that will destroy the protective layer and prevent its renewal, causing copper to become susceptible to corrosion in certain soils.

Aggressive copper corrosion scenarios can be expected where:

- There is a combination of elevated sulfate or chloride content and water content resulting from poor drainage, high soil capacity for moisture retention or moderate to heavy annual rainfall (usually more than 76 cm [30in.]). While elevated concentrations of sulfate, chloride, or both in the soil are probably the primary factor in underground corrosion of copper, considerable moisture must be present to support the electrochemical activity required. The sulfates and chlorides may not adversely affect the copper if rainfall is slight and drainage is adequate.
- There is very low soil resistivity (less than 100-500 ohm-cm).
- There are large quantities of organic matter (particularly soils containing organic acids).
- Cinder fills are present, either because of the sulfides present, or because of the galvanic action created by the carbon particles in the cinders. Copper is anodic to carbon, and corrosion should be expected if the cinders used for backfill contain appreciable amounts of carbon. Moisture must be present for the required galvanic action to take place.

²Corrosion of Aluminum and Aluminum Alloys, Edited by Joseph R. Davis, ©1999.

³Conditions Contributing to Underground Copper Corrosion, Edited by J.R. Myers and A. Cohen, Source: Copper.org.

- There are active anaerobic bacteria (sulfate-reducing species) that can produce sulfides.
- There are inorganic acids.
- There are soils containing appreciable amounts of ammonia compounds, which are usually corrosive to copper⁴.

Another handy rule of thumb: clay sand, gravel, loam, and chalk seldom possess the combination of properties that promote corrosion of copper in soil.

In electrical applications, where bare copper is commonly used for electrical grounding rings and electrodes, special attention needs to be paid to soil conditions.

Soil Corrosion of Aluminum

According to the US Army Corps of Engineers, “Aluminum has excellent corrosion resistance in a wide range of water and soil conditions because of the tough oxide film that forms on its surface. Although aluminum is an active metal in the galvanic series, the oxide film affords excellent protection except in several special cases. While it is true that aluminum’s protective oxide film is stable in a pH range from 4.5 to 8.5, the cocktail of compounds present is crucial. Certain soils tend to be more corrosive to aluminum, particularly non-draining clay-organic mucks. As a general rule, contact with clay soils should be minimized unless special corrosion treatment measures are instituted.”⁴ It is for this reason that the National Electric Code and the Canadian Electric Code ban the use of bare aluminum in soil.

Galvanic Corrosion of Steel, Copper and Aluminum

Galvanic corrosion is probably the leading cause of all corrosion experienced by steel and aluminum in electrical applications. Unlike structural or mechanical applications where metals can be electrically insulated, electrical applications require direct metal-to-metal contact.

Galvanic corrosion occurs when two metals of different potentials come into direct contact with one another while immersed in an electrolyte. The two metals’ difference in potential causes current to flow from the cathode to the anode, which, as we have seen, leads to oxidation of the anode and reduction of the cathode. As described previously, this results in the corrosion of the anode and the protection of the cathode from corrosion.

Figure 1 below shows the potential difference measured between various metals and the standard hydrogen electrode.

Element	Electrode Potential (Volts)
Lithium	-3.04
Rubidium	-2.92
Potassium	-2.92
Calcium	-2.87
Barium	-2.80
Sodium	-2.71
Magnesium	-2.37
Aluminum	-1.67
Zinc	-0.76
Chromium	-0.74
Iron	-0.44
Nickel	-0.24
Tin	-0.14
Lead	-0.13
Hydrogen	+0.00
Copper	+0.34
Iodine	+0.54
Silver	+0.80
Gold	+0.80
Mercury	+0.80
Iodide	+0.54
Bromine	+1.07
Chlorine	+1.36
Fluorine	+2.87

Figure 1: Electrode potential of various metals versus the standard hydrogen electrode.

Copper, which we have seen to be a relatively noble metal, does not usually exhibit a great deal of galvanic corrosion. However, in cases where bare copper is buried in soil with high cinder fill content, the carbon in the cinder fill will cause the copper to become anodic and corrosion to occur.

Due to its position in the galvanic series, steel is prone to galvanic corrosion. This is not typically an issue in electrical applications because steel components are not usually required to be electrically conductive. This means they can be insulated from the other metals to eliminate the metal-to-metal contact corrosion requires.

For aluminum, due to its inherent resistance to other forms of corrosion, the galvanic process is the most common cause of corrosion. When aluminum, a reactive metal in the galvanic series, comes into contact with other more cathodic metals, it acts as a sacrificial anode and becomes susceptible to corrosion.

Understanding galvanic corrosion has led to the use of metals

⁴United States Army Corps of Engineers, EM 1110-2 1614 Design of Seawalls and Bullheads. Washington, DC: USACE, 1995.

in the galvanic series for cathodic protection. For example, electrically connecting buried steel pipe with zinc, which is more anodic, allows the zinc to corrode before the steel. It is offered up as a sacrificial anode and limits the corrosion of the steel pipe until all of the zinc is consumed.

Preventative Measures

Atmospheric Corrosion

When steel is used for housing and structural components, it is chosen for its cost and strength. For all its benefits, it is relatively susceptible to atmospheric corrosion. Coating or painting is required to separate the steel from the water and other agents that facilitate the corrosive process. Millions of automobiles are a testament to the effectiveness of this approach.

Copper, which is highly noble, is well known as a suitable metal for most atmospheric applications. However, in locations with elevated sulfur (such as H₂S) and ammonia content, use of copper should be avoided. When copper conductors are used in these environments, special oxide inhibiting pastes need to be applied. This is the reason why nickel-plating and tin-plating are also widely used as means to prevent copper corrosion.

When working with copper, care must also be taken to remove the thickened oxide layer (patina), as this layer is non-conductive and will degrade the integrity of the electrical circuit.

Aluminum is typically corrosion resistant in most atmospheric conditions, and unlike copper, it does not corrode in sulfur or ammonia rich environments. However, it is also important to remember that aluminum is vulnerable to galvanic corrosion.

Soil Corrosion

As discussed earlier, soil corrosion is normally not a major concern for steel in electrical applications. Due to its cathodic nature, copper is the standard conductor for use in grounding electrodes and grounding rings. In order to eliminate the possibility of galvanic corrosion of copper caused by carbon content, care must be taken to ensure cinder fill is not present in areas where copper is being used. Care should also be taken to insulate underground steel pipes when grounding them to copper grounding conductors in order to prevent galvanic corrosion of the steel.

Generally speaking, aluminum in electrical applications is not permitted for use in direct contact with soil, and aluminum conductors are insulated to eliminate possible corrosion due to extreme soil pH levels outside of aluminum's safe range. Aluminum is considered to be corrosion resistant in soils

ranging from 4.5 – 8.5 pH.

Galvanic Corrosion

Unless exposed to high carbon content (cinder fill), galvanic corrosion does not usually arise as an issue for copper due to the noble nature of the metal.

Steel, less noble than copper, will corrode when the two metals are in contact with one another. Wherever possible, these two metals should be insulated from each other. In situations where direct contact is required such as copper bonding conductors connecting to steel enclosures, an oxide-inhibiting paste should be applied. This will keep moisture (electrolyte) away from the contact area and limit the potential for a galvanic reaction between the two metals.

Aluminum is the most reactive metal among the three metals discussed. As a result, galvanic corrosion is the most commonly occurring form of corrosion in aluminum electrical applications. Often used as an electrical conductor in either cable form, connector form or as the bussing in panels, aluminum will require tin-plated bussing and connectors to mitigate galvanic reaction when connected to copper or steel. An oxide-inhibiting compound should also be used to ensure moisture (electrolyte) does not reach the contact surface and facilitate galvanic reaction.

The best way to eliminate galvanic corrosion is to:

- Select metals that are close together in the galvanic series
- Isolate the metals from each other using insulating materials
- Eliminate the presence of electrolyte on the metal surface
- Maintain a large surface anodic area in relation to the cathodic area

Conclusion

Understanding the corrosion process will help in reducing the safety and economic impact of corrosion damage. As discussed in this paper, each metal used is subject to its own unique corrosion process. Aluminum and copper are both widely used conductor materials and each has its own benefits. The metal selected for each application needs to have the necessary mechanical, electrical and chemical properties to fulfill its intended function, while meeting the economic requirements of the installation.

