



SURFACE VEHICLE INFORMATION REPORT

J447™

APR2016

Issued 1956-01
Revised 1995-07
Stabilized 2016-04

Superseding J447 JUL1995

Prevention of Corrosion of Motor Vehicle Body and Chassis Components

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Foreword—Prevention of corrosion is an important design consideration for metals used in body and chassis components. In some cases, corrosion resistance may be the dominating factor governing the selection of material or process; in others, it will be secondary to manufacturing feasibility, appearance requirements, and availability. Means of preventing or retarding corrosion on specific parts may be important from the standpoint of assuring proper engineering function, contributing to service life, or producing and maintaining appearance. The designer should be familiar with the part that corrosion prevention plays in the selection of metal and/or treatment, so that the performance complies with the requirements.

With the use of salt for de-icing and dust control increasing at a rapid rate for the past decade, corrosion problems have been recognized as ones of primary importance. Components experiencing the most severe corrosion are those exposed to road splash thrown up by the wheels. Salt and mud poultices built up in these areas hold moisture in contact with the metal parts and extend the periods of wetness, which in turn accelerate deterioration by corrosion. The best way to prevent corrosion is to keep these critical surfaces free from prolonged contact with salt and mud. Therefore, the owner can help prevent corrosion by washing the vehicle, including the underbody, particularly during periods of high salt exposure.

This report is intended to provide information covering the corrosion preventive methods commonly used for both ferrous and nonferrous metals. The particular practices discussed are those considered typical within the automotive industry, but are believed applicable to parts and products for many other applications. Care has been taken to provide reliable data, but users should supplement this with their own experience and tests to be assured of satisfactory results for their own specific requirements. Optional methods may be equally suitable for typical classes of parts, and the choice may vary, with acceptable results. In some instances the preferred type of finish, coating, or treatment is indicated. Within the limits of whatever restrictions apply, after the selection is made, quality requirements are met by establishing suitable specifications, process controls, and acceptance tests.

The choice of corrosion preventive methods is greatly affected by the environmental and other conditions to which the part will be subjected in use, such as:

- a. Moisture
- b. Temperature
- c. Salt
- d. Galvanic Couples
- e. Abrasion

The applicable conditions of service should be evaluated and protection provided in terms of the expected life of the part. Also, the part design may have an important effect on prevention of corrosion in severe environments and should be considered in relation to the materials and/or treatments and coatings. Trapped moisture, lack of ventilation, crevices, and other design details or effects of design may be significant.

In general, the corrosion preventive requirements of most automotive parts may be satisfied by a combination of the following:

- a. Selection of material
- b. Design considerations
- c. Choice of protective treatments and/or coatings

The application of treatments or coatings to metal almost always requires some form of cleaning or other preparation for satisfactory results. Variations required for different coatings will be covered where they are considered important to the results obtained.

A general discussion of the methods, characteristics of materials, and specific applications is given in subsequent test.

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1. Scope—This SAE Information Report provides automotive engineers with the basic principles of corrosion, design guidelines to minimize corrosion, and a review of the various materials, treatments, and processes available to inhibit corrosion of both decorative and functional body and chassis components.

2. References

2.1 Applicable Publications—The following publications form a part of this specification to the extent specified herein. The latest issue of SAE publications shall apply.

2.1.1 SAE PUBLICATIONS—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE PAPER 912275—Proc. Automotive Corros. and Prevention Conference, Townsend, H. E., et al., 1991, p. 73

SAE Paper 912278—Lutze, F. and Shaffer, R. J., *ibid.*, p. 115

SAE Paper 912283—Petschel, M., *ibid.*, p. 179

SAE Paper 912284—Davidson, D. D. and Schumacher, W. A., *ibid.*, p. 205

SAE Paper 912285—Roudabush, L. A. and Dorsett, T. E., *ibid.*, p. 221

SAE Paper 912291—Roberto, O. E. and Hart, R. G., *ibid.*, p. 289

SAE Paper 950375—Simpson, T.C., Bryant, A.W., Hook, G., Daley, R.A., Swinko, R.J., and Miller, R.W.

2.1.2 ASTM PUBLICATIONS—Available from ASTM, 100 Bar Harbor St., Philadelphia, PA 19103-1187.

ASTM B 110—Dielectric Strength

ASTM B 117—Test Method of Salt Spray (Fog) Testing

ASTM B 136—Stain Resistance

ASTM B 137—Coating Weight

ASTM B 177—Practice for Chromium Electroplating on Steel for Engineering Use

ASTM B 183—Practice for Preparation of Low Carbon Steel for Electroplating

ASTM B 200—Specification of Electrodeposited Coatings of Lead and Lead-Tin Alloys on Steel and Ferrous Alloys

ASTM B 242—Practice for Preparation of High-Carbon Steel for Electroplating

ASTM B 252—Practice for Preparation of Zinc Alloy Die Castings for Electroplating and Conversion Coating

ASTM B 253—Guide for Preparation of Aluminum Alloys for Electroplating

ASTM B 254—Practice for Preparation of and Electroplating on Stainless Steel

ASTM B 281—Practice for Preparation of Copper and Copper-Base Alloys for Electroplating and Conversion Coatings

ASTM B 320—Practice for Preparation of Iron Castings for Electroplating

ASTM B 322—Practice for Cleaning Metals Prior to Electroplating

ASTM B 368—Method for Copper-Accelerated Acetic Acid-Salt Fog Testing (CASS Test)

ASTM B 380—Methods for Corrosion Testing of Decorative Chromium Electroplating by the Corrodokote Procedure
ASTM B 456—Specification for Electrodeposited Coatings of Copper Plus Nickel Plus Chromium and Nickel Plus Chromium
ASTM B 487—Test Method for Measurement of Metal and Oxide Coating Thickness by Microscopical Examination of a Cross Section
ASTM B 499—Test Method for Measurement of Coating Thickness by the Magnetic Method: Nonmagnetic Coatings on Magnetic Basis Metals
ASTM B 504—Test Method for Measurement of Thickness of Metallic Coatings by the Coulometric Method
ASTM B 530—Method for Measurement of Coating Thickness by the Magnetic Method: Electrodeposited Nickel Coatings on Magnetic and Nonmagnetic Substrates

2.1.3 SME PUBLICATIONS—Available from SME, P.O. Box 930, 1 SME Drive, Dearborn, MI 48121.

2.1.3.1 *SME Paper FC91-371* Jones, T.C., Proc. Finishing '91, 1991

2.1.3.2 Jones, T. C., The Finishing Line, SME, Third Quarter 1990, p. 1

2.1.3.3 User's Guide to Powder Coating, 2nd Edition," SME, 1987, Chapter 5, p. 55

2.1.4 OTHER PUBLICATIONS

2.1.4.1 Annual Statistical Report 1990, American Iron and Steel Institute, Washington, DC (1991), pp. 25–27

2.1.4.2 A. W. Bryant, L. M. Thompson, and W. C. Oldenburg, "U.S. Automotive Corrosion Trends at 5 and 6 Years," Automotive Corrosion and Prevention Conference Proceedings, P 228, L. Allegra, ed., Society of Automotive Engineers, Warrendale, PA (1989), p. 185

2.1.4.3 H. E. Gannon, ed., "The Making, Shaping, and Treating of Steel," 10th edition, United States Steel Corporation

2.1.4.4 H. E. Townsend, "Coated Steel Sheets for Corrosion-Resistant Automobiles," Materials Performance, October 1991, p. 60; National Association of Corrosion Engineers, Corrosion '91, Paper 91416, NACE, Houston, TX

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2.1.4.11 R. Baboian, "Causes and Effects of Corrosion Relating to Exterior Trim on Automobiles," Proceedings of the 2nd Automotive Corrosion and Prevention Conference, P-136, SAE, Warrendale, PA.

2.2 Related Publications—The following publications are provided for information purposes only and are not a required part of this document.

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- U. R. Evans, "The Corrosion and Oxidation of Metals," London, England, Edward Arnold, Ltd., 1960
- F. T. Laque and H. R. Copson, "Corrosion Resistance of Metals and Alloys," New York, NY, Reinhold Publishing Co., 1963
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- R. Baboian, "Materials Degradation Caused by Acid Rain," American Chemical Society, Washington, DC 1986.

3. Definitions

- 3.1 Acid**—Acids can be defined in several ways. For many purposes it is sufficient to say that an acid is a hydrogen containing substance which dissociates on solution in water to produce one or more hydrogen ions. The Bronsted concept states that an acid is any compound that can furnish a proton. The more general Lewis definition of an acid is anything that can attach itself to something with an unshared pair of electrons.
- 3.2 Acidic**—For aqueous solutions, anything having a pH that is less than 7 is considered acidic.
- 3.3 Alkaline**—For aqueous solutions, anything having a pH that is greater than 7 is considered alkaline.
- 3.4 Anodic Coating**—A coating that is anodic to the underlying substrate. Anodic coatings offer sacrificial protection to the substrate.
- 3.5 Barrier Protection**—A type of protection that relies on the coating preventing access of moisture or oxygen to the material being protected. Organic coatings often offer barrier protection to underlying substrates.
- 3.6 Base**—Bases can be defined in several ways. For many purposes it is sufficient to say that a base is a substance which dissociates on solution in water to produce one or more hydroxyl ions. The Bronsted concept states that a base is any compound that can accept a proton. The more general Lewis definition of a base is anything that has an unshared pair of electrons.
- 3.7 Basic**—For aqueous solutions, anything having a pH that is greater than 7 is considered basic.
- 3.8 Blister**—A region of lifted paint typically caused by loss of adhesion within the paint system or between the paint and metal surface.
- 3.9 Cathodic Delamination**—Type of corrosion damage caused by loss of adhesion between the paint finish and the metal.
- 3.10 Cathodic Coating**—A coating that is cathodic to the underlying substrate.

- 3.11 Cavitation Corrosion**—Cavitation Corrosion occurs on the low pressure side of propellers and pump impellers where interruption in smooth flow causes vapor bubbles to form. When these bubbles collapse, they can destroy any protective coating and remove minute particles of metal.
- 3.12 Chromated**—Parts treated with chromic acid to improve their corrosion resistance.
- 3.13 Clearcoat**—A paint without pigment applied over a color basecoat to enhance the appearance and durability of the total paint system.
- 3.14 Cosmetic Corrosion**—Corrosion typically characterized by blistering and/or rusting that is aesthetically displeasing, but does not result in catastrophic failure of the item.
- 3.15 Creepback**—The undercutting or the separation of paint from the substrate at an edge, damage site, or a scribe line.
- 3.16 Current**—The "flow" of electricity expressed in amperes, milliamperes and microamperes.
- 3.17 Cyclic Testing**—Accelerated testing and simulation of service conditions by the use of controlled alternating exposures to at least two corrosive environments, such as salt or other chemical exposure, water immersion, temperature variations, humidity variations, ultraviolet (UV) light exposure, mud or clay contamination, gravel or shot blasting, and driving.
- 3.18 Current Density**—The current per unit area; generally expressed as amps per sq cm.
- 3.19 Deicing Salt**—Salts, typically NaCl and/or CaCl₂, applied to highways to aid in seasonal deicing.
- 3.20 Deionized Water**—Water that has had the charged species (Cl⁻, Ca²⁺, etc.) removed from it.
- 3.21 Diffusion**—The movement of one substance through another. Diffusion of contaminants into a paint system is often the cause of corrosion attack.
- 3.22 Differentially Zinc Coated**—A sheet (usually steel) with a zinc coating of a different thickness on one side than on the other side.
- 3.23 Dip-Spin**—A process using a perforated basket in which parts are placed to be dipped into an organic/inorganic finish, spun to remove excess coating then normally placed in an oven to cure the finish.
- 3.24 Electrochemical Reaction**—A chemical reaction which is driven by a difference in electrode potential from one site to another on the same or different parts.
- 3.25 Electrocoat, E-coat, ELPO**—A coating for metals deposited by the application of high voltages between an anode and a cathode in an electrolyte. Cathodic electrocoating is commonly used in the automotive industry.
- 3.26 Electrogalvanized**—Steel containing a zinc coating produced by continuously electroplating zinc onto the steel surface.
- 3.27 Electroplated Coatings**—Coatings applied in a low temperature continuous process where negatively charged steel sheet is passed between positively charged anodes. Metallic ions in an electrolyte bath are reduced and plated on the surface of the steel sheet forming the coating.
- 3.28 Flash Coating**—A very thin coating of paint or plating applied to provide limited corrosion protection or to improve the adhesion of subsequent coatings.

- 3.29 Hot Dip Galvanized**—Steel containing a zinc coating produced by immersion of the steel in a molten zinc bath.
- 3.30 Galvanneal**—Steel containing a zinc/iron alloy coating produced by the hot-dip process.
- 3.31 Gravelometer**—Machine used to cause consistent intentional paint damage to samples prior to or during laboratory corrosion testing. A gravelometer propels gravel or metal shot of a particular size and shape at the surface of a painted test specimen. The gravelometer is used to simulate the type of field paint damage caused by gravel or other road debris.
- 3.32 Hem Flange**—A method of joining two pieces of metal together in which the edge of one piece is folded tightly over the edge of the other.
- 3.33 Hot-Dip Coating**—A continuous process of applying coatings to steel in which the steel is immersed in a molten bath of the material to be coated.
- 3.34 Inside-Out Corrosion**—Corrosion that starts from the inside surface of a body panel and works outward.
- 3.35 Localized Corrosion**—Corrosion resulting in differential attack across a metallic surface. Localized corrosion is typically of a cosmetic nature, but can lead to catastrophic failure if a primary structural component is the site of severe attack.
- 3.36 Neutral**—In aqueous solutions, a substance having a pH of 7 is considered neutral.
- 3.37 Organic Coatings**—Coatings, primarily paints, applied to metallic or other substrates typically to provide corrosion protection and to improve aesthetic characteristics of the material.
- 3.38 Outside-In Corrosion**—Corrosion that starts from the outside surface of a body panel and works inward.
- 3.39 Perforation Corrosion**—Penetration of a panel due to corrosion. Perforation corrosion is usually associated with inside-out corrosion.
- 3.40 Phosphate Coatings**—Protective coatings formed by reaction of a metallic substrate with an acidic phosphate containing solution. The primary role of the phosphate coating is to enhance adhesion of the primer (electrocoat or other) to the metal. Phosphate coatings are typically Zn, Fe, Zn-Ni, or Zn-Ni-Mn phosphates.
- 3.41 Pitting Corrosion**—A type of perforation corrosion. Pitting corrosion is highly localized corrosion resulting in deep penetration at only a few spots.
- 3.42 Potential**—See electrochemical potential.
- 3.43 Poultice**—An accumulation of mud, sand, salt, and other road debris on the interior surface joints of body panels and structural components.
- 3.44 Pre-coated**—A material that has been coated prior to the manufacture of the ware or part.
- 3.45 Pre-treatment**—The treatment of a surface prior to the process of interest, for example: a phosphate coating is a pre-treatment for electrocoat or painting.
- 3.46 Proving Ground Tests**—Cyclical programs primarily conducted by the automotive companies to evaluate the effects of corrosive elements on the performance of fully assembled vehicles. Proving Ground Tests often combine on-road exposures with exposures in environmental chambers.
- 3.47 Reaction Cell**—A cell at which a chemical reaction is occurring.

- 3.48 Rust Proofing**—The application of coatings intended to prevent or greatly reduce the formation of rust on steel parts.
- 3.49 Saponification Corrosion**—Formation of a soap by the reaction of corrosion products with some organic coatings.
- 3.50 Scab Corrosion**—Cosmetic corrosion caused by break down of the surface protection system often proceeded by blisters.
- 3.51 Scribe**—An intentional paint damage typically used for material evaluation during corrosion testing.
- 3.52 Sealers**—Products applied to joints or seams to prevent the entry of moisture or contaminants. Paint coatings applied to prevent the undesirable interaction of a subsequent coating with a previous coating or to enhance adhesion or corrosion protection.
- 3.53 Undercutting**—See Creepback
- 3.54 Uniform Corrosion**—Corrosion which occurs uniformly on the surface of a part. Uniform corrosion is not associated with joints and is not pitting.

4. Chapter 1—Principles of Corrosion

- 4.1 Electrochemical Theory**—Corrosion in the broad sense is accepted as the deterioration of any material because of a reaction with its environment, which means that materials such as plastics, ceramics, concrete, glass, and many others would be included in that definition. Most often, however, corrosion is associated with the deterioration of metals and alloys. The processes involved with corrosion of metals and alloys are predominantly electrochemical. An electrochemical process is one that involves a transfer of electrons in an oxidation-reduction reaction. Corrosion by direct chemical reaction (which does not involve a transfer of electrons) and hot corrosion (which involves high-temperature gases or molten salts) will not be discussed here.

The principle of electrochemical corrosion is the same as that involved with the functioning of a dry cell battery, which contains a graphite cathode¹ and a zinc anode in contact with a conductive solution (electrolyte). When the two electrodes are connected with an electrically conductive material, current will flow between them because of the difference in their oxidation-reduction (electrical) potentials. This current flow gradually destroys the anode. The degree of destruction depends upon the total amount of current flow. Faraday's law states it another way: "The mass of a substance liberated in an electrolytic cell is proportional to the quantity of electricity passing through the cell." These concepts of anode-cathode relationships and current flow are fundamental to understanding electrochemical corrosion.

The three essential parts of a corrosion cell are: (a) an anode, (b) a cathode, and (c) a conductive solution called an electrolyte. If any one part is missing, or if there is an interruption in the electrical path, current cannot flow and electrochemical corrosion cannot occur. Figure 1 shows how the current flows in a corroding system.

1. Because of convention, the graphite rod carries the "+" (positive) designation in the typical dry cell battery. Electrochemically, it is the cathode and carries the "-" (negative) designation.

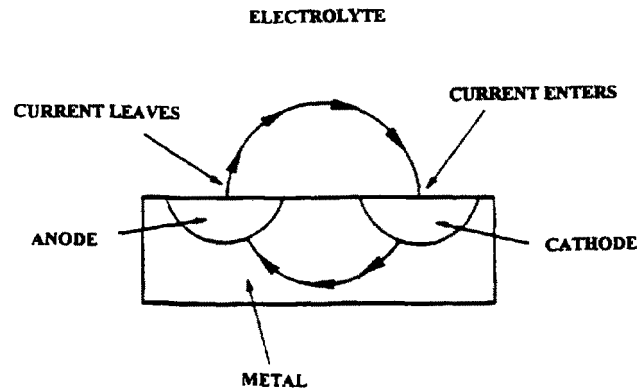
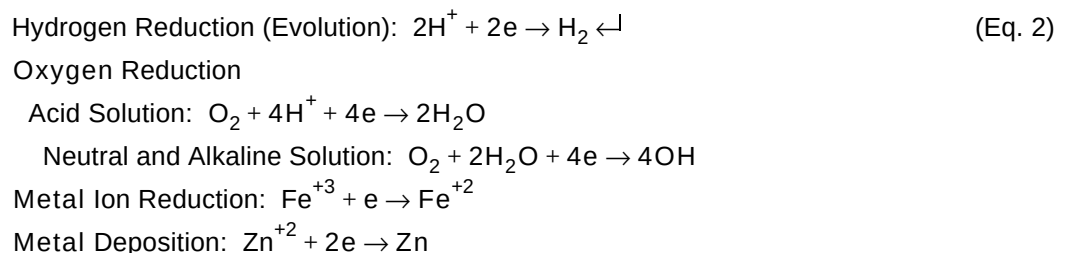


FIGURE 1—CURRENT FLOW IN A CORRODING SYSTEM

When a metal corrodes, oxidation occurs at the anode, which loses electrons, and reduction occurs at the cathode, which gains electrons. The direction of flow of electrons is the opposite to the current flow. The reactions at the anode and cathode are called half-cell reactions, and both must occur for corrosion to occur. They can occur on the same metal surface or on separated metal surfaces, provided there is some form of metallic contact between the surfaces and they share a common electrolyte. Some typical half-cell reactions for the anodic process are shown as follows:



When iron corrodes, ferrous ions (Fe^{++}) are found at the anode by the oxidation of the iron metal. Eventually, they are further oxidized at ferric ions that combine with oxygen and water to form hydrated ferric oxide (rust). The electrons lost at the anode are transported to the cathode, which allows the reduction reaction to take place. Half-cell reactions for the cathode process vary with the environment and involve consumption of electrons as shown as follows:



Hydrogen evolution is a very common cathodic reaction in acid solutions, and oxygen reduction can occur in any solution in contact with air. Metal ion reduction and metal deposition are less commonly associated with the corrosion process, but may be found in chemical process systems.

General chemistry uses the principle of an electrochemical corrosion reaction to produce hydrogen gas, H_2 . This occurs when zinc particles are added to dilute hydrochloric acid. The acid attacks the zinc metal forming zinc ions (Zn^{++}) and the zinc atom gives up two electrons (oxidation). This area becomes the anode. The electrolyte, dilute HCl, contains hydrogen ions (H^{+}) and chloride ions (Cl^{-}). The electrons leave the metal (this area becomes the cathode), are accepted by the hydrogen ions, and form a free hydrogen gas molecule (reduction). To complete the reaction, the zinc ion (Zn^{++}) joins with two chloride ions (Cl^{-}) and forms ZnCl_2 . The complete chemical reaction is:



The previous concept is illustrated in Figure 2.

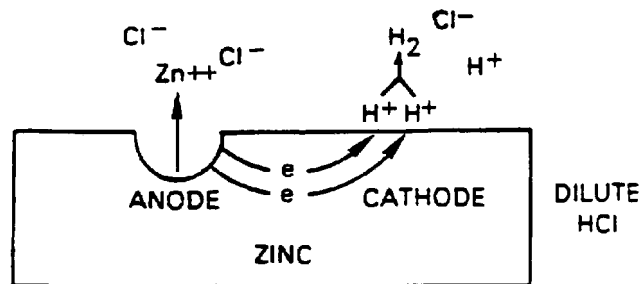


FIGURE 2—ANODIC AND CATHODIC REACTIONS WITH ZINC METAL IN DILUTE HYDROCHLORIC ACID

The possibility for corrosion to occur in a particular environment depends upon whether the free-energy change (ΔG) is negative in the following equation:

$$\Delta G + -nFE \quad (\text{Eq. 4})$$

where:

n = Number of electrons involved
 F = Faraday constant
 E = Cell potential

The cell potential (E) is the difference between the equilibrium potentials of the cathodic and anodic half-cell reactions, and can be determined from half-cell potentials that were measured under standard conditions. A list of such potentials is shown in Table 1. An example of how to determine the feasibility of a reaction between aluminum and moist air is as follows:

E = the potential of the cathodic reaction minus the potential of the anodic reaction
 $E(\text{O}_2/\text{OH}^-) - E(\text{Al}/\text{Al}^{+++})$
 $E + 0.401 - (-1.662) = 2.063$

The cell potential for this reaction is positive, and when substituted in the free-energy equation, it is found that the reaction can occur because ΔG is negative.

In summary, corrosion occurs when metal atoms are oxidized at the anode and enter the solution as ions, leaving behind an excess of negatively charged electrons in the metal. Electrons flow through the metallic circuit to the cathode, where positively charged hydrogen ions at the cathode surface are reduced to hydrogen atoms which combine to form hydrogen gas. When this reaction does not occur readily, oxygen is reduced and it combines with hydrogen ions or with water. The corrosion rate is dependent upon the ease with which these reactions occur and the driving force, or potential difference, between anodic and cathodic sites.

The essential requirement for corrosion is that a potential difference exist between two sites which are joined by an electrolyte and by an electrical path. Corrosion prevention is simply a means of interfering with the continuity of the circuit. The degree of success is determined by the extent of the interference.

**TABLE 1—STANDARD OXIDATION-REDUCTION (REDOX)
POTENTIALS (25 °C, VOLTS VS. NORMAL HYDROGEN ELECTRODE)⁽¹⁾**

Element	Electrode Reaction	Redox Potential
Gold	$\text{Au} = \text{Au}^{+3} + 3\text{e}$	+1.498
Oxygen (acid media)	$\text{O}_2 + 4\text{H}^+ + 4\text{e} = 2\text{H}_2\text{O}$	+1.229
Palladium	$\text{Pt} = \text{Pt}^{+2} + 2\text{e}$	+1.2
Platinum	$\text{Pd} = \text{Pd}^{+2} + 2\text{e}$	+0.987
Mercury	$\text{Hg} = \text{Hg}^+ + \text{e}$	+0.799
Silver	$2\text{Ag} = \text{Ag}_2^{+2} + 2\text{e}$	+0.788
Iron (ferric)	$\text{Fe}^{+2} = \text{Fe}^{+3} + \text{e}$	+0.771
Oxygen (neutral or alkaline media)	$\text{O}_2 + 2\text{H}_2\text{O} + 4\text{e} = 4\text{OH}^-$	+0.401
Copper	$\text{Cu} = \text{Cu}^{+2} + 2\text{e}$	+0.337
Tin (stannic)	$\text{Sn}^{+2} = \text{Sn}^{+4} + 2\text{e}$	+0.15
Hydrogen	$\text{H}_2 = 2\text{H}^+ + 2\text{e}$	0.000
Lead	$\text{Pb} = \text{Pb}^{+2} + 2\text{e}$	-0.126
Tin (stannous)	$\text{Sn} = \text{Sn}^{+2} + 2\text{e}$	-0.136
Nickel	$\text{Ni} = \text{Ni}^{+2} + 2\text{e}$	-0.250
Cobalt	$\text{Co} = \text{Co}^{+2} + 2\text{e}$	-0.277
Cadmium	$\text{Cd} = \text{Cd}^{+2} + 2\text{e}$	-0.403
Iron (ferrous)	$\text{Fe} = \text{Fe}^{+2} + 2\text{e}$	-0.440
Chromium	$\text{Cr} = \text{Cr}^{+3} + 3\text{e}$	-0.744
Zinc	$\text{Zn} = \text{Zn}^{+2} + 2\text{e}$	-0.763
Aluminum	$\text{Al} = \text{Al}^{+3} + 3\text{e}$	-1.662
Magnesium	$\text{Mg} = \text{Mg}^{+2} + 2\text{e}$	-2.363
Sodium	$\text{Na} = \text{Na}^+ + \text{e}$	-2.714
Potassium	$\text{K} = \text{K}^+ + \text{e}$	-2.925

1. Electrode potential values are given and are invariant (e.g., $\text{Zn} = \text{Zn}^{+2} + 2\text{e}$ and $\text{Zn}^{+2} + 2\text{e} = \text{Zn}$ are identical and represent zinc in equilibrium with its ions with a potential of -0.763 V versus normal hydrogen electrode.)

- 4.2 Factors Affecting Corrosion Rate**—Among some of the more common parameters that affect the corrosion rate for a given metal or alloy are: (a) the chemical composition of the electrolyte, (b) temperature, (c) relative humidity, (d) surface conditions, (e) metal stress, (f) galvanic effects, and (g) ratio of electrode areas.

The effect of the chemical composition of the electrolyte is associated mostly with salt concentration, pH, and the nature of the ions. For a solution to be corrosive, it must be conductive; that is, it must have sufficient ionic strength to pass a reasonable amount of current. The acidity or alkalinity of a solution affects different metals differently. Such metals as zinc, aluminum, lead, and tin are soluble in acids as well as alkalis, but are more soluble when the solution pH is either very high or very low. Other metals, such as nickel, copper, cobalt, chromium, manganese, cadmium, magnesium, and iron are soluble in acids, but are generally insoluble in alkalis. Certain ions, particularly chloride ions, are highly mobile and have the ability to penetrate oxide films on the metal surface, which can lead to localized corrosion. Also, the species of salts in the electrolyte will often determine whether the corrosion products formed on the surface are adherent and protective or whether they are loose and permeable to the solution, allowing corrosion to continue.

Increasing temperature generally increases reaction rates, but it can also affect corrosion through its effect on films. It may increase their solubility or otherwise change their nature to make them less protective, or it can change the solubility characteristics of certain products and cause a precipitate to form that is protective. Temperature differential may also create an anode/cathode relationship on a given piece of metal; the part at elevated temperature may be anodic to the part at the lower temperature.

Relative humidity can have a very dramatic effect on the corrosion of metals, and for certain metals there is such a thing as a critical relative humidity above which corrosion will proceed at an accelerated rate. For example, the critical relative humidity for iron, copper, nickel, and zinc generally falls between 50 and 70%.

A dirty surface often exerts a very strong influence on the initiation and rate of corrosion. For example, dirt, debris, and hygroscopic substances can absorb and retain moisture, and also create local anodes and cathodes on a surface, which can initiate and prolong corrosive attack. Topographical irregularities and metallurgical variations and inhomogeneities at the surface are potential sites for initiation of corrosion. Surface films, particularly if they are discontinuous, can contribute to corrosion. Corrosion products can be very voluminous, and may accelerate corrosion by absorbing and retaining moisture.

Stressed materials often corrode faster than unstressed materials, and those under tension will corrode sooner and at a higher rate than the same material under compressive stress.

Galvanic effects result from the coupling of dissimilar metals and are particularly devastating when the electromotive (driving) force, or potential difference, between the metals is large. In addition, there is an area effect to consider because the corrosion rate of the more anodic member of the couple will increase almost in direct proportion to the cathode-to-anode area ratio. The worst case is when a large cathode is connected to a small anode. Besides the obvious situation where dissimilar metals are coupled, many galvanic effects result from dissimilar surface conditions discussed previously.

- 4.3 Forms of Corrosion**—The forms of corrosion are broadly classified as: (a) uniform, or general corrosion; and (b) localized corrosion. Uniform corrosion occurs over the entire surface at about the same rate, which varies depending on the environment. In acids or other aggressive solutions, the attack may be very rapid, while in ordinary air atmospheres, the attack may be slow because of the formation of protective corrosion deposits. Uniform corrosion normally does not cause metal failures as rapidly as localized corrosion, but it is detrimental to appearance. Localized corrosion affects smaller portions of the metal surface, but the rate of penetration of the affected area can often be very fast, perhaps hundreds to thousands of micrometers per year. Some metals are more susceptible to one form of localized corrosion than to another. This type of information should be known before selecting a material for a particular application. The following brief descriptions of various forms of localized corrosion serve only as an introduction. More extensive information may be obtained from the literature.

- 4.3.1 CONCENTRATION CELL CORROSION—One of the most serious causes of localized corrosion is the concentration cell. This is a condition in which a local potential difference arises between two areas of metal exposed to different concentrations of dissolved ions in the same solution. Concentration cells are usually associated with crevices, recessed areas, scale, or surface deposits. The two major types of cells are: (a) the differential-aeration cell, and (b) the metal-ion cell.

The differential-aeration cell is formed as a result of a difference in the concentration of dissolved oxygen in the solution to which two areas of metal are exposed. The area that is exposed to the higher oxygen concentration tends to be cathodic, and the area exposed to the lower oxygen concentration tends to become anodic. These variations in concentration occur because oxygen is readily replenished at exposed areas of metal but not in stagnant areas. A typical differential-aeration cell is shown in Figure 3.

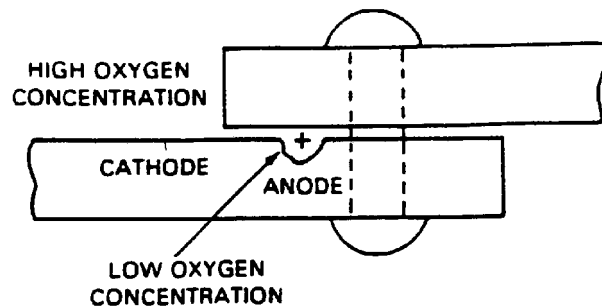


FIGURE 3—DIFFERENTIAL-AERATION CELL AT CREVICE FORMED WHEN TWO PARTS ARE BOLTED TOGETHER

A special case of the differential-aeration cell is called the active-passive cell. This type of cell is usually associated with metals, such as stainless steel, that require oxygen to retain their passivity. In the passive condition, these metals are very resistant to corrosion. If the film on the metal surface is damaged and cannot be reformed because of a lack of oxygen, the surface assumes a potential different from that of the surrounding passive surface, and a concentration cell is established. Because the anodic area is usually quite small, the attack can be very severe, developing deep pits in the surface. A typical example of this type of cell is that of attached trim molding. It is difficult for that area of aluminum or stainless steel in contact with painted body sheet metal to remain passive because air flow over it is slight, whereas the remainder of the molding surface is freely exposed to air, and it can remain passive. An active-passive cell is established between these two portions of the metal surface.

A metal-ion cell is formed when there is a variation in the concentration of metal ions at two different locations in a solution. Differences in metal-ion concentration result because open or exposed areas can have metal ions diffused or swept away more readily than when they are in stagnant areas. A difference of potential is found between these two locations, and current can flow. Corrosion occurs at the anode, which is the point where metal ions diffuse away from the surface. The area of attack in this case is opposite to that of the differential-aeration cell. An example of a metal-ion cell is shown in Figure 4.

Concentration cells can be set up by differences in temperature, agitation, illumination, liquid velocity, and other factors that affect solution homogeneity. This type of corrosion so often with crevices that it is frequently referred to as "crevice corrosion." When it occurs under deposits on the surface, it is sometimes called "poultice corrosion."

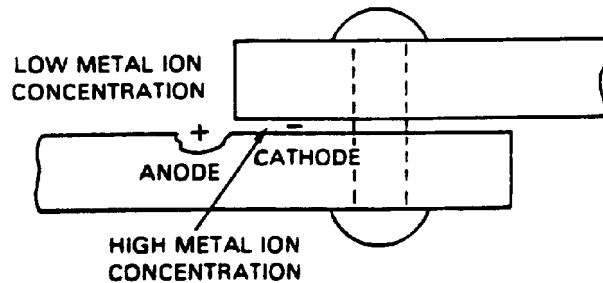


FIGURE 4—METAL-ION CONCENTRATION CELL AT CREVICE FORMED BETWEEN TWO PIECES OF METAL BOLTED TOGETHER

4.3.1.1 Prevention

- Use welded joints in preference to bolted or riveted joints.
- Caulk or seal unavoidable crevices effectively, using durable and noncorrosive materials.
- Minimize the contact between metal and plastics, fabrics, debris, etc.
- Avoid contact with materials which are known to contain corrosive elements or which are hygroscopic, since they may accelerate the cell effect. (Stainless steel has pitted when in contact with insulation containing only a few parts per million of chloride ion.)
- Avoid sharp corners, ledges, and pockets where debris can accumulate.

4.3.2 PITTING CORROSION—Pitting corrosion is a form of localized attack at a metal surface where small areas corrode preferentially. The rate of penetration is usually more rapid than it is in uniform corrosion. Some metals have a greater tendency to pit than others, but most metals will pit under some specific set of conditions. Metals such as aluminum or stainless steel, which form passive films, are especially susceptible to pitting corrosion.

Pitting should be considered a two-step process: one of initiation and the other of propagation. The exact cause of pit initiation is not well understood, but some differences must exist at the metal surface to account for the difference in potential which is necessary for corrosion to occur. Conditions which are usually associated with pitting are inhomogeneities in the metal surface, breaks in a protective film, deposits on a surface, and various kinds of imperfections. Pits vary greatly in size, depth of penetration, and frequency of occurrence. The increase in depth usually proceeds at a faster rate than the increase in width. Pits often have well-defined boundaries.

The environment has an important bearing on the initiation and growth of pits. Halides or halogen-containing ions contribute greatly to pitting; chlorides, bromides, and hypochlorites are considered to be the most aggressive. The chloride ion, for example, not only interferes with the formation of a protective film, but because of its size and mobility diffuses through weak points in the oxide film and enters into the corrosion reaction.

The auto-catalytic nature of a pit is responsible for its continued propagation at a fast rate. Chloride ions continue to migrate into the pit, and the solution within the pit becomes acidic. The acidity prevents the formation of a protective film, and the metal surface in the pit is kept in an active condition. As more metal ions are formed, more chloride ions diffuse into the pit, and the process continues.

4.3.2.1 Prevention

- a. Use materials with alloying elements designed to minimize pitting susceptibility, for example, molybdenum in stainless steel.
- b. Provide a surface as homogeneous as possible through proper cleaning, heat treating, and surface finishing.
- c. Reduce exposure to aggressive ions by shielding the part, coating the part, or by reducing the concentration of these ions.
- d. Increase the capability of the solution to make the metal passive. If the metal is immersed, use inhibitors or other additives.
- e. Minimize the effects of external factors on the design features which lead to localized corrosion; for example, the effects of differential aeration on crevices.

4.3.3 GALVANIC CORROSION—This type of corrosion occurs when two dissimilar metals are coupled and exposed to an electrolyte. The intensity of the galvanic effect will be determined by the potential difference between the metals and the ratio of the cathode-to-anode areas mentioned earlier. The farther apart metals are in the electromotive series, the greater will be the accelerated corrosion of the least noble metals (anode).

The ratio of cathode surface area to anode surface area is important because it determines the current density on the anode surface. A large cathode area and a small anode area result in a high current density at the anode, whereas the reverse situation results in a low anode current density. In both cases the potential difference may be the same and the total current passing between two metals may be the same, but the rate of penetration is different because it is directly proportional to the current density. This effect, which is shown schematically in Figure 5, applies particularly to joints where rivets, screws, or bolts are used to join two pieces of metal together.

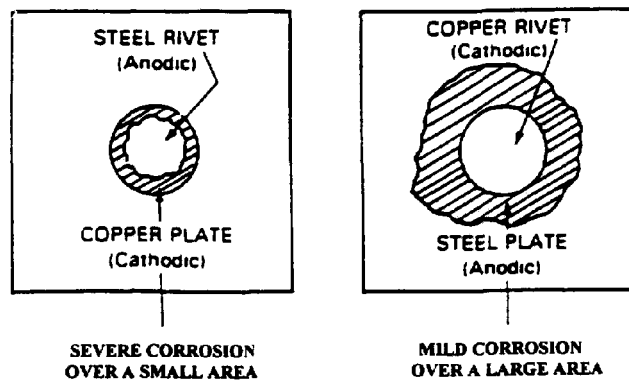


FIGURE 5—GALVANIC CORROSION BETWEEN STEEL AND COPPER (CORROSION OF STEEL IS SEVERE WHEN CORROSION IS CONCENTRATED ON A SMALL AREA)

Since the potential difference between two metals is so important to galvanic corrosion, a series, such as that shown in Table 2, is often used to estimate the likelihood of galvanic corrosion occurring and its magnitude. This series, based on a sea water environment, is at most a guide, since some variations are found in other environments. Ideally, a separate series should be determined for each environment, but this is hardly feasible. Alloys or metals which appear lower on the list corrode preferentially over those above them, when they are in galvanic contact. Metals are grouped together, and those in the same group should have little effect on each other.

TABLE 2—GALVANIC SERIES IN SEA WATER⁽¹⁾

Reactivity	Material
Cathodic (Noble)	Platinum
	Gold
	Graphite
	Silver
	Stainless Steel, SAE Types 30310, 30316 (Passive)
	Stainless Steel, SAE Types 30301, 30304 (Passive)
	Titanium
	Stainless Steel, SAE Types 51410, 51430 (Passive)
	67Ni-33Cu Alloy (Monel)
	76Ni-16Cr-7Fe Alloy (Passive) (Inconel)
	Nickel (Passive)
	Silver Solder
	Bronze
	70-30 Cupro-Nickel
	Silicon Bronze
	Copper
	Brasses
	76Ni-16Cr-7Fe Alloy (Active) (Inconel)
	Nickel (Active)
	Manganese Bronze
	Muntz Metal
	Tin
	Lead
	Lead-Tin Solder
	Stainless Steel, SAE Types 30310, 30316 (Active)
	Stainless Steel, SAE Types 30301, 30304 (Active)
	Stainless Steel, Types 51410, 51430 (Active)
	Cast Iron
	Wrought Iron
	Mild Steel
	Aluminum 2024
	Cadmium
	Alclad Aluminum
	Aluminum 1100, 3003, 5052, 6053
	Galvanized Steel
	Zinc
Anodic (Active)	Magnesium Alloys
	Magnesium

1. Modified from "Corrosion Resistance of Metals and Alloys," LaQue and Copson, 2nd Edition.

4.3.3.1 Prevention

- a. Avoid the use of combinations of metals which are widely separated in the galvanic series.
- b. Avoid combinations where the area of the anodic metal is small compared with that of the cathodic metal. Use more noble metals for rivets, bolts, and fasteners.
- c. Insulate joints of dissimilar metals when possible; even paint or plastic coatings will be helpful.
- d. Paint or coat all surfaces when possible. Avoid painting only the anodic metal, since corrosion may be accelerated at imperfections or breaks in the coating.
- e. Seal faying surfaces.
- f. Apply metallic coatings to reduce the potential difference between dissimilar metals.
- g. Avoid threaded connections if dissimilar metals that are far apart in the galvanic series must be used.
- h. Increase the thickness of replaceable sections of less noble metal.
- i. Attach sacrificial anodes such as zinc, magnesium, or aluminum to the metal to be protected, provided there is electrolytic contact.
- j. Use chemical inhibitors in solutions if possible.

4.3.4 STRESS CORROSION—Stress corrosion of a metal occurs when the metal is under the combined influence of sustained tensile stress, either applied or residual, and corrosion. Damage usually appears as localized cracks. The attack may be intergranular, transgranular, or a combination of the two. The conditions for stress corrosion are:

- a. A susceptible material
- b. An appropriate environment
- c. Stress
- d. Time

An example of intergranular stress corrosion cracking is shown schematically in Figure 6.

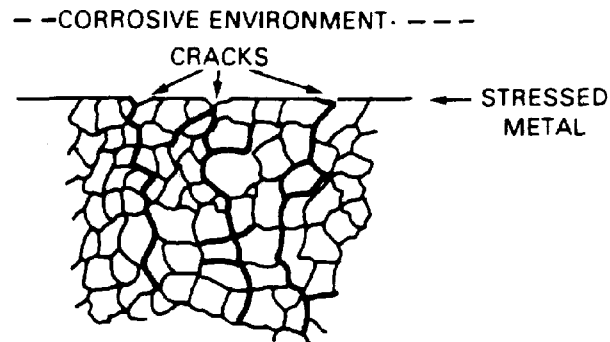


FIGURE 6—INTERGRANULAR STRESS CORROSION CRACKING

There is no known mechanism that explains all of the experimental evidence for stress corrosion. Three basic theories have been proposed: (a) electrochemical, (b) mechanical, and (c) surface energy. The electrochemical theory presumes the formation of fissures at grain boundaries because of either tensile stress or specific corrosion such as pitting or intergranular. Once the surface has been broken, the conditions are sufficient for accelerated corrosion, since film-free metal and grain boundaries are known to be anodic to film-covered metal and crystal faces, respectively. Regions of stress concentration develop after the onset of corrosion. When the stresses become sufficient, cracks develop and penetrate into the metal. Cracking stops when plastic deformation of metal, caused by strain and the cracking process, increases the energy necessary to propagate the crack. If a new film does not form over the freshly exposed metal, a new fissure starts at the notch of the crack by electrochemical corrosion, and the process is repeated.