Electrical cell

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Jump to: navigation, search

An **electrical cell** is a device that is used to generate electricity, or one that is used to make chemical reactions possible by applying electricity.

Contents

[hide]

[change] Cells producing electricity

The simple electrical cells were first developed in 1800s.[1] They are also called *galvanic cells*, because an Italian scientist named Luigi Galvani invented these cells.

Special chemical reactions which occur inside the electrical cell, result in oxidation and reduction of the substances inside the cell.[1] This produces electrical energy. Normal batteries work like this.

Some of the electrical cells produce electricity

Electrolysis

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This article is about the chemical process. For the cosmetic hair removal procedure, see Electrology.

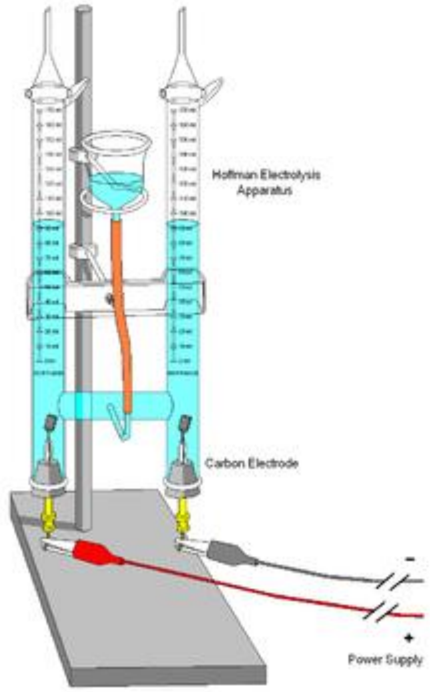


Illustration of an electrolysis apparatus used in a school laboratory.

In chemistry and manufacturing, **electrolysis** is a method of using a direct electric current (DC) to drive an otherwise non-spontaneous chemical reaction. Electrolysis is commercially highly important as a stage in the separation of elements from naturally occurring sources such as ores using an electrolytic cell.

Contents

[hide]

Corrosion

From Wikipedia, the free encyclopedia

Jump to: navigation, search

[hide]

- v ·
- t ·
- e

Mechanical failure modes

- Buckling ·
- **Corrosion** ·
- Corrosion Fatigue ·
- Creep ·
- Fatigue ·
- Fouling ·
- Fracture ·
- Hydrogen embrittlement ·
- Impact ·
- Mechanical overload ·
- Stress corrosion cracking ·
- Thermal shock ·
- Wear ·
- Yielding

Corrosion is the gradual destruction of material, usually metals, by chemical reaction with its environment. In the most common use of the word, this means electrochemical oxidation of metals in reaction with an oxidant such as oxygen. Rusting, the formation of iron oxides, is a well-known example of electrochemical corrosion. This type of damage typically produces oxide(s) or salt(s) of the original metal. Corrosion can also occur in materials other than metals, such as ceramics or polymers, although in this context, the term degradation is more common. Corrosion degrades the useful properties of materials and structures including strength, appearance and permeability to liquids and gases.

Many structural alloys corrode merely from exposure to moisture in air, but the process can be strongly affected by exposure to certain substances. Corrosion can be concentrated locally to form a pit or crack, or it can extend across a wide area more or less uniformly corroding the surface. Because corrosion is a diffusion-controlled process, it occurs on exposed surfaces. As a result, methods to reduce the activity of the exposed surface, such as passivation and chromate conversion, can increase a material's corrosion resistance. However, some corrosion mechanisms are less visible and less predictable.

Rust, the most familiar example of corrosion.

Volcanic gases have accelerated the corrosion of this abandoned mining machinery.

Corrosion on exposed metal.

Contents

[hide]

[edit] Galvanic corrosion

Main article: Galvanic corrosion

Galvanic corrosion of aluminium. A 67-cm-thick Al alloy plate is physically (and hence, electrically) connected to a 10-mm-thick mild steel structural support. Galvanic corrosion occurred on the Al plate along the joint with the steel. Perforation of Al plate occurred within 2 years.[1]

Galvanic corrosion occurs when two different metals have physical or electrical contact with each other and are immersed in a common electrolyte, or when the same metal is exposed to electrolyte with different concentrations. In a galvanic couple, the more active metal (the anode) corrodes at an accelerated rate and the more noble metal (the cathode) corrodes at a retarded rate. When immersed separately, each metal corrodes at its own rate. What type of metal(s) to use is readily determined by following the galvanic series. For example, zinc is often used as a sacrificial anode for steel structures. Galvanic corrosion is of major interest to the marine industry and also anywhere water (containing salts) contacts pipes or metal structures.

Factors such as relative size of anode, types of metal, and operating conditions (temperature, humidity, salinity, etc.) affect galvanic corrosion. The surface area ratio of the anode and cathode directly affects the corrosion rates of the materials. Galvanic corrosion is often utilized in sacrificial anodes.

[edit] Galvanic series

Main article: Galvanic series

In a given environment (one standard medium is aerated, room-temperature seawater), one metal will be either more *noble* or more *active* than others, based on how strongly its ions are bound to the surface. Two metals in electrical contact share the same electrons, so that the "tug-of-war" at each surface is analogous to competition for free electrons between the two materials. Using the electrolyte as a host for the flow of ions in the same direction, the active metal will take electrons from the noble one. The resulting mass flow or electrical current can be measured to establish a hierarchy of materials in the medium of interest. This hierarchy is called a *galvanic series* and is useful in predicting and understanding corrosion.

[edit] Corrosion removal

Often it is possible to chemically remove the products of corrosion. For example phosphoric acid in the form of naval jelly is often applied to ferrous tools or surfaces to remove rust. Corrosion removal should not be confused with electropolishing, which removes some layers of the underlying metal to make a smooth surface. For example, phosphoric acid may also be used to electropolish copper but it does this by removing copper, not the products of copper corrosion.

[edit] Resistance to corrosion

Some metals are more intrinsically resistant to corrosion than others (for some examples, see galvanic series). There are various ways of protecting metals from corrosion including painting, hot dip galvanizing, and combinations of these.[2]

[edit] Intrinsic chemistry

Gold nuggets do not naturally corrode, even on a geological time scale.

The materials most resistant to corrosion are those for which corrosion is thermodynamically unfavorable. Any corrosion products of gold or platinum tend to decompose spontaneously into pure metal, which is why these elements can be found in metallic form on Earth and have long been valued. More common "base" metals can only be protected by more temporary means.

Some metals have naturally slow reaction kinetics, even though their corrosion is thermodynamically favorable. These include such metals as zinc, magnesium, and cadmium. While corrosion of these metals is continuous and ongoing, it happens at an acceptably slow rate. An extreme example is graphite, which releases large amounts of energy upon oxidation, but has such slow kinetics that it is effectively immune to electrochemical corrosion under normal conditions.

[edit] Passivation

Main article: Passivation (chemistry)

Passivation refers to the spontaneous formation of an ultrathin film of corrosion products known as passive film, on the metal's surface that act as a barrier to further oxidation. The chemical composition and microstructure of a passive film are different from the underlying metal. Typical passive film thickness on aluminium, stainless steels and alloys is within 10 nanometers. The passive film is different from oxide layers that are formed upon heating and are in the micrometer thickness range – the passive film recovers if removed or damaged whereas the oxide layer does not. Passivation in natural environments such as air, water and soil at moderate pH is seen in such materials as aluminium, stainless steel, titanium, and silicon.

Passivation is primarily determined by metallurgical and environmental factors. The effect of pH is summarized using Pourbaix diagrams, but many other factors are influential. Some conditions that inhibit passivation include high pH for aluminium and zinc, low pH or the presence of chloride ions for stainless steel, high temperature for titanium (in which case the oxide dissolves into the metal, rather than the electrolyte) and fluoride ions for silicon. On the other hand, unusual conditions may result in passivation of materials that are normally unprotected, as the alkaline environment of concrete does for steel rebar. Exposure to a liquid metal such as mercury or hot solder can often circumvent passivation mechanisms.

[edit] Corrosion in passivated materials

Passivation is extremely useful in mitigating corrosion damage, however even a high-quality alloy will corrode if its ability to form a passivating film is hindered. Proper selection of the right grade of material for the specific environment is important for the long-lasting performance of this group of materials. If breakdown occurs in the passive film due to chemical or mechanical factors, the resulting major modes of corrosion may include pitting corrosion, crevice corrosion and stress corrosion cracking.

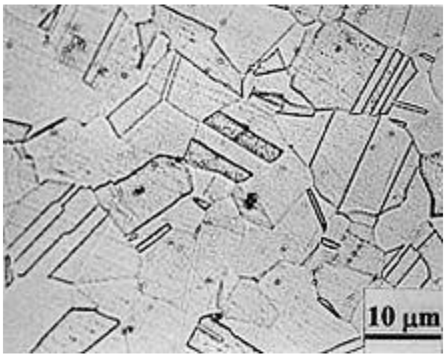
[edit] Pitting corrosion

Main article: Pitting corrosion

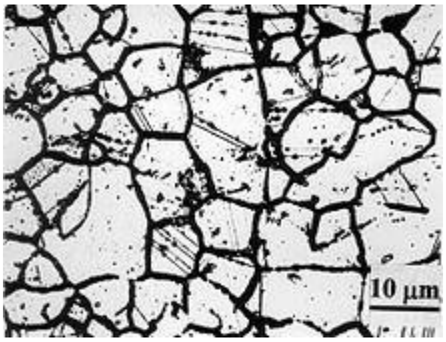
The scheme of pitting corrosion

Certain conditions, such as low concentrations of oxygen or high concentrations of species such as chloride which complete as anions, can interfere with a given alloy's ability to re-form a passivating film. In the worst case, almost all of the surface will remain protected, but tiny local fluctuations will degrade the oxide film in a few critical points. Corrosion at these points will be greatly amplified, and can cause *corrosion pits* of several types, depending upon conditions. While the corrosion pits only nucleate under fairly extreme circumstances, they can continue to grow even when conditions return to normal, since the interior of a pit is naturally deprived of oxygen and locally the pH decreases to very low values and the corrosion rate increases due to an autocatalytic process. In extreme cases, the sharp tips of extremely long and narrow corrosion pits can cause stress concentration to the point that otherwise tough alloys can shatter; a thin film pierced by an invisibly small hole can hide a thumb sized pit from view. These problems are especially dangerous because they are difficult to detect before a part or structure fails. Pitting remains among the most common and damaging forms of corrosion in passivated alloys[citation needed], but it can be prevented by control of the alloy's environment.

[edit] Weld decay and knifeline attack



Normal microstructure



Sensitized microstructure

Main article: Intergranular corrosion

Stainless steel can pose special corrosion challenges, since its passivating behavior relies on the presence of a major alloying component (chromium, at least 11.5%). Because of the elevated temperatures of welding and heat treatment, chromium carbides can form in the grain boundaries of stainless alloys. This chemical reaction robs the material of chromium in the zone near the grain boundary, making those areas much less resistant to corrosion. This creates a galvanic couple with the well-protected alloy nearby, which leads to *weld decay* (corrosion of the grain boundaries in the heat affected zones) in highly corrosive environments.

A stainless steel is said to be sensitized if chromium carbides are formed in the microstructure. A typical microstructure of a normalized type-304 stainless steel shows no signs of sensitization while a heavily sensitized steel shows the presence of grain boundary precipitates. The dark lines in the sensitized microstructure are networks of chromium carbides formed along the grain boundaries.[3]

Special alloys, either with low carbon content or with added carbon "getters" such as titanium and niobium (in types 321 and 347, respectively), can prevent this effect, but the latter require special heat treatment after welding to prevent the similar phenomenon of *knifeline attack*. As its name implies, corrosion is limited to a very narrow zone adjacent to the weld, often only a few micrometers across, making it even less noticeable.

[edit] Crevice corrosion

Main article: Crevice corrosion

Corrosion in the crevice between the tube and tube sheet (both made of type-316 stainless steel) of a heat exchanger in a seawater desalination plant.[4]

Crevice corrosion is a localized form of corrosion occurring in confined spaces (crevices), to which the access of the working fluid from the environment is limited. Formation of a differential aeration cell leads to corrosion inside the crevices. Examples of crevices are gaps and contact areas between parts, under gaskets or seals, inside cracks and seams, spaces filled with deposits and under sludge piles.

Crevice corrosion is influenced by the crevice type (metal-metal, metal-nonmetal), crevice geometry (size, surface finish), and metallurgical and environmental factors. The susceptibility to crevice corrosion can be evaluated with ASTM standard procedures. A critical crevice corrosion temperature is commonly used to rank a material's resistance to crevice corrosion.

[edit] Microbial corrosion

Main article: Microbial corrosion

Microbial corrosion, or commonly known as microbiologically influenced corrosion (MIC), is a corrosion caused or promoted by microorganisms, usually chemoautotrophs. It can apply to both metallic and non-metallic materials, in the presence or absence of oxygen. Sulfate-reducing bacteria are active in the absence of oxygen (anaerobic); they produce hydrogen sulfide, causing sulfide stress cracking. In the presence of oxygen (aerobic), some bacteria may directly oxidize iron to iron oxides and hydroxides, other bacteria oxidize sulfur and produce sulfuric acid causing biogenic sulfide corrosion. Concentration cells can form in the deposits of corrosion products, leading to localized corrosion.

Accelerated low-water corrosion (ALWC) is a particularly aggressive form of MIC that affects steel piles in seawater near the low water tide mark. It is characterized by an orange sludge, which smells of hydrogen sulfide when treated with acid. Corrosion rates can be very high and design corrosion allowances can soon be exceeded leading to premature failure of the steel pile.[5] Piles that have been coating and have cathodic protection installed at the time of construction are not susceptible to ALWC. For unprotected piles, sacrificial anodes can be installed local to the affected areas to inhibit the corrosion or a complete retrofitted sacrificial anode system can be installed. Affected areas can also be treated electrochemically by using an electrode to first produce chlorine to kill the bacteria, and then to produced a calcareous deposit, which will help shield the metal from further attack.

[edit] High-temperature corrosion

High-temperature corrosion is chemical deterioration of a material (typically a metal) as a result of heating. This non-galvanic form of corrosion can occur when a metal is subjected to a hot atmosphere containing oxygen, sulfur or other compounds capable of oxidizing (or assisting the oxidation of) the material concerned. For example, materials used in aerospace, power generation and even in car engines have to resist sustained periods at high temperature in which they may be exposed to an atmosphere containing potentially highly corrosive products of combustion.

The products of high-temperature corrosion can potentially be turned to the advantage of the engineer. The formation of oxides on stainless steels, for example, can provide a protective layer preventing further atmospheric attack, allowing for a material to be used for sustained periods at both room and high temperatures in hostile conditions. Such high-temperature corrosion products, in the form of compacted oxide layer glazes, prevent or reduce wear during high-temperature sliding contact of metallic (or metallic and ceramic) surfaces.

[edit] Metal Dusting

Main article: Metal dusting

Metal dusting is a catastrophic form of corrosion that occurs when susceptible materials are exposed to environments with high carbon activities, such as synthesis gas and other high-CO environments. The corrosion manifests itself as a break-up of bulk metal to metal powder. The suspected mechanism is firstly the deposition of a graphite layer on the surface of the metal, usually from carbon monoxide (CO) in the vapour phase. This graphite layer is then thought to form metastable M_3C species (where M is the metal), which migrate away from the metal surface. However, in some regimes no M_3C species is observed indicating a direct transfer of metal atoms into the graphite layer.

[edit] Protection from corrosion

[edit] Surface treatments

[edit] Applied coatings

Main article: Galvanization

Galvanized surface

Plating, painting, and the application of enamel are the most common anti-corrosion treatments. They work by providing a barrier of corrosion-resistant material between the damaging environment and the structural material. Aside from cosmetic and manufacturing issues, there are tradeoffs in mechanical flexibility versus resistance to abrasion and high temperature. Platings usually fail only in small sections, and if the plating is more noble than the substrate (for example, chromium on steel), a galvanic couple will cause any exposed area to corrode much more rapidly than an unplated surface would. For this reason, it is often wise to plate with active metal such as zinc or cadmium. Painting either by roller or brush is more desirable for tight spaces; spray would be better for larger coating areas such as steel decks and waterfront applications. Flexible polyurethane coatings, like Durabak-M26 for example, can provide an anti-corrosive seal with a highly durable slip resistant membrane. Painted coatings are relatively easy to apply and have fast drying times although temperature and humidity may cause dry times to vary.

[edit] Reactive coatings

If the environment is controlled (especially in recirculating systems), corrosion inhibitors can often be added to it. These form an electrically insulating or chemically impermeable coating on exposed metal surfaces, to suppress electrochemical reactions. Such methods obviously make the system less sensitive to scratches or defects in the coating, since extra inhibitors can be made available wherever metal becomes exposed. Chemicals that inhibit corrosion include some of the salts in hard water (Roman water systems are famous for their mineral deposits), chromates, phosphates, polyaniline, other conducting polymers and a wide range of specially-designed chemicals that resemble surfactants (i.e. long-chain organic molecules with ionic end groups).

[edit] Anodization

Main article: Anodizing

This climbing descender is anodized with a yellow finish.

Aluminium alloys often undergo a surface treatment. Electrochemical conditions in the bath are carefully adjusted so that uniform pores several nanometers wide appear in the metal's oxide film. These pores allow the oxide to grow much thicker than passivating conditions would allow. At the end of the treatment, the pores are allowed to seal, forming a harder-than-usual surface layer. If this coating is scratched, normal passivation processes take over to protect the damaged area.

Anodizing is very resilient to weathering and corrosion, so it is commonly used for building facades and other areas that the surface will come into regular contact with the elements. Whilst being resilient, it must be cleaned frequently. If left without cleaning, panel edge staining will naturally occur.

[edit] Biofilm coatings

A new form of protection has been developed by applying certain species of bacterial films to the surface of metals in highly corrosive environments. This process increases the corrosion resistance substantially. Alternatively, antimicrobial-producing biofilms can be used to inhibit mild steel corrosion from sulfate-reducing bacteria.[6]

[edit] Controlled permeability formwork

Main article: Controlled permeability formwork

Controlled permeability formwork (CPF) is a method of preventing the corrosion of reinforcement by naturally enhancing the durability of the cover during concrete placement. CPF has been used in environments to combat the effects of carbonation, chlorides, frost and abrasion.

[edit] Cathodic protection

Main article: Cathodic protection

Cathodic protection (CP) is a technique to control the corrosion of a metal surface by making that surface the cathode of an electrochemical cell. Cathodic protection systems are most commonly used to protect steel, water, and fuel pipelines and tanks; steel pier piles, ships, and offshore oil platforms.

[edit] Sacrificial anode protection

Sacrificial anode in the hull of a ship.

For effective CP, the potential of the steel surface is polarized (pushed) more negative until the metal surface has a uniform potential. With a uniform potential, the driving force for the corrosion reaction is halted. For galvanic CP systems, the anode material corrodes under the influence of the steel, and eventually it must be replaced. The polarization is caused by the current flow from the anode to the cathode, driven by the difference in electrochemical potential between the anode and the cathode.

[edit] Impressed current cathodic protection

For larger structures, galvanic anodes cannot economically deliver enough current to provide complete protection. Impressed current cathodic protection (ICCP) systems use anodes connected to a DC power source (such as a cathodic protection rectifier). Anodes for ICCP systems are tubular and solid rod shapes of various specialized materials. These include high silicon cast iron, graphite, mixed metal oxide or platinum coated titanium or niobium coated rod and wires.

[edit] Anodic protection

Main article: Anodic protection

Anodic protection impresses anodic current on the structure to be protected (opposite to the cathodic protection). It is appropriate for metals that exhibit passivity (e.g., stainless steel) and suitably small passive current over a wide range of potentials. It is used in aggressive environments, e.g., solutions of sulfuric acid.

[edit] Rate of corrosion

A simple test for measuring corrosion is the weight loss method.[*citation needed*] The method involves exposing a clean weighed piece of the metal or alloy to the corrosive environment for a specified time followed by cleaning to remove corrosion products and weighing the piece to determine the loss of weight. The rate of corrosion (R) is calculated as

$$R = KW/(\rho At)$$

where k is a constant, W is the weight loss of the metal in time t, A is the surface area of the metal exposed, and ρ is the density of the metal (in g/cm^3).

[edit] Economic impact

The collapsed Silver Bridge, as seen from the Ohio side

In 2002, the US Federal Highway Administration released a study titled *Corrosion Costs and Preventive Strategies in the United States* on the direct costs associated with metallic corrosion in the U.S. industry. In 1998, the total annual direct cost of corrosion in the U.S. was ca. $276 billion (ca. 3.2% of the US gross domestic product).[7]

Rust is one of the most common causes of bridge accidents. As rust has a much higher volume than the originating mass of iron, its build-up can also cause failure by forcing apart adjacent parts. It was the cause of the collapse of the Mianus river bridge in 1983, when the bearings rusted internally and pushed one corner of the road slab off its support. Three drivers on the roadway at the time died as the slab fell into the river below. The following NTSB investigation showed that a drain in the road had been blocked for road re-surfacing, and had not been unblocked; as a result, runoff water penetrated the support hangers. Rust was also an important factor in the Silver Bridge disaster of 1967 in West Virginia, when a steel suspension bridge collapsed within a minute, killing 46 drivers and passengers on the bridge at the time.

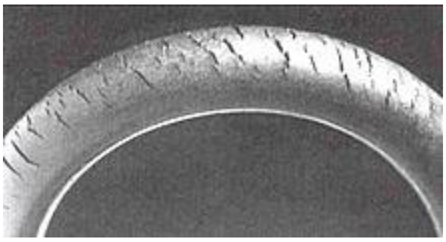
Similarly, corrosion of concrete-covered steel and iron can cause the concrete to spall, creating severe structural problems. It is one of the most common failure modes of reinforced concrete bridges. Measuring instruments based on the half-cell potential can detect the potential corrosion spots before total failure of the concrete structure is reached.

Until 20–30 years ago; galvanized steel pipe was used extensively in the potable water systems for single and multi-family residents as well as commercial and public construction. Today, these systems have long consumed the protective zinc and are corroding internally resulting in poor water quality and pipe failures.[8] The economic impact on homeowners, condo dwellers, and the public infrastructure is estimated at 22 billion dollars as insurance industry braces for a wave of claims due to pipe failures.

[edit] Corrosion in nonmetals

Most ceramic materials are almost entirely immune to corrosion. The strong chemical bonds that hold them together leave very little free chemical energy in the structure; they can be thought of as already corroded. When corrosion does occur, it is almost always a simple dissolution of the material or chemical reaction, rather than an electrochemical process. A common example of corrosion protection in ceramics is the lime added to soda-lime glass to reduce its solubility in water; though it is not nearly as soluble as pure sodium silicate, normal glass does form sub-microscopic flaws when exposed to moisture. Due to its brittleness, such flaws cause a dramatic reduction in the strength of a glass object during its first few hours at room temperature.

[edit] Corrosion of polymers



Ozone cracking in natural rubber tubing

Polymer degradation involves several complex and often poorly-understood physiochemical processes. These are strikingly different from the other processes discussed here, and so the term "corrosion" is only applied to them in a loose sense of the word. Because of their large molecular weight, very little entropy can be gained by mixing a given mass of polymer with another substance, making them generally quite difficult to dissolve. While dissolution is a problem in some polymer applications, it is relatively simple to design against. A more common and related problem is *swelling*, where small molecules infiltrate the structure, reducing strength and stiffness and causing a volume change. Conversely, many polymers (notably flexible vinyl) are intentionally swelled with plasticizers, which can be leached out of the structure, causing brittleness or other undesirable changes. The most common form of degradation, however, is a decrease in polymer chain length. Mechanisms which break polymer chains are familiar to biologists because of their effect on DNA: ionizing radiation (most commonly ultraviolet light), free radicals, and oxidizers such as oxygen, ozone, and chlorine. Ozone cracking is a well-known problem affecting natural rubber for example. Additives can slow these process very effectively, and can be as simple as a UV-absorbing pigment (i.e., titanium dioxide or carbon black). Plastic shopping bags often do not include these additives so that they break down more easily as litter.

[edit] Corrosion of glasses

Glass corrosion

Glass disease is the corrosion of silicate glasses in aqueous solutions. It is governed by two mechanisms: diffusion-controlled leaching (ion exchange) and hydrolytic dissolution of the glass network.[9] Both mechanisms strongly depend on the pH of contacting solution: the rate of ion exchange decreases with pH as $10^{-0.5pH}$ whereas the rate of hydrolytic dissolution increases with pH as $10^{0.5pH}$.[10]

Mathematically, corrosion rates of glasses are characterized by normalized corrosion rates of elements NR_i (g/cm²·d) which are determined as the ratio of total amount of released species into the water M_i (g) to the water-contacting surface area S (cm²), time of contact t (days) and weight fraction content of the element in the glass f_i:

$$NR_i = \frac{M_i}{S f_i t}.$$

The overall corrosion rate is a sum of contributions from both mechanisms (leaching + dissolution) $NR_i=Nrx_i+NRh$. Diffusion-controlled leaching (ion exchange) is characteristic of the initial phase of corrosion and involves replacement of alkali ions in the glass by a hydronium (H_3O^+) ion from the solution. It causes an ion-selective depletion of near surface layers of glasses and gives an inverse square root dependence of corrosion rate with exposure time. The diffusion-controlled normalized leaching rate of cations from glasses (g/cm²·d) is given by:

$$NRx_i = 2\rho\sqrt{\frac{D_i}{\pi t}},$$

where t is time, D_i is the i-th cation effective diffusion coefficient (cm^2/d), which depends on pH of contacting water as $D_i = D_{i0} \cdot 10^{-pH}$, and ρ is the density of the glass (g/cm^3).

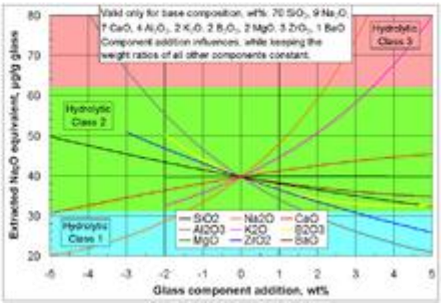
Glass network dissolution is characteristic of the later phases of corrosion and causes a congruent release of ions into the water solution at a time-independent rate in dilute solutions ($g/cm^2 \cdot d$):

$$NRh = \rho r_h,$$

where r_h is the stationary hydrolysis (dissolution) rate of the glass (cm/d). In closed systems the consumption of protons from the aqueous phase increases the pH and causes a fast transition to hydrolysis.[11] However, a further saturation of solution with silica impedes hydrolysis and causes the glass to return to an ion-exchange, e.g. diffusion-controlled regime of corrosion.

In typical natural conditions normalized corrosion rates of silicate glasses are very low and are of the order of 10^{-7}–10^{-5} $g/(cm^2 \cdot d)$. The very high durability of silicate glasses in water makes them suitable for hazardous and nuclear waste immobilisation.

[edit] Glass corrosion tests



Effect of addition of a certain glass component on the chemical durability against water corrosion of a specific base glass (corrosion test ISO 719).[12]

There exist numerous standardized procedures for measuring the corrosion (also called **chemical durability**) of glasses in neutral, basic, and acidic environments, under simulated environmental conditions, in simulated body fluid, at high temperature and pressure,[13] and under other conditions.

The standard procedure ISO 719[14] describes a test of the extraction of water-soluble basic compounds under neutral conditions: 2 g of glass, particle size 300–500 µm, is kept for 60 min in 50 ml de-ionized water of grade 2 at 98 °C; 25 ml of the obtained solution is titrated against 0.01 mol/l HCl solution. The volume of HCl required for neutralization is classified according to the table below.

Amount of 0.01M HCl needed to neutralize extracted basic oxides, ml	**Extracted Na_2O equivalent, µg**	**Hydrolytic class**

< 0.1	< 31	1
0.1-0.2	31-62	2
0.2-0.85	62-264	3
0.85-2.0	264-620	4
2.0-3.5	620-1085	5
> 3.5	> 1085	> 5

[edit] See also

- Anaerobic corrosion
- Chemical hazard label
- Copper band corrosion.
- Corrosion in space
- Electronegativity
- Electrical resistivity measurement of concrete
- Environmental stress fracture
- Forensic engineering
- FRP tanks and vessels
- Hydrogen analyzer
- Hydrogen embrittlement
- Kelvin probe force microscope
- Oxidation potential
- Redox
- Reduction potential
- Periodic table
- Rouging
- Salt spray test
- Stress corrosion cracking
- Tribocorrosion
- Zinc pest
- Corrosion Inhibitors in the Oilfield

[edit] References

1. ^ Galvanic Corrosion. Corrosionclinic.com. Retrieved on 2012-07-15.
2. ^ Methods of Protecting Against Corrosion Piping Technology & Products, (retrieved January 2012)
3. ^ Intergranular Corrosion. Corrosionclinic.com. Retrieved on 2012-07-15.
4. ^ Crevice Corrosion. Corrosionclinic.com. Retrieved on 2012-07-15.
5. ^ JE Breakell, M Siegwart, K Foster, D Marshall, M Hodgson, R Cottis, S Lyon. *Management of Accelerated Low Water Corrosion in Steel Maritime Structures*, Volume 634 of CIRIA Series, 2005, ISBN 0-86017-634-7
6. ^ R. Zuo, D. Örnek, B.C. Syrett, R.M. Green, C.-H. Hsu, F.B. Mansfeld and T.K. Wood (2004). "Inhibiting mild steel corrosion from sulfate-reducing bacteria using antimicrobial-producing biofilms

in Three-Mile-Island process water". *Appl. Microbiol. Biotechnol.* **64**: 275–283. doi:10.1007/s00253-003-1403-7.

7. ^ Gerhardus H. Koch, Michiel P.H.Brongers, Neil G. Thompson, Y. Paul Virmani and Joe H. Payer. CORROSION COSTS AND PREVENTIVE STRATEGIES IN THE UNITED STATES – report by CC Technologies Laboratories, Inc. to Federal Highway Administration (FHWA), September 2001.
8. ^ Robles, PE, Daniel. "Potable Water Pipe Condition Assessment For a High Rise Condominium in The Pacific Northwest". GSG Group, Inc. Dan Robles, PE. http://crmanage.com/potable-water-pipe-condition-assessment-for-a-high-rise-structure-in-the-pacific-northwest/. Retrieved 10 December 2012.
9. ^ A.K. Varshneya. *Fundamentals of inorganic glasses*. Gulf Professional Publishing, 1994 ISBN 0127149708.
10. ^ M.I. Ojovan, W.E. Lee. *New Developments in Glassy Nuclear Wasteforms*. Nova Science Publishers, New York (2007) ISBN 1600217834 pp. 100 ff.
11. ^ *Corrosion of Glass, Ceramics and Ceramic Superconductors*. D.E. Clark, B.K. Zoitos (eds.), William Andrew Publishing/Noyes (1992) ISBN 081551283X.
12. ^ Calculation of the Chemical Durability (Hydrolytic Class) of Glasses. Glassproperties.com. Retrieved on 2012-07-15.
13. ^ Vapor Hydration Testing (VHT). Vscht.cz. Retrieved on 2012-07-15.
14. ^ International Organization for Standardization, Procedure 719 (1985). Iso.org (2011-01-21). Retrieved on 2012-07-15.

[edit] Further reading

- Jones, Denny (1996). *Principles and Prevention of Corrosion* (2nd edition ed.). Upper Saddle River, New Jersey: Prentice Hall. ISBN 0-13-359993-0.

[edit] External links

Wikimedia Commons has media related to: ***Corrosion***

- Corrosion Prevention Association
- NACE International -Professional society for corrosion engineers (NACE)
- Working Safely with Corrosive Chemicals
- efcweb.org – European Federation of Corrosion
- Metal Corrosion – Corrosion Theory
- Electrochemistry of corrosion
- A 3.4-Mb pdf handbook "Corrosion Prevention and Control", 2006, 296 pages, US DoD
- How do you remove and prevent flash rust on stainless steel? Article about the preventions of flash rust
- DoITPoMS Teaching and Learning Package- "Kinetics of Aqueous Corrosion"

Retrieved from "http://en.wikipedia.org/w/index.php?title=Corrosion&oldid=539420865"

Categories:

- Corrosion
- Glass chemistry

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- All articles with unsourced statements
- Articles with unsourced statements from May 2010
- Articles with unsourced statements from July 2012

Navigation menu

Personal tools

- Create account
- Log in

Namespaces

- Article
- Talk

Variants

Views

- Read
- Edit
- View history

Actions

Search

Search

Navigation

- Main page
- Contents
- Featured content
- Current events
- Random article
- Donate to Wikipedia

Interaction

- Help
- About Wikipedia
- Community portal
- Recent changes
- Contact Wikipedia

Toolbox

- What links here
- Related changes

- Upload file
- Special pages
- Permanent link
- Page information
- Cite this page

Print/export

- Create a book
- Download as PDF
- Printable version

Languages

- Alemannisch
- العربية
- Беларуская
- Български
- Bosanski
- Català
- Česky
- ChiShona
- Dansk
- Deutsch
- Eesti
- Ελληνικά
- Español
- Esperanto
- Euskara
- فارسی
- Français
- Galego
- 한국어
- हिन्दी
- Hrvatski
- Ido
- Bahasa Indonesia
- Íslenska
- Italiano
- עברית
- Basa Jawa
- Қазақша
- Latviešu
- Lietuvių
- Magyar
- മലയാളം
- Nederlands
- 日本語
- Norsk bokmål
- Norsk nynorsk
- Occitan

- Polski
- Português
- Română
- Русский
- Shqip
- Simple English
- Slovenčina
- Slovenščina
- Српски / srpski
- Srpskohrvatski / српскохрватски
- Suomi
- Svenska
- தமிழ்
- ไทย
- Türkçe
- Українська
- 中文
- Edit links

- Privacy policy
- About Wikipedia
- Disclaimers
- Mobile view

Why Metals Corrode

Metals corrode because we use them in environments where they are chemically unstable. Only copper and the precious metals (gold, silver, platinum, etc.) are found in nature in their metallic state. All other metals, to include iron-the metal most commonly used-are processed from minerals or ores into metals which are inherently unstable in their environments.

This golden statue in Bangkok, Thailand, is made of the only metal which is thermodynamically stable in room temperature air. All other metals are unstable and have a tendency to revert to their more stable mineral forms. Some metals form protective ceramic films (passive films) on their surfaces and these prevent, or slow down, their corrosion process. The woman in the picture below is wearing anodized titanium earrings. The thickness of the titanium oxide on the metal surface refracts the light and causes the rainbow colors on her earrings. Her husband is wearing stainless steel eyeglasses. The passive film that formed on his eyeglasses is only about a dozen atoms thick, but this passive film is so protective that his eyeglasses are protected from corrosion. We can prevent corrosion by using metals that form naturally protective passive films, but these alloys are usually expensive, so we have developed other means of corrosion control.

The Nature of Matter

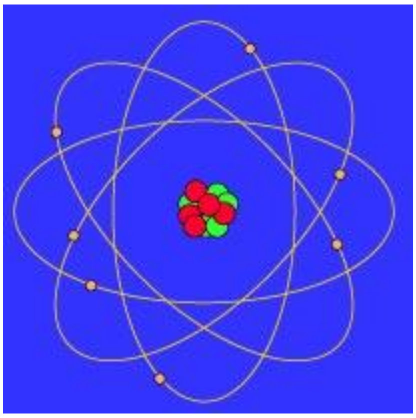
Atoms

Ions

Molecules

Acids and Bases

Atoms:

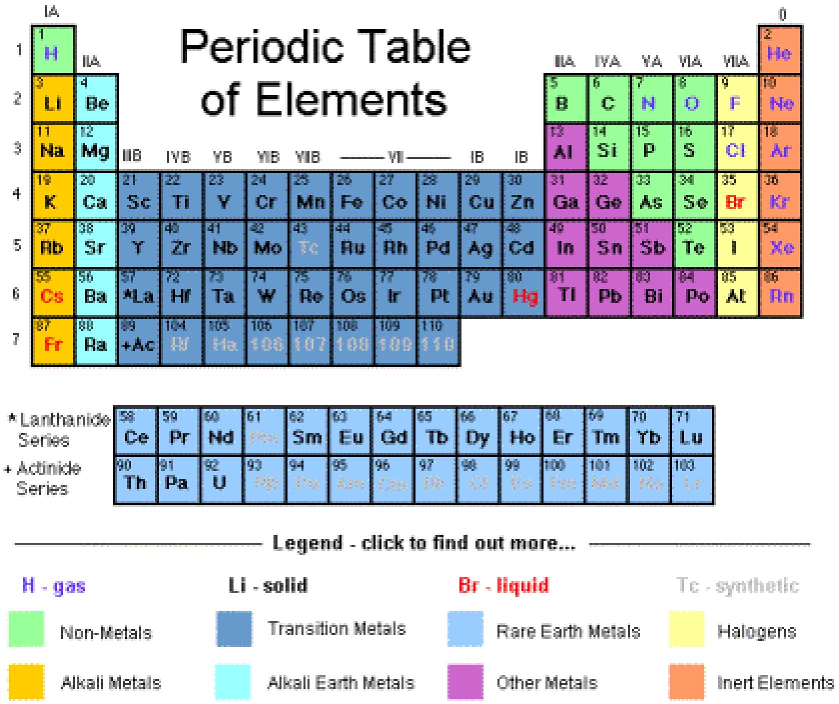


All matter is made of atoms composed of protons, neutrons, and electrons. The center, or nucleus, of the atom is composed of positively charge protons and neutral neutrons. The outside of the atom has negatively charged electrons in various orbits. This is shown schematically in the picture to the right where the electrons are shown orbiting the center, or nucleus, of the atom in much the same way that the planets orbit the sun in our solar system.

All atoms have the same number of protons (positively charged) and electrons (negatively charged). Therefore all atoms have a neutral charge (the positive and negative charges cancel each other). Most atoms have approximately the same number of neutrons as they do protons or electrons, although this is not necessary, and the number of neutrons does not affect the identity of the element.

The number of protons (atomic number) in an atom determines which kind of atom we have, and the atomic mass (weight) of the atom is determined by the number of protons and neutrons in the nucleus (the electrons are so small as to be almost weightless).

There are over 100 different elements that have been discovered. These are shown in the Periodic Table of the Elements below. The letter symbols for the elements come from their Latin names, so for example, H stands for hydrogen, C for Carbon, O for oxygen, while Fe stands for iron and Cu stands for copper.



Periodic Table of Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 106	107 107	108 108	109 109	110 110								

*Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Legend - click to find out more...

H - gas Li - solid Br - liquid Tc - synthetic

🟩 Non-Metals 🟦 Transition Metals 🟦 Rare Earth Metals 🟨 Halogens

🟧 Alkali Metals 🟦 Alkali Earth Metals 🟪 Other Metals 🟧 Inert Elements

Only a few of the elements are common, and most corrosion occurs due to only a dozen or so metallic elements (iron, aluminum, copper, zinc, etc.) reacting with common nonmetallic elements (oxygen, chlorine, sulfur, etc.).

Ions:

Ions are formed when atoms, or groups of atoms, lose or gain electrons.

Metals lose some of their electrons to form positively charged ions, e.g.

Fe^{+2}, Al^{+3}, Cu^{+2}, etc.

Nonmetals gain electrons and form negatively charged ions, e.g.

Cl^{-}, O^{-2}, S^{-2}, etc.

Molecules:

Compounds are groups of metals and nonmetals that form distinct chemicals. Most of us are familiar with the formula H_2O, which indicates that each water molecule is made of two hydrogen atoms and one oxygen atom. Many molecules are formed by sharing electrons between adjacent atoms. A water molecule has adjacent hydrogen and oxygen atoms sharing some of their electrons.

Acids and bases:

Water is the most common chemical on the face of the earth. It is made of three different constituents, hydrogen ions, hydroxide ions, and covalently bonded (shared electron) water molecules. Most of water is composed of water molecules, but it also has low concentrations of H^{+} ions and OH^{-} ions.

Neutral water has an equal number of H^+ ions and OH^- ions. When water has an excess of H^+ ions, we call the resultant liquid an acid. If water has more OH^- ions, then we call it a base.

We measure the strength of an acid or a base on the pH scale. pH is defined by the following equation:

$$pH = -\log [H^+]$$

A detailed explanation of pH and acids and bases is beyond the scope of this web site. It is sufficient to note that some metals (e.g. zinc and aluminum) will corrode at faster rates in acids or bases than in neutral environments. Other metals, e.g. steel, will corrode at relatively high rates in acids but have lower corrosion rates in most neutral and basic environments.

Even a strong acid, with a pH of 0, will be less than 1/1000th by weight hydrogen ions. Neutral water, at a pH of 7, is less than 1 part H^+ in 10 million parts covalently bonded water molecules.

Mnemonic device: Many people have a hard time remembering whether an acid or a base has a high pH number. Just remember that acid comes before base in the alphabet and that low numbers come before high numbers. Acids have low numbers (less than 7), bases have high numbers (greater than 7). Neutral waters have pH's near 7 and tend to be relatively noncorrosive to many materials.

Electrochemical Cells

Oxidation and Reduction Electrochemical Reactions

Oxidation and Reduction:

Metals are elements that tend to lose electrons when they are involved in chemical reactions, and nonmetals are those elements that tend to gain electrons.
Sometimes these elements form ions, charged elements or groups of elements. Metallic ions, because they are formed from atoms that have lost electrons, are positively charged (the nucleus is unchanged). When an atom or ion loses electrons it is said to have been **oxidized**.
A common oxidation reaction in corrosion is the oxidation of neutral iron atoms to positively charged iron ions:

$$Fe \gg Fe^{+2} + 2e^-$$

The electrons lost from a metal must go somewhere, and they usually end up on a nonmetallic atom forming a negatively charged nonmetallic ion. Because the charge of these ions has become smaller (more negative charges) the ion or atom which has gained the electron(s) is said to have been **reduced**.

$$4H^+ + O_2 + 4e^- \gg 2H_2O$$

or

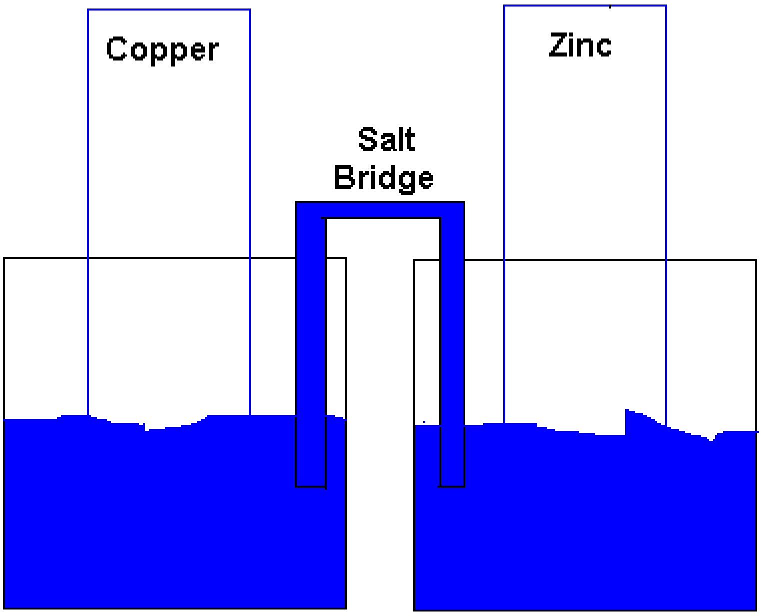
$$2H+ + 2e^- \gg H_2$$

While other reduction reactions are possible, the reduction of oxygen is involved in well over 90% of all corrosion reactions. Thus the amount of oxygen present in an environment, and its ability to absorb electrons, is an important factor in determining the amount of oxidation, or corrosion, of metal that occurs.

Mnemonic device: Many people have a hard time remembering what oxidation and reduction mean in terms of chemical reactions. If you just remember that reduction means "get smaller," then you can remember that the electrical charge on a reduced chemical has gotten smaller (has more negative charges). The opposite reaction, oxidation, means that the charge has gotten larger (not so easy to remember).

Electrochemical Reactions:

The two metal strips shown below are exposed to the same acid.



Both metals undergo similar oxidation reactions:

$$Cu \gg Cu^{+2} + 2e^{-}$$

and

$$Zn \gg Zn^{+2} + 2e^{-}$$

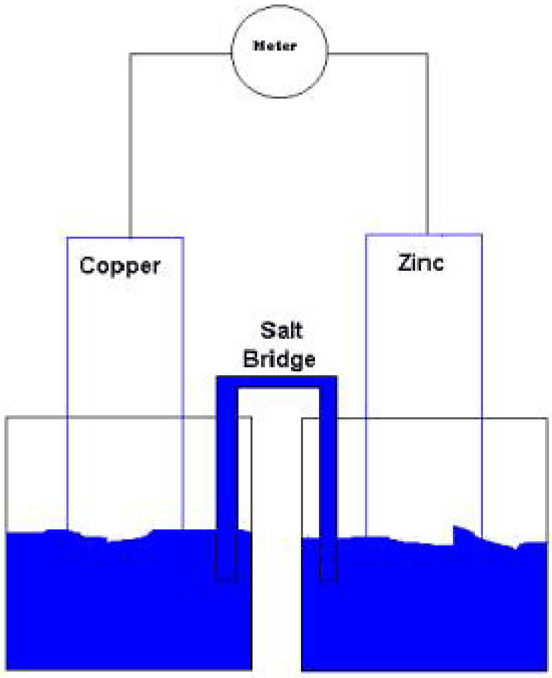
The electrons freed by the oxidation reactions are consumed by reduction reactions. On the copper the reduction reaction is:

$$4H^{+} + O_2 + 4e^{-} \gg 2H_2O$$

The corrosion rate of the copper is limited by the amount of dissolved oxygen in acid. On the zinc the reduction reaction is:

$$2H^{+} + 2e^{-} \gg H_2$$

The hydrogen ions are converted to hydrogen gas molecules and can actually be seen bubbling off from the acid.
If we now connect the two metal samples with a wire and measure the electricity through the connecting wire, we find that one of the electrodes becomes different in potential than the other and that the corrosion rate of the copper decreases while the corrosion rate of the zinc increases. By connecting the two metals, we have made the copper a **cathode** in an electrochemical cell, and the zinc has become an **anode**. The accelerated corrosion of the zinc may be so much that all of the oxidation of the copper stops and it becomes protected from corrosion. We call this method of corrosion control cathodic protection.



The reaction at the copper (cathode) becomes:

$$2H^{+} + 2e^{-} » H_2$$

The voltage of the copper shifts to a point where hydrogen ion reduction can occur at the copper surface. The oxidation (corrosion) of the copper cathode may completely stop due to the electrical connection to the zinc anode.
The reaction at the zinc (anode) remains the same,

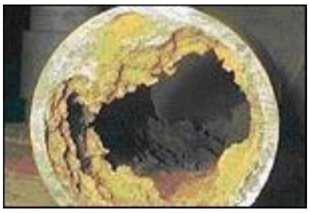
$$Zn » Zn^{+2} + 2e^{-}$$

but the reaction rate increases due to the fact that the surface area of the clean (uncorroding) copper surface can now support a reduction reaction at a high rate. Thus connecting these two metals virtually stopped the corrosion of the copper and increased the corrosion rate of the zinc. We say that the zinc cathodically protected the copper from corrosion. Cathodic protection is a common means of corrosion control.
Mnemonic device: Anodes are those portions of an electrochemical cell that have mostly oxidation reactions. Cathodes are those locations of an electrochemical cell that have mostly reduction reactions. One way to remember which kind of reaction predominates at each kind of electrode is to note that anode comes before cathode in the alphabet just like oxidation comes before reduction. Anodes oxidize; cathodes

reduce.

The forms of corrosion described here use the terminology in use at NASA-KSC. There are other equally valid methods of classifying corrosion, and no universally-accepted terminology is in use. Keep in mind that a given situation may lead to several forms of corrosion on the same piece of material.

(Click on Title for a Detail Explanation)

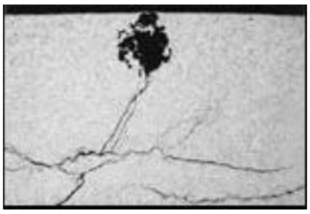
Illustration	Form of Corrosion
	Uniform Corrosion This is also called general corrosion. The surface effect produced by most direct chemical attacks (e.g., as by an acid) is a uniform etching of the metal.
	Galvanic Corrosion Galvanic corrosion is an electrochemical action of two dissimilar metals in the presence of an electrolyte and an electron conductive path. It occurs when dissimilar metals are in contact.
	Concentration Cell Corrosion Concentration cell corrosion occurs when two or more areas of a metal surface are in contact with different concentrations of the same solution.
	Pitting Corrosion Pitting corrosion is localized corrosion that occurs at microscopic defects on a metal surface. The pits are often found underneath surface deposits caused by corrosion product accumulation.
	Crevice Corrosion Crevice or contact corrosion is the corrosion produced at the region of contact of metals with metals or metals with nonmetals. It may occur at washers, under barnacles, at sand grains, under applied protective films, and at pockets formed by threaded joints.

Filiform Corrosion

This type of corrosion occurs on painted or plated surfaces when moisture permeates the coating. Long branching filaments of corrosion product extend out from the original corrosion pit and cause degradation of the protective coating.

Intergranular Corrosion

Intergranular corrosion is an attack on or adjacent to the grain boundaries of a metal or alloy.

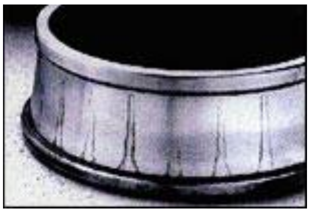


Stress Corrosion Cracking

Stress corrosion cracking (SCC) is caused by the simultaneous effects of tensile stress and a specific corrosive environment. Stresses may be due to applied loads, residual stresses from the manufacturing process, or a combination of both.

Corrosion Fatigue

Corrosion fatigue is a special case of stress corrosion caused by the combined effects of cyclic stress and corrosion. No metal is immune from some reduction of its resistance to cyclic stressing if the metal is in a corrosive environment.

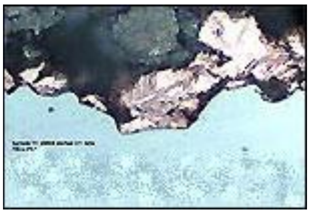


Fretting Corrosion

The rapid corrosion that occurs at the interface between contacting, highly loaded metal surfaces when subjected to slight vibratory motions is known as fretting corrosion.

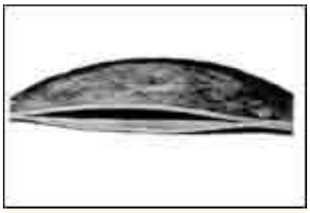
Erosion Corrosion

Erosion corrosion is the result of a combination of an aggressive chemical environment and high fluid-surface velocities.



Dealloying

Dealloying is a rare form of corrosion found in copper alloys, gray cast iron, and some other alloys. Dealloying occurs when the alloy loses the active component of the metal and retains the more corrosion resistant component in a porous "sponge" on the metal surface.

	**Hydrogen Damage** Hydrogen embrittlement is a problem with high-strength steels, titanium, and some other metals. Control is by eliminating hydrogen from the environment or by the use of resistant alloys.
	**Corrosion in Concrete** Concrete is a widely-used structural material that is frequently reinforced with carbon steel reinforcing rods, post-tensioning cable or prestressing wires. The steel is necessary to maintain the strength of the structure, but it is subject to corrosion.
	**Microbial Corrosion** Microbial corrosion (also called microbiologically -influenced corrosion or MIC) is corrosion that is caused by the presence and activities of microbes. This corrosion can take many forms and can be controlled by biocides or by conventional corrosion control methods.

Uniform Corrosion

This is also called general corrosion. The surface effect produced by most direct chemical attacks (e.g., as by an acid) is a uniform etching of the metal. On a polished surface, this type of corrosion is first seen as a general dulling of the surface and, if allowed to continue, the surface becomes rough and possibly frosted in appearance. The discoloration or general dulling of metal created by its exposure to elevated temperatures is not to be considered as uniform etch corrosion. The use of chemical-resistant protective coatings or more resistant materials will control these problems.

While this is the most common form of corrosion, it is generally of little engineering significance, because structures will normally become unsightly and attract maintenance long before they become structurally affected. The facilities shown in the picuture below show how this corrosion can progress if control measures are not taken.

Galvanic Corrosion

Galvanic corrosion is an electrochemical action of two dissimilar metals in the presence of an electrolyte and an electron conductive path. It occurs when dissimilar metals are in contact.

It is recognizable by the presence of a buildup of corrosion at the joint between the dissimilar metals. For example, when aluminum alloys or magnesium alloys are in contact with steel (carbon steel or stainless steel), galvanic corrosion can occur and accelerate the corrosion of the aluminum or magnesium. This can be seen on the photo above where the aluminum helicopter blade has corroded near where it was in contact with a steel counterbalance.

Galvanic Series In Sea Water

Noble
(least active)

Platinum
Gold
Graphite
Silver
18-8-3 Stainless steel, type 316 (passive)
18-8 Stainless steel, type 304 (passive)
Titanium
13 percent chromium stainless steel, type 410 (passive)
7NI-33Cu alloy
75NI-16Cr-7Fe alloy (passive)
Nickel (passive)
Silver solder
M-Bronze
G-Bronze
70-30 cupro-nickel
Silicon bronze
Copper
Red brass
Aluminum bronze
Admiralty brass
Yellow brass
76NI-16Cr-7Fe alloy (active)
Nickel (active)
Naval brass
Manganese bronze
Muntz metal
Tin
Lead
18-8-3 Stainless steel, type 316 (active)
18-8 Stainless steel, type 304 (active)
13 percent chromium stainless steel, type 410 (active)
Cast iron
Mild steel
Aluminum 2024
Cadmium
Alclad
Aluminum 6053

Galvanized steel
Zinc
Magnesium alloys
Magnesium

Anodic
(most active)

The natural differences in metal potentials produce galvanic differences, such as the galvanic series in sea water. If electrical contact is made between any two of these materials in the presence of an electrolyte, current must flow between them. The farther apart the metals are in the galvanic series, the greater the galvanic corrosion effect or rate will be. Metals or alloys at the upper end are noble while those at the lower end are active. The more active metal is the anode or the one that will corrode.

Control of galvanic corrosion is achieved by using metals closer to each other in the galvanic series or by electrically isolating metals from each other. Cathodic protection can also be used to control galvanic corrosion effects.

The scuba tank above suffered galvanic corrosion when the brass valve and the steel tank were wetted by condensation. Electrical isolation flanges like those shown on the right are used to prevent galvanic corrosion. Insulating gaskets, usually polymers, are inserted between the flanges, and insulating sleeves and washers isolate the bolted connections.

KSC conducts research on the effects of galvanic corrosion. The photo below shows the corrosion caused by a stainless steel screw causing galvanic corrosion of aluminum. The picture shows the corrosion resulting from only six months exposure at the Atmospheric Test Site.

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G-Bronze
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Silicon bronze
Copper
Red brass
Aluminum bronze
Admiralty brass
Yellow brass
76NI-16Cr-7Fe alloy (active)
Nickel (active)
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Manganese bronze
Muntz metal
Tin
Lead
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18-8 Stainless steel, type 304 (active)
13 percent chromium stainless steel, type 410 (active)
Cast iron
Mild steel
Aluminum 2024
Cadmium

Alclad
Aluminum 6053
Galvanized steel
Zinc
Magnesium alloys
Magnesium

Anodic
(most active)

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Concentration Cell Corrosion

Concentration cell corrosion occurs when two or more areas of a metal surface are in contact with different concentrations of the same solution. There are three general types of concentration cell corrosion:

1. metal ion concentration cells
2. oxygen concentration cells, and
3. active-passive cells.

Metal Ion Concentration Cells

In the presence of water, a high concentration of metal ions will exist under faying surfaces and a low concentration of metal ions will exist adjacent to the crevice created by the faying surfaces. An electrical potential will exist between the two points. The area of the metal in contact with the low concentration of metal ions will be cathodic and will be protected, and the area of metal in contact with the high metal ion concentration will be anodic and corroded. This condition can be eliminated by sealing the faying surfaces in a manner to exclude moisture. Proper protective coating application with inorganic zinc primers is also effective in reducing faying surface corrosion.

Oxygen Concentration Cells

A water solution in contact with the metal surface will normally contain dissolved oxygen. An oxygen cell can develop at any point where the oxygen in the air is not allowed to diffuse uniformly into the solution, thereby creating a difference in oxygen concentration between two points. Typical locations of oxygen concentration cells are under either metallic or nonmetallic deposits (dirt) on the metal surface and under faying surfaces such as riveted lap joints. Oxygen cells can also develop under gaskets, wood, rubber, plastic tape, and other materials in contact with the metal surface. Corrosion will occur at the area of low-oxygen concentration (anode). The severity of corrosion due to these conditions can be minimized by sealing, maintaining surfaces clean, and avoiding the use of material that permits wicking of moisture between faying surfaces.

Active-Passive Cells

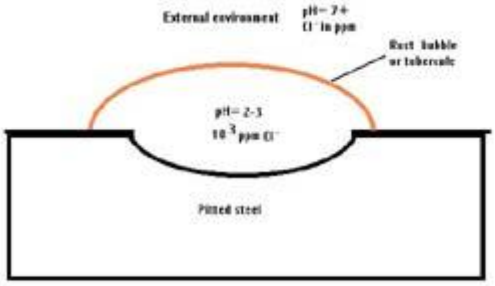
Metals that depend on a tightly adhering passive film (usually an oxide) for corrosion protection; e.g., austenitic corrosion-resistant steel, can be corroded by active-passive cells. The corrosive action usually starts as an oxygen concentration cell; e.g., salt deposits on the metal surface in the presence of water containing oxygen can create the oxygen cell. If the passive film is broken beneath the salt deposit, the active metal beneath the film will be exposed to corrosive attack. An electrical potential will develop between the large area of the cathode (passive film) and the small area of the anode (active metal). Rapid pitting of the active metal will result. This type of corrosion can be avoided by frequent cleaning and by application of protective coatings

Pitting Corrosion

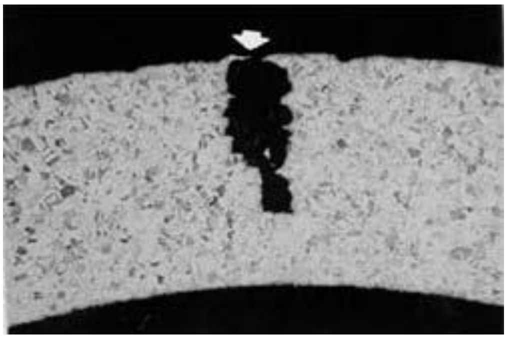
Passive metals, such as stainless steel, resist corrosive media and can perform well over long periods of time. However, if corrosion does occur, it forms at random in pits. Pitting is most likely to occur in the presence of chloride ions, combined with such depolarizers as oxygen or oxidizing salts. Methods that can be used to control pitting include maintaining clean surfaces, application of a protective coating, and use of inhibitors or cathodic protection for immersion service. Molybdenum additions to stainless steel (e.g. in 316 stainless) are intended to reduce pitting corrosion.

(Courtesy of www.eci-ndt.com)

The rust bubbles or tubercules on the cast iron above indicate that pitting is occurring. Researchers have found that the environment inside the rust bubbles is almost always higher in chlorides and lower in pH (more acidic) than the overall external environment. This leads to concentrated attack inside the pits.

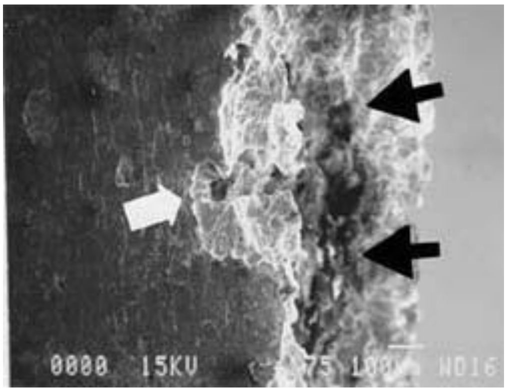


Similar changes in environment occur inside crevices, stress corrosion cracks, and corrosion fatigue cracks. All of these forms of corrosion are sometimes included in the term "occluded cell corrosion."



Pitting corrosion can lead to unexpected catastrophic system failure. The split tubing above left was caused by pitting corrosion of stainless steel. A typical pit on this tubing is shown above right.

Sometimes pitting corrosion can be quite small on the surface and very large below the surface. The figure below left shows this effect, which is common on stainless steels and other film-protected metals. The pitting shown below right (white arrow) led to the stress corrosion fracture shown by the black arrows.



A complete discussion of this corrosion is contained in Steven J. McDanels, "*Failure Analysis Of Launch Pad Tubing From The Kennedy Space Center*," Microstructural Science, Vol. 25, 1998, ASM International, Materials Park, OH, pp. 125-129.

Crevice Corrosion

Crevice or contact corrosion is the corrosion produced at the region of contact of metals with metals or metals with nonmetals. It may occur at washers, under barnacles, at sand grains, under applied protective films, and at pockets formed by threaded joints. Whether or not stainless steels are free of pit nuclei, they are always susceptible to this kind of corrosion because a nucleus is not necessary.

Cleanliness, the proper use of sealants, and protective coatings are effective means of controlling this problem. Molybdenum-containing grades of stainless steel (e.g. 316 and 316L) have increased crevice corrosion resistance.

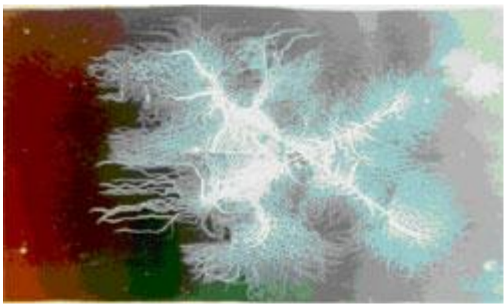
The crevice corrosion shown above happened when an aerospace alloy (titanium - 6 aluminum - 4 vanadium) was used instead of a more corrosion-resistant grade of titanium. Special alloying additions are added to titanium to make alloys which are crevice corrosion resistant even at elevated temperatures.

Screws and fasteners have are common sources of crevice corrosion problems. The stainless steel screws shown below corroded in the moist atmosphere of a pleasure boat hull.

(Courtesy of marinesurvey.com)

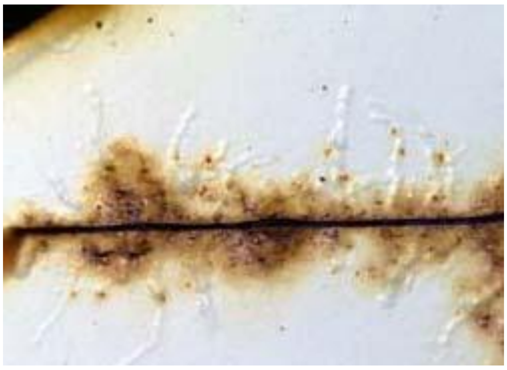
Filiform Corrosion

This type of corrosion occurs under painted or plated surfaces when moisture permeates the coating. Lacquers and "quick-dry" paints are most susceptible to the problem. Their use should be avoided unless absence of an adverse effect has been proven by field experience. Where a coating is required, it should exhibit low water vapor transmission characteristics and excellent adhesion. Zinc-rich coatings should also be considered for coating carbon steel because of their cathodic protection quality.



(Courtesy of www.cp.umist.ac.uk)

Filiform corrosion normally starts at small, sometimes microscopic, defects in the coating.

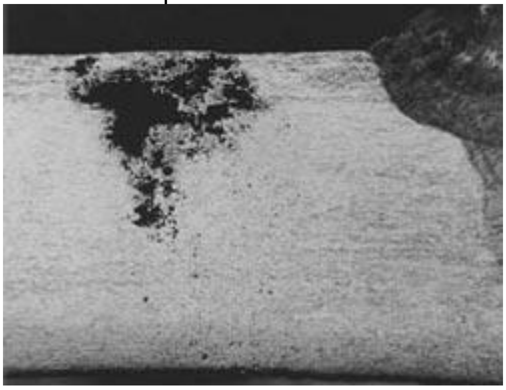


The picture on the left shows filiform corrosion causing bleed-through on a welded tank. The picture on the right shows "worm-like" filiform corrosion tunnels forming under a coating at the Atmospheric Test Site.

Filiform corrosion is minimized by careful surface preparation prior to coating, by the use of coatings that are resistant to this form of corrosion (see above), and by careful inspection of coatings to insure that holidays, or holes, in the coating are minimized.

Intergranular Corrosion

Intergranular corrosion is an attack on or adjacent to the grain boundaries of a metal or alloy. A highly magnified cross section of most commercial alloys will show its granular structure. This structure consists of quantities of individual grains, and each of these tiny grains has a clearly defined boundary that chemically differs from the metal within the grain center. Heat treatment of stainless steels and aluminum alloys accentuates this problem.



The picture above shows a stainless steel which corroded in the heat affected zone a short distance from the weld. This is typical of intergranular corrosion in austenitic stainless steels. This corrosion can be eliminated by using stabilized stainless steels (321 or 347) or by using low-carbon stainless grades (304L or 3I6L).

Heat-treatable aluminum alloys (2000, 6000, and 7000 series alloys) can also have this problem. See the section on exfoliation corrosion below.

Exfoliation Corrosion

Exfoliation is a form of intergranular corrosion. It manifests itself by lifting up the surface grains of a metal by the force of expanding corrosion products occurring at the grain boundaries just below the surface. It is visible evidence of intergranular corrosion and most often seen on extruded sections where grain thickness is less than in rolled forms. This form of corrosion is common on aluminum, and it may occur on carbon steel.

The picture on the left shows exfoliation of aluminum. Exfoliation of carbon steel is apparent in the channel on the coating exposure panel on the right. The expansion of the metal caused by exfoliation corrosion can create stresses that bend or break connections and lead to structural failure.

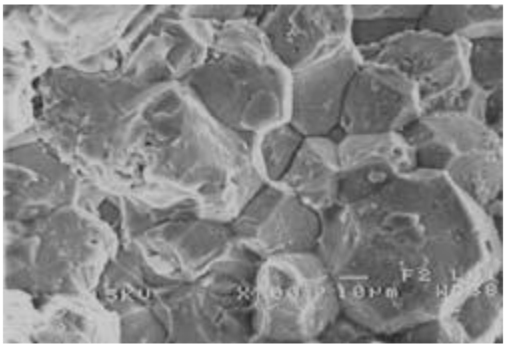
Stress Corrosion Cracking

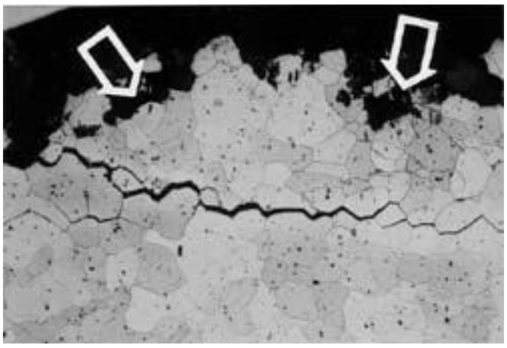
Stress corrosion cracking (SCC) is caused by the simultaneous effects of tensile stress and a specific corrosive environment. Stresses may be due to applied loads, residual stresses from the manufacturing process, or a combination of both.

Cross sections of SCC frequently show branched cracks. This river branching pattern is unique to SCC and is used in failure analysis to identify when this form of corrosion has occurred.

The photo below shows SCC of an insulated stainless-steel condensate line. Water wetted the insulation and caused chlorides to leach from the insulation onto the hot metal surface. This is a common problem on steam and condensate lines. Control is by maintaining the jackets around the lines so that moisture doesn't enter the insulation or is quickly drained off.

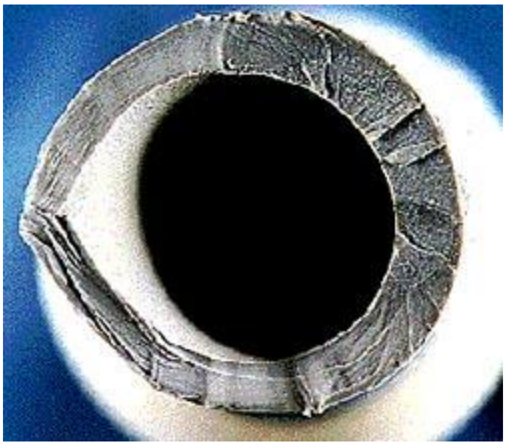
The next two photos show intergranular SCC of an aluminum aerospace part. The intergranular nature of the corrosion can be seen in the scanning electron microscope image on the left and in the microscopic cross section on the right. The arrows indicate the primary crack shown in both pictures. Note that secondary cracks are also apparent. These secondary cracks are common in stress corrosion cracking.





The failure above occurred on an aluminum alloy subjected to residual stresses and salt water. Changes in alloy heat treatment recommended by KSC Materials Laboratory eliminated this problem. McDanels, S. J., "*An Overview of Fatigue and Other Metallurgical Failure Modes and Analysis at the Kennedy Space Center*", *Flammability and Sensitivity of Materials in Oxygen-Enriched Atmospheres: Eight Volume*, ASTM STP 1319, W. T. Royals, T. C. Chou, and T.A. Steinberg, Eds., American Society for Testing and Materials, 1997.

Several years ago, wide spread use of plastic tubing was started in new house construction and for repair of old systems. Flexible tubing was used to connect faucets to the fixed metal piping. The picture below shows stress corrosion cracking after eight years in this service. The tubing was bent and stress cracks started at the outside tensile side of the tube. Flexible plastic piping is now used less often in this service-especially for hot water service.



(Courtesy of www.skyinc.net/~kpr)

Additional photos of stress corrosion cracking are shown in the section on microbial corrosion.

Corrosion Fatigue

Corrosion fatigue is a special case of stress corrosion caused by the combined effects of cyclic stress and corrosion. No metal is immune from some reduction of its resistance to cyclic stressing if the metal is in a corrosive environment. Damage from corrosion fatigue is greater than the sum of the damage from both cyclic stresses and corrosion. Control of corrosion fatigue can be accomplished by either lowering the cyclic stresses or by corrosion control.

The "beach marks" on the propeller shown below mark the progression of fatigue on this surface.

Beach Marks

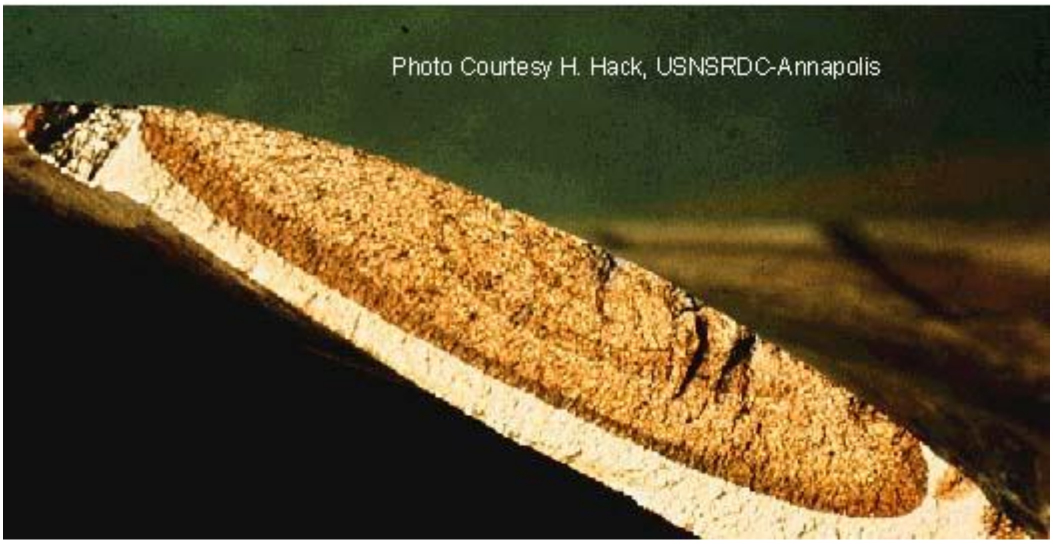
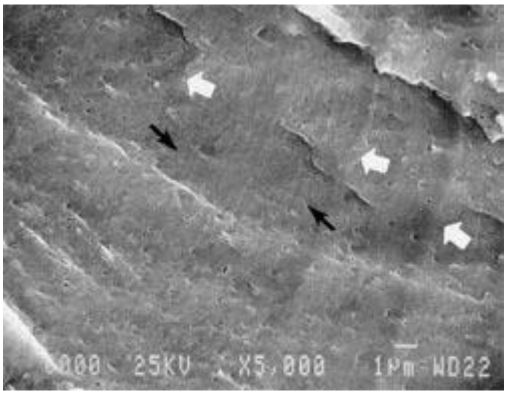


Photo Courtesy H. Hack, USNSRDC-Annapolis

Similar beach marks are shown on the aerospace part below left. The high magnification scanning electron microscope image on the right shows striations (individual crack progression marks). The part shown below is also discussed in the section on fretting corrosion.



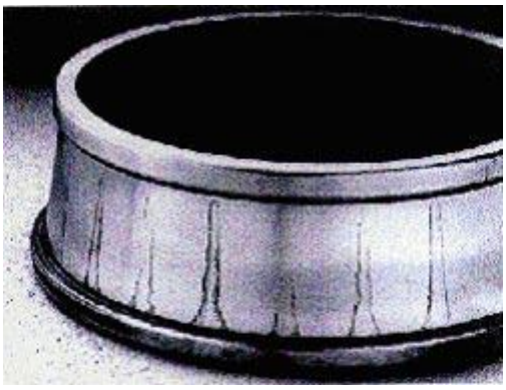
An infamous example of corrosion fatigue occured in 1988 on an airliner flying between the Hawaiian islands. This disaster, which cost one life, prompted the airlines to look at their airplanes and inspect for corrosion fatigue.

Fretting Corrosion

The rapid corrosion that occurs at the interface between contacting, highly loaded metal surfaces when subjected to slight vibratory motions is known as fretting corrosion.

The photo above shows fretting corrosion of a fence post and wires which swing in the wind and wear against the post. Both the fence post and the connecting wires are experiencing fretting corrosion.

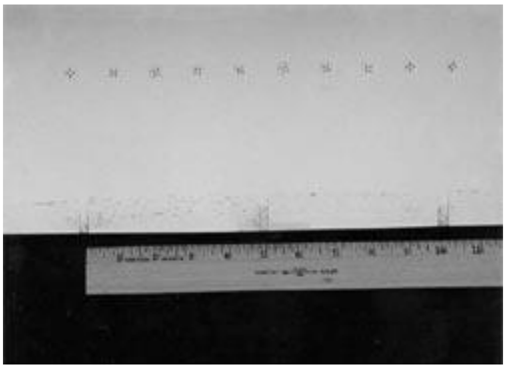
This type of corrosion is most common in bearing surfaces in machinery, such as connecting rods, splined shafts, and bearing supports, and often causes a fatigue failure. It can occur in structural members such as trusses where highly loaded bolts are used and some relative motion occurs between the bolted members.

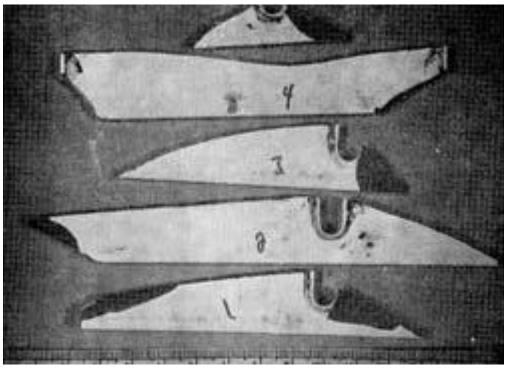


(Courtesy of www.emersonbearing.com)

Fretting corrosion is greatly retarded when the contacting surfaces can be well lubricated as in machinery-bearing surfaces so as to exclude direct contact with air.

The bearing race above is a classic example of fretting corrosion. This is greatly retarded when the contacting surfaces can be well lubricated as in machinery-bearing surfaces so as to exclude direct contact with air.

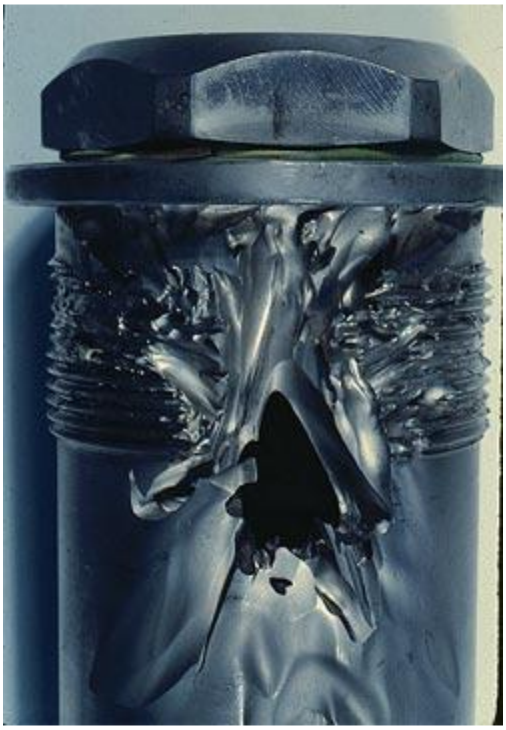




The fretting on a large aluminum part (above left) led to deposits of debris (shown in the cross sections on the right). The vibratory motions rubbing back and forth also produced the fatigue cracks shown in the section on fatigue corrosion.

Erosion Corrosion

Erosion corrosion is the result of a combination of an aggressive chemical environment and high fluid-surface velocities. This can be the result of fast fluid flow past a stationary object, such as the case with the oil-field check valve shown on the left below, or it can result from the quick motion of an object in a stationary fluid, such as happens when a ship's propeller churns the ocean.



Surfaces which have undergone erosion corrosion are generally fairly clean, unlike the surfaces from many other forms of corrosion.

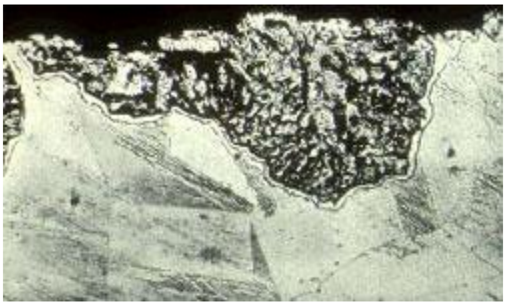
Erosion corrosion can be controlled by the use of harder alloys (including flame-sprayed or welded hard facings) or by using a more corrosion resistant alloy. Alterations in fluid velocity and changes in flow patterns can also reduce the effects of erosion corrosion.

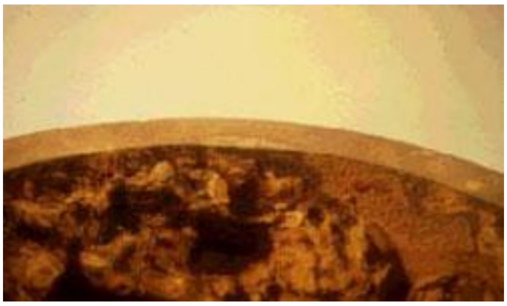
Erosion corrosion is often the result of the wearing away of a protective scale or coating on the metal surface. The oil field production tubing shown above on the right corroded when the pressure on the well became low enough to cause multiphase fluid flow. The impact of collapsing gas bubbles caused the damage at joints where the tubing was connected and turbulence was greater.

Many people assume that erosion corrosion is associated with turbulent flow. This is true, because all practical piping systems require turbulent flow-the fluid would not flow fast enough if lamellar (nonturbulent) flow were maintained. Most, if not all, erosion corrosion can be attributed to multiphase fluid flow. The check valve on the left above failed due to sand and other particles in an otherwise noncorrosive fluid. The tubing on the right failed due to the pressure differences caused when gas bubbles collapsed against the pipe wall and destroyed the protective mineral scale that was limiting corrosion

Dealloying

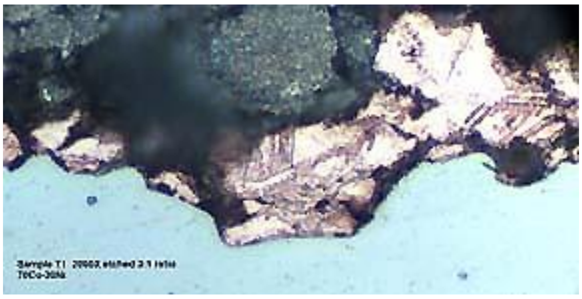
Dealloying is a rare form of corrosion found in copper alloys, gray cast iron, and some other alloys. Dealloying occurs when the alloy loses the active component of the metal and retains the more corrosion resistant component in a porous "sponge" on the metal surface. It can also occur by redeposition of the noble component of the alloy on the metal surface.
Control is by the use of more resistant alloys-inhibited brasses and malleable or nodular cast iron.





The brass on the left dezincified leaving a porous copper plug on the surface. The gray cast iron water pipe shown on the right photo has graphitized and left graphitic surface plugs which can be seen on the cut surface. The rust tubercules or bubbles are also an indication of pitting corrosion.

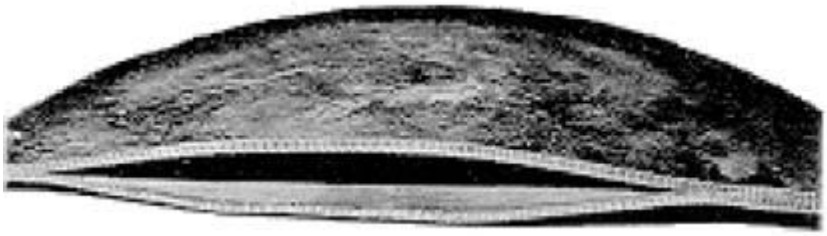
The bottom photo shows a layer of copper on the surface of a dealloyed 70% copper-30% nickel cupronickel heat exchanger tube removed from a ship. Stagnant seawater is so corrosive that even this normally corrosion-resistant alloy has corroded. Virtually all copper alloys are subject to dealloying in some environments.



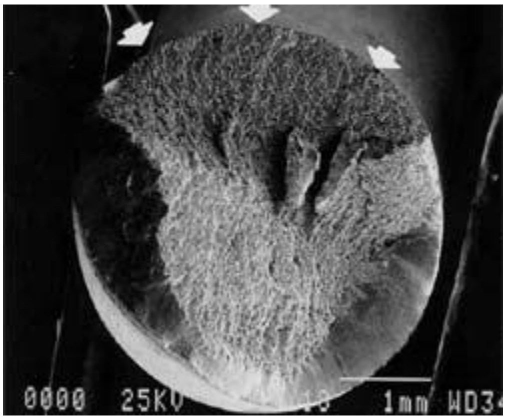
Hydrogen Damage

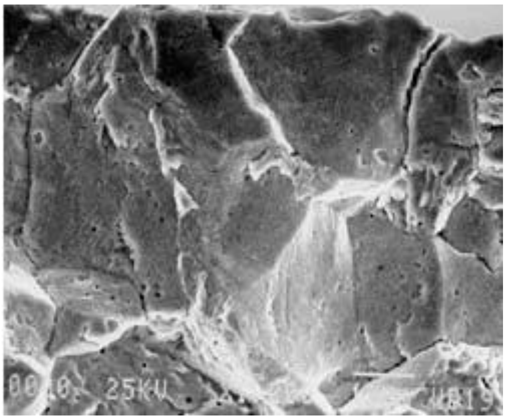
Hydrogen can cause a number of corrosion problems. Hydrogen embrittlement is a problem with high-strength steels, titanium, and some other metals. Control is by eliminating hydrogen from the environment or by the use of resistant alloys.

Hydrogen blistering can occur when hydrogen enters steel as a result of the reduction reaction on a metal cathode. Single-atom nacent hydrogen atoms then diffuse through the metal until they meet with another atom, usually at inclusions or defects in the metal. The resultant diatomic hydrogen molecules are then too big to migrate and become trapped. Eventually a gas blister builds up and may split the metal as shown in the picture below.



Hydrogen blistering is controlled by minimizing corrosion in acidic environments. It is not a problem in neutral or caustic environments or with high-quality steels that have low impurity and inclusion levels.





The broken spring above on the left was brought to the KSC Materials Laboratory for failure analysis. Examination at high magnification in the scanning electron microscope (above right) revealed intergranular cleavage characteristic of hydrogen assisted cracking (hydrogen embrittlement). The part was zinc plated during refurbishment, and the hydrogen which entered the metal during the plating process had not been baked out. A postplating bakeout procedure should be standard for high strength steels.

Corrosion in Concrete

The picture on the left shows cracking and staining of a seawall near the Kennedy Space Center. The pitting corrosion in the right photo occured on an aluminum railing on a concrete causeway over an inlet to the Atlantic Ocean.

Concrete is a widely-used structural material that is frequently reinforced with carbon steel reinforcing rods, post-tensioning cable or prestressing wires. The steel is necessary to maintain the strength of the structure, but it is subject to corrosion. The cracking associated with corrosion in concrete is a major concern in areas with marine environments (like KSC) and in areas which use deicing salts.

There are two theories on how corrosion in concrete occurs:

1. Salts and other chemicals enter the concrete and cause corrosion. Corrosion of the metal leads to expansive forces that cause cracking of the concrete structure.

2. Cracks in the concrete allow moisture and salts to reach the metal surface and cause corrosion.

Both possibilities have their advocates, and it is also possible that corrosion in concrete can occur either way. The mechanism isn't truly important, the corrosion leads to damage, and the damage must be controlled.

In new construction, corrosion in concrete is usually controlled by embedding the steel deep enough so that chemicals from the surface don't reach the steel (adequate depth of cover). Other controls include keeping the water/cement ratio below 0.4, having a high cement factor, proper detailing to prevent cracking and ponding, and the use of chemical admixtures. These methods are very effective, and most concrete structures, even in marine environments, do not corrode.

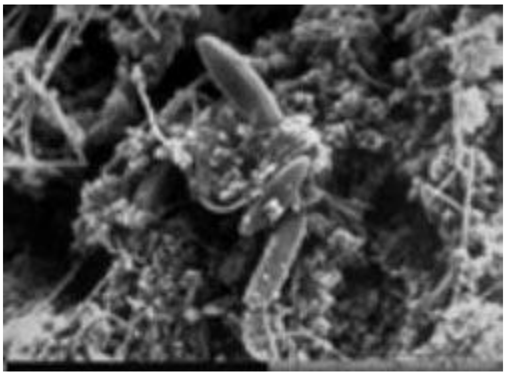
Unfortunately, some concrete structures do corrode. When this happens, remedial action can include repairing the cracked and spalled concrete, coating the surface to prevent further entry of corrosive chemicals into the structure, and cathodic protection, an electrical means of corrosion control. KSC has experience with all of these methods of controlling corrosion on existing concrete structures.

Microbial Corrosion

Microbial corrosion (also called microbiologically-influenced corrosion or MIC) is corrosion that is caused by the presence and activities of microbes. This corrosion can take many forms and can be controlled by biocides or by conventional corrosion control methods.

There are a number of mechanisms associated with this form of corrosion, and detailed explanations are available at the web sites listed at the bottom of this section. Most MIC takes the form of pits that form underneath colonies of living organic matter and mineral and biodeposits. This biofilm creates a protective environment where conditions can become quite corrosive and corrosion is accelerated.

The picture below shows a biofilm on a metallic condenser surface. These biofilms can allow corrosive chemicals to collect within and under the films. Thus the corrosive conditions under a biofilm can be very aggressive, even in locations where the bulk environment is noncorrosive.



(Courtesy of www.asm.org)

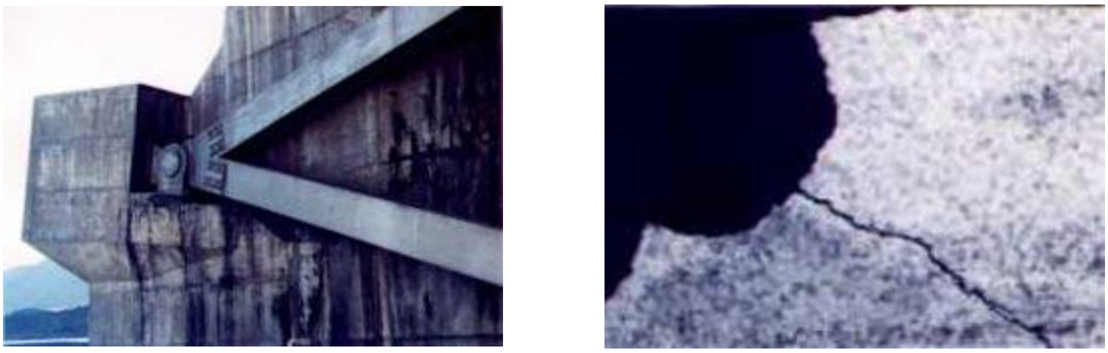
(Courtesy of www.micscan.com)

MIC can be a serious problem in stagnant water systems such as the fire-protection system that produced the pits shown above. (see Pitting Corrosion). The use of biocides and mechanical cleaning methods can reduce MIC, but anywhere where stagnant water is likely to collect is a location where MIC can occur.

Corrosion (oxidation of metal) can only occur if some other chemical is present to be reduced. In most environments, the chemical that is reduced is either dissolved oxygen or hydrogen ions in acids. In anaerobic conditions (no oxygen or air present), some bacteria (anaerobic bacteria) can thrive. These bacteria can provide the reducible chemicals that allow corrosion to occur. That's how the limited corrosion that was found on the hull of the Titanic occurred. The picture below shows a "rusticle" removed from the hull of Titanic. This combination of rust and organic debris clearly shows the location of rivet holes and where two steel plates overlapped.

(Couresy of www.dbi.sk.ca)

Much microbial corrosion involves anaerobic or stagnant conditions, but it can also be found on structures exposed to air. The pictures below show a spillway



(Courtesy of www.meic.com)

gate from a hydroelectric dam on the Columbia River. The stress corrosion cracks were caused by pigeon droppings which produced ammonia-a chemical that causes stress corrosion cracking on copper alloys like the washers used on this structure. Since it's impossible to potty train pigeons, a new alloy resistant to ammonia was necessary.

In addition to the use of corrosion resistant alloys, control of MIC involves the use of biocides and cleaning methods that remove deposits from metal surfaces. Bacteria are very small, and it is often very difficult to get a metal system smooth enough and clean enough to prevent MIC.

Corrosion Control

There are a number of means of controlling corrosion. The choice of a means of corrosion control depends on economics, safety requirements, and a number of technical considerations. The NASA Kennedy Space Center has a group of trained corrosion professionals who can provide guidance on corrosion control.

- Design
- Materials Selection
- Protective Coatings
- Inhibitors and Other Means of Environmental Alteration
- Corrosion Allowances
- Cathodic Protection

Return to Corrosion Fundamentals Page

Design

Engineering design is a complicated process that includes design for purpose, manufacturability, inspection, and maintenance. One of the considerations often overlooked in designing manufactured products is drainage. The corrosion of the automobile side panel above could have been minimized by providing drainage to allow any water and debris to fall off of the car instead of collecting and causing corrosion from the far side of the panel.

All of the other methods of corrosion control should be considered in the design process.

Return to Corrosion Control Page

Materials Selection

Carbon Steel

Most large metal structures are made from carbon steel-the world's most useful structural material. Carbon steel is inexpensive, readily available in a variety of forms, and can be machined, welded, and formed into many shapes.

This large statue by Pablo Picasso in front of the Chicago city hall is made from a special form of carbon steel known as weathering steel. Weathering steel does not need painting in many boldly exposed environments. Unfortunately, weathering steel has been misused in many circumstances where it could not drain and form a protective rust film. This has given the alloy a mixed reputation in the construction industry.

Where other means of corrosion control are not practical, other alloys can be substituted for carbon steel. This normally doubles or more the material cost for a structure, and other corrosion control methods must be considered before deciding on the use of more expensive alternates to carbon steel.

Some forms of carbon steel are subject to special types of corrosion such as hydrogen embrittlement, etc. It is common practice to limit the allowable strength levels of carbon steel to avoid brittle behavior in environments where environmental cracking may occur. High strength bolts cannot be galvanized for the same reason-a concern that they may hydrogen embrittle due to corrosion on the surface.

Protective coatings, cathodic protection, and corrosion inhibitors are all extensively used to prolong the life of carbon steel structures and to allow their use in environments such as the Kennedy Space Center where the environment would otherwise be too corrosive for their use.

Stainless Steels

The stainless steel body on this sports car is one example of how stainless steels can be used. The stainless steel is virtually immune to corrosion in this application-at least in comparison to the corrosion that would be experienced by conventional carbon steel or aluminum auto bodies.

Stainless steels are a common alternative to carbon steels. There are many kinds of stainless steels, but the most common austenitic stainless steels (300-series stainless steels) are based on the general formula of iron with approximately 18% chromium and 8% nickel. These austenitic stainless steels are frequently immune to general corrosion, but they may experience pitting and crevice corrosion and undergo stress corrosion cracking in some environments.

Aluminum

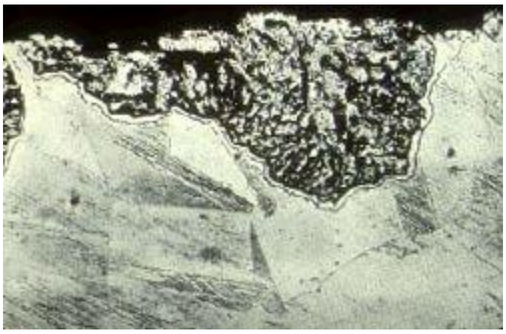
Aluminum alloys are widely used in aerospace applications where their favorable strength-to-weight ratios make them the structural metal of choice. They can have excellent atmospheric corrosion capabilities. Unfortunately, the protective properties of the aluminum oxide films that form on these alloys can break down locally and allow extensive corrosion. This is discussed further in the section on intergranular corrosion.

The highway guardrail shown on the right is located near the ocean in Florida. The aluminum alloy maintains a silvery shine except in locations where the passive film has suffered mechanical damage. The wear caused by the rail touching the wooden post at this location destroyed the passive film on the edges of the rail and allowed intergranular corrosion to proceed and cause the exfoliation corrosion shown above. While the corrosion above is very interesting and makes for an interesting web site, it is important to note that the railing is decades old and would have never lasted as long in this location if it were made of carbon steel.

Intergranular corrosion is a major problem on airplanes and other structures made from aluminum alloys. It frequently occurs at bolt and rivet holes or at cutouts where the small grain boundaries perpendicular to the metal surface are exposed.

Copper Alloys

Brasses and bronzes are commonly used piping materials, and they are also used for valves and fittings. They are subject to stress corrosion cracking in the presence of ammonia compounds. They also suffer from dealloying and can cause galvanic corrosion when coupled with steel and other structural metals. Most copper alloys are relatively soft and subject to erosion corrosion.



The dezincification shown above could have been controlled by using inhibited brasses which have been commercially available since the 1930's.

Titanium

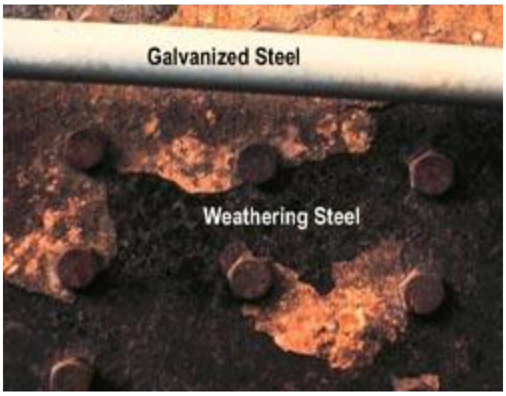
Titanium is one of the more common metals in nature, but its limited use means that small-scale production operations result in a relatively expensive metal. In the United States it finds extensive use in the aerospace industry. The Japanese make extensive use of titanium in the chemical process industries.

There are two general types of titanium alloys-aerospace alloys and corrosion resistant alloys. The crevice corrosion of an aerospace alloy flange in a saltwater application is a classic example of how titanium gets misused

Protective Coatings

Protective coatings are the most commonly used method of corrosion control. They are the subject of several sections of this web site.

Protective coatings can be metallic, such as the galvanized steel shown below, or they can be applied as a liquid "paint." Most of the research and testing of protective coatings at the Kennedy Space Center is related to paint-like protective coatings.



(Courtesy of www.corrosion-doctors.org)

[Filiform corrosion]() occurs underneath protective coatings. The air conditioner on the left is starting to show rust stains due to problems with protective coating. The same types of problems are starting to appear on the aluminum airplane wing shown on the right.

and Other Means of Environmental Alteration

Corrosion inhibitors are chemicals that are added to controlled environments to reduce the corrosivity of these environments. Examples of corrosion inhibitors include the chemicals added to automobile antifreezes to make them less corrosive. Most of the Kennedy Space Center's corrosion inhibitor research involves the effectiveness of inhibitors added to protective coatings.

Corrosion Allowances

Engineering designers must consider how much metal is necessary to withstand the anticipated load for a given application. Since they can make mistakes, the use of the structure can change, or the structure can be misused, they usually are required to over design the structure by a safety factor that can vary from 20% to over 300%. Once the necessary mechanical load safety factor has been considered, it becomes necessary to consider whether or not a corrosion allowance is necessary to keep the structure safe if it does corrode.

The picture above shows extra steel added to the bottom of an offshore oil production platform. The one inch of extra steel was added as a **corrosion allowance**

Cathodic Protection

Cathodic protection is an electrical means of corrosion control. Cathodic protection can be applied using sacrificial (galvanic) anodes or by means of more complicated impressed current systems.

This Louisiana fishing boat has sacrificial zinc anodes welded to the hull to slow down corrosion. No pattern is apparent to how the anodes were attached-the design philosophy seems to be that if one anode is good, more is better.

The Kennedy Space Center's cathodic protection research has concentrated on the use of sacrificial and impressed current systems for minimizing corrosion of embedded steel in concrete structures.

Re

Sources of Additional Information

Guidance on how to solve corrosion problems is contained in NASA-KSC TM-584C, "Corrosion Control and Treatment Manual".

Additional information on corrosion can be obtained by contacting the following organizations:

NACE International
ASM International
American Society for Testing of Materials
Society for Protective Coatings

Textbooks and references on corrosion include:

1. H. Uhlig and W. Revie, Corrosion and Corrosion Control, Wiley, New York, 2008, 4th Edition.
2. R. S. Treseder, NACE Corrosion Engineer's Reference Book, NACE, Houston, 2002, 3rd Edition.
3. Corrosion, Vol. 13, Metals Handbook, American Society for Metals, Metals Park, Ohio, 1987.
4. Landrum, Fundamentals of Designing for Corrosion Control: A Corrosion Aid for the Designer, NACE, Houston, 1990.
5. M. Fontana, Corrosion Engineering, McGraw-Hill, New York, 1986.
6. S. Chawla and R. Gupta, Materials Selection for Corrosion Control, ASM International, Materials Park, Ohio, 1993.

All of these books can be obtained from NACE International.