

# CORROSION

is the deterioration of materials through chemical or electrochemical attack. It is a vital factor in materials selection and design; more materials are damaged by corrosion than in any other way. Although rapid strides are being made in developing new and better materials, the rate of progress is offset considerably by the steady worsening of operating conditions that materials have to withstand. Corrosive industrial atmospheres show no significant signs of abating, temperatures are getting higher and operating periods longer, and new

continued

and highly corrosive media are being encountered in the process industries. The problem of meeting these tough conditions is compounded by the fact that corrosion is an exceedingly complex phenomenon: corrosive attack can take many different forms, and the corrosion resistance of a material can change drastically with just a small change in the environment. Because of corrosion's complexity, engineers have to maintain a high level of sophistication in selecting materials. To do the job properly you should understand the basic fundamentals and forms of corrosion, and you should understand the limitations of present knowledge. You should be able to select an appropriate laboratory or field test and to evaluate corrosion data intelligently. And you should be fully aware of the possibilities of minimizing or preventing corrosion by applying protective coatings or altering the product design. All of these aspects of combatting corrosion will be examined in detail in separate articles in this special issue, planned and edited by M/DE associate editor Robert J. Fabian. Because much of this information is timeless you should find it a valuable reference to consult in solving your present and future corrosion problems.

# The Many Faces of Corrosion

*How the 13 basic types of corrosion get started and what you can do to prevent them.*

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and Robert J. Fabian, Associate Editor, Materials in Design Engineering

CORROSION IS A complex form of materials deterioration. We already know a great deal about it but, despite intensive research and experimentation, we still have a lot to learn.

One of the reasons for corrosion's complexity is that it can take so many different forms, some of which are quite subtle. Direct chemical attack is, of course, the most obvious, but others such as intergranular corrosion are less obvious and can be equally damaging. Still others, such as crevice corrosion, stem from mechanical and design factors which start and promote materials deterioration. Thus, as the following analysis shows, even where corrosion may not appear to be a materials selection or design factor, you have to be continually on the alert for its presence.

## Galvanic corrosion

Galvanic corrosion is the accelerated electrochemical corrosion that occurs when one metal is joined to a more noble metal by the same corroding medium or electrolyte. This type of corrosion—which can be likened to the action of a simple battery cell—usually produces a higher rate of reaction on the less noble metal and protects the more noble metal. For example, if a simple galvanic cell composed of copper and zinc strips is immersed in a solution of sulfuric acid, the less noble zinc strip will corrode quickly, while the more noble copper will be virtually unattacked.

*The galvanic series.* The tendencies of various metals to form galvanic cells are shown in the table on p 86 which can be used to predict the probable

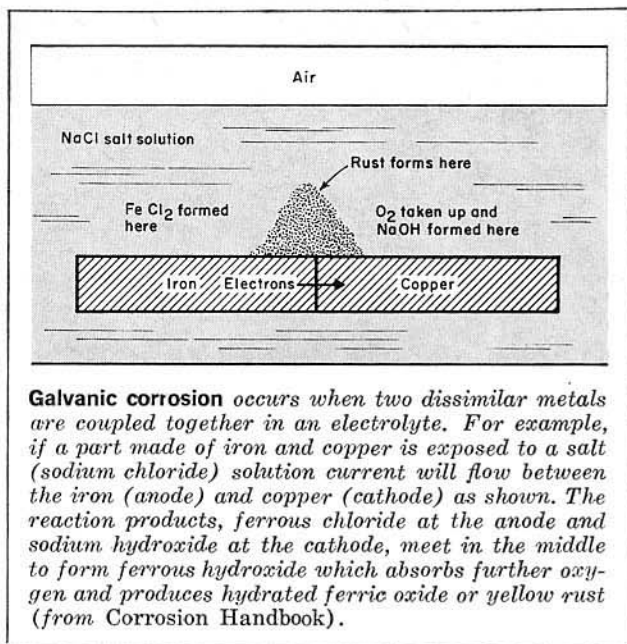
direction of galvanic action. This table is based on laboratory and actual corrosion tests and should not be confused with the theoretical "electromotive series."

Metals that are grouped together in the table have relatively little tendency to produce galvanic corrosion between one another and are relatively safe to use in electrical contact with each other. However, if two metals from substantially different groups (i.e., distant from each other in the list) are coupled, then the metal that is higher on the list will suffer accelerated galvanic corrosion. The further apart the metals are on the list, the greater will be their tendency to corrode through galvanic action.

Although the relative positions of metals within a group sometimes change with external conditions, changes rarely occur from group to group. Exceptions are the chromium-iron and chromium-nickel iron alloys which frequently change position depending on the makeup of the corrosive medium, particularly on its oxidizing power and acidity, or on the presence of oxidizing ions such as halides. Thus, the position of these alloys in the galvanic series may be anywhere between the extremes indicated.

Actually, galvanic effects are not responsible for as many cases of corrosion failure as are generally attributed to them. For example, in the case where magnesium and aluminum are in contact in sea water the higher solution potential of the magnesium (anode) causes current to flow in the direction which should electrolytically protect the aluminum (cathode). However, in this couple the strongly alkaline corrosion products caused by the rapidly corroding mag-





nesium will severely attack the aluminum, thus causing both metals to corrode rapidly.

**Current must flow.** Galvanic corrosion cannot take place unless there is a flow of current. One of the most important factors that determine the magnitude and ease of current flow is the conductivity of the circuit; there must be a complete circuit through the conducting metals and the electrolyte.

Because metals are such good conductors of electricity, the total resistance of a galvanic circuit is usually controlled by the resistance of the solution or electrolyte. Thus, no appreciable galvanic corrosion is produced in distilled water since it is a relatively poor conductor. Galvanic corrosion is more likely to occur in ordinary tap water which contains sufficient ionizable salts to make it moderately conductive.

In solutions of relatively low conductivity, galvanic influences are usually localized so that the less noble metal (the anode) suffers most of its accelerated corrosion in a region in the immediate vicinity of the more noble metal (the cathode). In highly conductive solutions, such as strong salt solutions (brines and sea water) and strong solutions of chemicals (acids and alkalis), corrosion is likely to be distributed over the entire anode surface.

Galvanic corrosion can even occur with thin films of condensed moisture in the presence of dissolved salts or ionizable gases which cause the corrosion circuit to be completed; however, in this case corrosion tends to be localized near the points of contact.

**Effect of polarization.** The effective potential difference between the anode and the cathode may be reduced considerably by polarization; this may occur at the anode from accumulated corrosion products, or at the cathode from the deposition of hydrogen. Of the two types of polarization, hydrogen accumulation, or cathodic polarization, is more often of controlling importance.

For example, when copper is in contact with steel

## GALVANIC SERIES OF METALS

### CORRODED END (anodic, or least noble)

Magnesium  
Magnesium alloys

Zinc

Aluminum 1100

Cadmium

Aluminum 2017

Steel or iron

Cast iron

Chromium-iron (active)

Ni-Resist irons

18-8 Chromium-nickel-iron (active)

18-8-3 Cr-Ni-Mo-Fe (active)

Lead-tin solders

Lead

Tin

Nickel (active)

Inconel (active)

Hastelloy C (active)

Brasses

Copper

Bronzes

Copper-nickel alloys

Monel

Silver solder

Nickel (passive)

Inconel (passive)

Chromium-iron (passive)

Titanium

18-8 Chromium-nickel-iron (passive)

18-8-3 Cr-Ni-Mo-Fe (passive)

Hastelloy C (passive)

Silver

Graphite

Gold

Platinum

### PROTECTED END (cathodic, or more noble)



in sea water containing dissolved air, galvanic corrosion will proceed under a potential difference of as much as  $\frac{1}{2}$  v. However, in air-free sea water, hydrogen polarization of the copper will reduce the potential to such an extent that galvanic corrosion becomes insignificant.

Cathodic polarization frequently becomes so dominant in galvanic corrosion that the total corrosion of the anodic material is practically independent of the cathodic material. For example, polarization can cause iron to corrode at the same rate whether it be in contact with copper, bronze, brass or monel.

**Cathodic protection.** Cathodic protection is based on the principle that if an anodic current promotes corrosion, then a cathodic current will prevent corrosion. In the case of pipelines, cathodic protection can be provided by using a sacrificial or nonsacrificial anode. Sacrificial anodes, connected to the pipe by a wire, can be made of zinc, or of a magnesium or aluminum alloy. No external current is needed, electrochemical action alone generating the current (a potential of about 0.9 v is required to make the pipeline cathodic). With nonsacrificial anodes, such as a large ground bed of graphite, external current is usually required.

Cathodic protection can also be used to protect ships, storage and water tanks, and other equipment exposed to water or moisture. Typical of the anode materials that can be used in these applications are zinc, lead alloy, platinum, titanium, stainless steel and scrap iron.

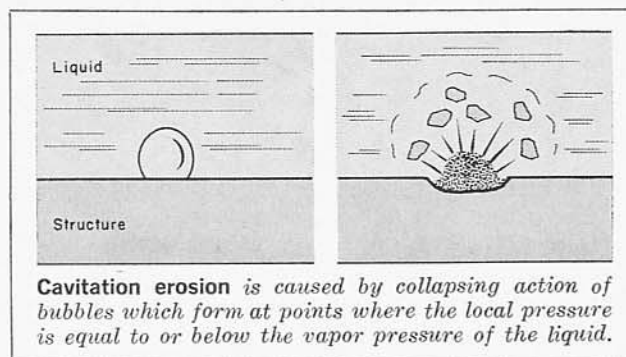
#### Caustic embrittlement

Caustic embrittlement is actually a form of stress corrosion and can occur when mild steel is exposed to caustics (such as sodium hydroxide solutions), basic water solutions, and sometimes nitrates and phosphates under a combination of high temperature and stress. It usually occurs in the form of intergranular cracks and is most often encountered in pressure vessels and heat exchangers at rivets and crevices where stresses are high and concentrated solutions accumulate. Intensity of attack is a function of caustic concentration, temperature and stress level, and, if the conditions are right, attack can occur in a very short time.

Caustic embrittlement in mild steel boilers can be minimized by preventing the steel from being stressed beyond its yield point and by eliminating stresses left from any cold work that causes deformation (e.g., roll forming and riveting). The degree of caustic embrittlement is little affected by the alloy composition of mild steels, or by the normal stresses produced by steam pressure or uniformly distributed structural loads.

#### Cavitation erosion

Cavitation erosion is caused by the collapse of bubbles and cavities within a liquid. In addition to producing vibration and noise and lowering hydraulic efficiency, the mechanical action of cavitation causes



materials to erode. The erosion is characterized by deep pits, depressions and pock marks and can occur on many metals, as well as on nonmetallics such as glass, rubber, plastics, wood and concrete.

Cavitation erosion can be minimized or eliminated by switching to a more resistant material or by using a protective coating or layer. In general, the stainless steels and aluminum bronzes have quite good resistance to cavitation damage. Materials such as cast iron, bronze and steel castings, and steel plate have relatively poor resistance to cavitation damage, but they can be protected with welded layers, sprayed metal coatings, and some nonmetallic coatings. As is to be expected, welded layers of stainless steel and aluminum bronze provide good protection, but many other types of welding materials also perform well. Some sprayed metal coatings also provide good protection where cavitation is not too severe. Some elastomeric and plastic coatings look promising, especially for hydrofoil applications.

#### Corrosion fatigue

Corrosion combined with repeated stress is potentially more damaging than either corrosion or fatigue alone. As noted by *Guy*, this is borne out by the "damage ratios" (corrosion fatigue strength divided by normal fatigue strength) of various materials. Typical damage ratios for materials in salt water are: 0.2 for carbon steels, 0.5 for stainless steels, 0.4 for aluminum alloys, and 1 for copper. Thus carbon steels, for example, have only one-fifth their normal fatigue strength when exposed to salt water.

One of the dangers of corrosion fatigue is that bending tends to break down protective films on the metal. This may not be important with metals that have good "self-repair" characteristics, but with most metals it enables corrosion to proceed more rapidly.

Naturally, the best way to prevent corrosion fatigue is to keep mechanically vibrating parts away from corrosive environments. However, this is not often practical and in such cases it is usually wise to conduct tests to determine the suitability of materials. Some data on corrosion fatigue have been published but they have to be used carefully because it takes considerable experience to apply published data to specific products. Usually, the only data valid in a particular application are those which were collected under identical circumstances. Part of the trouble

## THE THEORY BEHIND CORROSION

CORROSION CAN BE broadly defined as materials deterioration that is caused by chemical or electrochemical attack. Although direct chemical attack can occur with all materials, electrochemical attack usually occurs only with metals because, unlike other materials, their electrons are free to move (as in a storage battery). Since plastics do not have this mobile structure they are usually susceptible only to chemical, not electrochemical, attack.

One of the reasons why metals are so susceptible to attack is that they naturally occur as oxides, hydroxides, carbonates and other compounds with low free energy. In their refined state, as *Jastrzebski* points out, they are "in a much higher energy state than their corresponding ores, and they will show a natural tendency to return to their lower energy or combined state. Thus, the corrosion of metal can be regarded as the reverse process of reducing metals from their ores."

### Electrolytes are common

It is not surprising that corrosion occurs so frequently because electrolytes—which are the basis of electrochemical action—occur naturally in everyday environments. These electrolytes, which produce what can be called wet corrosion, usually consist of aqueous solutions of salts, acids or alkalis. Their action differs from that occurring in so-called dry corrosion which usually involves a chemical reaction between a gas (e.g., ammonia) and the metal, or by the pressure and the resulting strains that are caused by a buildup in gas pressure (e.g., hydrogen embrittlement).

The basic theory behind all the different types of electrochemical corrosion is the tendency of metals to pass into solution in the form of ions when they are exposed to an electrolyte. The tendencies of different metals to go into solution can be expressed by their electrode potentials which, in turn, can be arranged into the well-known electrochemical series and galvanic series. Thus, metals which have a greater potential tend to be more active. Of the two series, the electrochemical one is more theoretical and is based on materials which are free of oxides. The galvanic series is more practical and is based on metals with natural surface films and on environmental conditions more likely to be found in service.

### Potential differences arise easily

Aside from the obvious galvanic couple, there are many internal and external factors that can lead to damaging potential differences. For example, even in a metal which does not contain any impurities it is still possible for potential differences to arise from the orientation of individual crystal grains. Potential differences in alloyed metals can arise internally by changes in the point-to-point concentration of alloying elements caused by precipitation.

Here again, as *Jastrzebski* notes, "the precipitated particles themselves may have a potential different from that of the adjacent solution, or the depleted areas of a solid solution from which the precipitate has formed may exert a potential different from other areas in which no precipitation has occurred."

Internal differences in potential can also be caused by the different phases of heterogeneous alloys. A good example of this is a type of attack known as graphitization which occurs in gray iron containing three different phases—ferrite, cementite and graphite flakes. In the presence of some acids an electrolytic cell is formed in which the iron acts as an anode and the graphite as a cathode.

Thus, the theory of potential difference can be used to explain many of the common forms of corrosion. In the case of intergranular corrosion which occurs along grain boundaries, attack is believed to be caused by impoverished materials along grain boundaries having a higher solution potential than the grain center and the precipitated compound. Thus, the impoverished material is preferentially attacked by the corrosive environment.

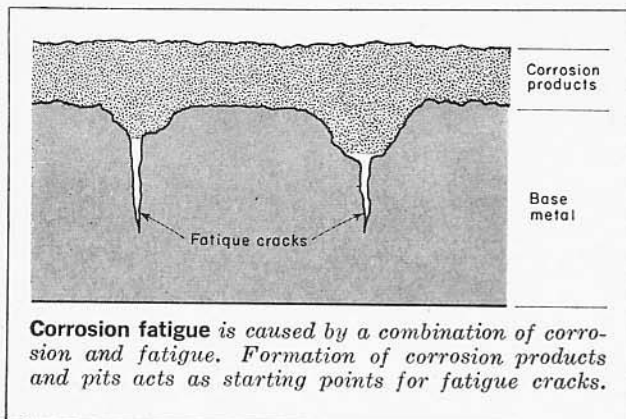
### Electrochemical action is common

Electrochemical action is also believed to be responsible for fretting corrosion which, at first examination, appears to be caused solely by mechanical forces. However, corrosion is believed to be caused by the exposure of activated spots which can be a source of galvanic attack or concentration cell action.

There are many other sources of potential differences that are responsible for electrochemical attack. For example, in the metal itself potential differences can arise from residual and applied stresses, from surface impurities, and from protective oxide films and adsorbed films, all of which may be present before the metal is exposed to an electrolyte. Areas that are stressed are more anodic than unstressed areas. Also, because internal stresses are confined to certain areas they can produce localized attack which may penetrate rapidly.

Many differences in potential can arise from the electrolyte itself. The most obvious variable is the concentration of the solution which can cause changes in potential difference; even local changes in concentration can have an effect. Other potential changes can result from the presence of dissolved gases, from the presence of agents which change the polarization and characteristics of surface anodic and cathodic areas, and from the formation of protective layers during corrosion. Other local changes in potential difference can be caused by temperature changes and thermal gradients, and by the amount of agitation experienced by the electrolyte.

In the above description, the editor has made liberal use of the corrosion theories summarized in *Nature and Properties of Engineering Materials*, by Zbigniew D. Jastrzebski, John Wiley & Sons, Inc., New York, 1959.

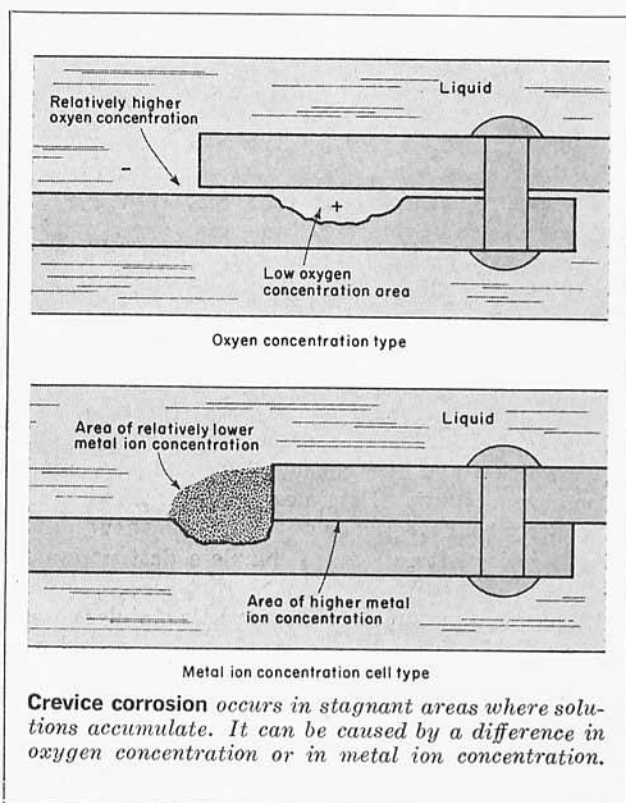


in applying data stems from the fact that there can be no "real" endurance limit in a corrosive environment, and an "apparent" endurance limit has to be used. The reason for this is that corrosion alone would cause failure if the metal were exposed for a sufficient time.

#### Crevice corrosion

This is one of the most familiar types of corrosion as, from common experience, we all know that corrosion is more likely to occur in crevices which retain solutions and take longer to dry out. It is also possible for corrosion to occur at crevices even when they are completely immersed. Accelerated corrosion, for example, can occur from either excess oxygen concentration which causes direct attack, or from a deficiency of oxygen which can cause corrosion through differential aeration.

Crevices can also lead to differences in metal ion



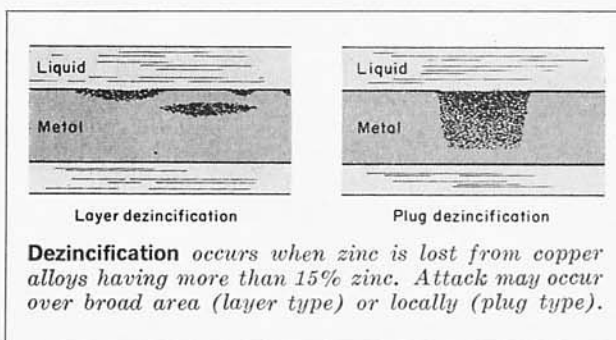
concentration at different locations. For example, it is possible for the area in a crevice to have a higher metallic ion concentration than the area outside. Thus, corrosion can take place at the edge of a mechanical joint.

Naturally, the best way to avoid these forms of attack is to eliminate crevices entirely by changing the design. If this is not possible then you should fill in joints that are liable to cause trouble.

#### Dezincification

As its name implies, dezincification is a corrosive phenomenon in which zinc is lost from an alloy. It occurs with many copper-zinc (brass) alloys containing less than 85% copper when they are used in contact with water having a high content of oxygen and carbon dioxide, or in stagnant solutions. The effect tends to accelerate as temperature rises.

Dezincification may occur either in a local area or throughout the metal structure. Local attack usually known as plug-type dezincification, is characterized by a deep, perpendicular penetration in the surface of the metal. This type of attack is very active and can produce rapid penetration. Broad attack, which is known as uniform or layer-type dezincification, is



characterized by layers of degraded metal, one over the other.

In both types of attack the net result is to leave a porous, friable and weak surface over a porous copper structure. Naturally, the strength of the metal is substantially lowered and it becomes susceptible to leaking—a problem in such applications as pressure vessels, valves and pipe. In such cases, you can prevent dezincification by using a brass with lower zinc content, or one containing tin or arsenic which tend to inhibit dezincification.

#### Direct attack

Direct attack by corrosive media is, of course, one of the most common types of corrosion. The most obvious way to prevent it is to select a more resistant material. (As a selection aid, we have prepared a comprehensive table starting on p 106 which describes the resistance of the major engineering materials to direct attack.—Ed.)

Oxidizing agents have an important effect on corrosion; although they normally accelerate corrosion greatly, they sometimes act as a deterrent. For ex-



ample, oxidizing agents that accelerate the corrosion of some materials may retard corrosion of others by forming surface oxides or layers of adsorbed oxygen which increase the resistance of the base materials to chemical attack.

#### **Erosion corrosion**

Erosion corrosion is caused by the direct action of gases, liquids or solids on the surface of a material. It usually occurs during turbulent flow at high velocities and differs from cavitation erosion which is caused by differences in vapor pressure. In addition to directly attacking the material, erosion corrosion can prevent protective insoluble layers of corrosion products from forming, or remove the layers after they have formed.

Naturally, if the fluid contains insoluble solids then an abrasive action will occur at high velocities. Aside from using more resistant materials, erosion corrosion can be minimized by avoiding abrupt changes in the direction of fluid flow, by using "spoilers" to break up the fluid flow or change its direction, or by filtering out abrasive materials before the fluid enters processing equipment.

#### **Fretting corrosion**

Fretting corrosion is produced by vibration which results in striking or rubbing at the interface of closely fitting, highly loaded surfaces, as between leaves of springs and the components of ball bearings. This action, combined with some slipping, opens up unprotected spots of activated metal which are susceptible to galvanic attack, and consequent pitting or indentation. In addition to destroying dimensions, these scars increase the danger of fatigue and structural failure.

Although it most commonly occurs between two metals, fretting corrosion has also been observed between a metal and a nonmetallic surface such as paper, wood and glass. Most ordinary metals are susceptible to fretting corrosion, the most susceptible being stainless steel (with itself or in combination with another metal) and the most resistant being brass.

There are several ways in which fretting corrosion can be overcome. Naturally, the most obvious way is to remove the source of vibration. If this cannot be done then relative motion can sometimes be stopped by increasing the load so that the increased friction between surfaces will stop the relative motion. Because fretting corrosion is more likely to attack soft steels rather than hard, another alternative is to increase the hardness of the surfaces. Finally, it can sometimes be prevented by using a lubricant between the surfaces so as to lower frictional heat and to prevent welding.

#### **Graphitization**

Graphitization is defined here as the accumulation of graphite occurring on the surface of gray iron castings during corrosion. This type of graphitization should not be confused with true graphitization which

can occur in irons above 1200 F when iron carbide breaks down into iron and graphite (a troublesome problem in steam power plants).

All gray irons contain dispersed graphite particles which, as noted in the *Gray Iron Castings Handbook*, have a negative potential with respect to ferrite in aqueous solutions. During ordinary corrosion the graphite is unattacked and it may actually hold the corrosion products together, preventing further attack by the corrosive. Furthermore, the graphite particles may stop small pits from forming and prevent local attack.

On the other hand, if gray iron is exposed to strong acids, coarse graphite flakes can interrupt the formation of a protective surface film and allow the acid to penetrate, as in the case of concentrated sulfuric acid where graphite prevents the formation of a protective scale of ferrous sulfate. However, in dilute acids, the graphite may induce a lower corrosion rate in the material.

#### **Hydrogen embrittlement**

Hydrogen embrittlement is a form of surface or structural damage that occurs in steels as a result of gaseous hydrogen. When the hydrogen is trapped in voids or cracks, its pressure builds up until it exceeds the yield strength of the metal, thereby causing blisters and cracks and reducing the strength and ductility of the metal.

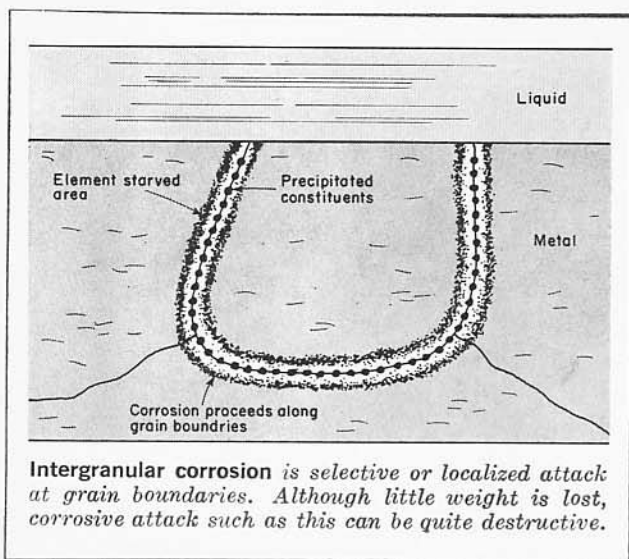
Hydrogen embrittlement often results from the hydrogen that is picked up during pickling and electroplating. Hydrogen absorption during pickling can be minimized in several ways, including: anodic pickling, dipping in an oxidizing acid bath, using restrainers (inhibitors), and subsequent heating. Restrainers cut down hydrogen production and lessen the amount of hydrogen that enters the metal surface. Subsequent treatment such as exposure of the metal to hot water or warm air also helps to expel excess hydrogen.

In the case of electroplating (cadmium and chromium electroplating cause the most trouble), embrittlement can be minimized to some extent by using proper pickling procedures before plating, and by carefully controlling the plating bath and operating conditions.

#### **Intergranular corrosion**

Intergranular corrosion is the selective or localized attack that occurs at the grain boundaries of some copper, nickel, and high nickel alloys, and particularly some chromium-nickel stainless steels when they are improperly heat treated or welded. Even though little weight is lost, it can cause complete destruction of the metal.

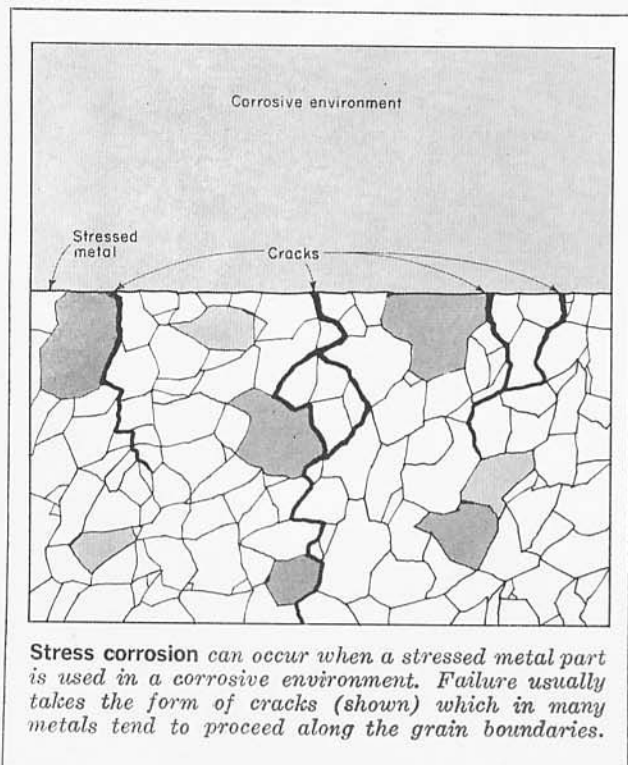
In a typical material, 18-8 austenitic stainless steel, heating at 950 to 1400 F causes chromium carbides to precipitate at grain boundaries, thereby robbing the matrix of chromium and reducing corrosion resistance. During corrosive attack a galvanic cell is produced which results in degradation of the anodic ("starved") area.



Intergranular corrosion in stainless steels can be avoided by stabilizing them with columbium, titanium and tantalum, which preferentially unite with the carbon and prevent formation of chromium carbides. Another solution is to heat the metal high enough (about 1950 F) so that the chromium carbides dissolve, then cool rapidly by quenching to prevent them from reforming. Where such procedures are impractical the most obvious way around the problem is to avoid alloys and conditions that tend to promote intergranular corrosion.

#### Stress corrosion

Stress corrosion is the deterioration that occurs when an internally or externally stressed metal is exposed to a corrosive environment. Damage usually takes



the form of localized cracks. The magnitude of stress necessary to cause failure depends on the corrosive medium and on the structure of the base metal; although a high stress (i.e., one approaching the yield strength) is usually required, failure sometimes occurs at low levels.

Stress corrosion is one of the most important types of corrosion because it can occur with so many metals. Almost any metal can be attacked in certain environments, yet the same conditions that cause cracking in one metal will not cause cracking in another. Thus, it is difficult to predict where attack will occur.

The presence of nitrogen in iron and steel tends to make them more prone to stress corrosion cracking in some nitrate solutions. Steels containing aluminum have better resistance to stress corrosion because the aluminum combines with nitrogen to form aluminum nitride.

Some stainless steels are susceptible to stress corrosion cracking in the presence of chlorides, e.g., in solutions of sodium chloride, calcium chloride and several others. Although they will pit badly in the presence of chlorides, the ferritic stainless steels are less likely to fail from stress corrosion than the austenitic or martensitic grades.

Stress corrosion cracking can also occur with stressed copper alloys when they are exposed to ammonia and its compounds, especially in the presence of oxygen and carbon dioxide. Mercury and its compounds can also attack copper alloys but, except in some heat transfer equipment, these materials are not likely to be encountered. Stress corrosion in copper alloys can be minimized by avoiding residual stresses, by using protective coatings and, in the case of brasses, by keeping zinc content below 15%. Brasses containing 20 to 40% zinc are highly susceptible to attack.

Some aluminum alloys are also susceptible to stress corrosion cracking, notably the heat treated, high strength 2000 and 7000 series alloys. Failures in these alloys appear to be caused by residual fabricating or assembly stresses in relatively thick sections. In order to avoid residual stresses the alloys should be in an annealed condition during severe forming, after which they should be given a thermal stress relief treatment. Mechanical treatments (e.g., shot peening) that counteract or relieve internal stresses are also beneficial. ■ ■

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## Evaluating Materials for Corrosive Service

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*How to predict behavior of materials through laboratory and field testing: what you should know about simulating the environment, conducting tests, and evaluating results*

by F. L. LaQue, Vice President, International Nickel Co., Inc.

*Checking progress of a typical underwater test designed to show extent of attack by sea water organisms on metals.*





IT IS VERY RARE—and indeed bad practice—for an engineering material to be selected for a potentially corrosive application without being put through a corrosion test. If you are selecting a material for a new application where the corrosive effects of the environment are unknown it is foolhardy to proceed without making a corrosion test on the material to find out how it will perform. And, even if the application is not new, there are many cases where you will want to continue running corrosion tests to obtain long-term data, to study other materials or to find out what effect a change in operating conditions—such as temperature, concentration and velocity—may have.

Thus, you can use corrosion tests to:

- Study the fundamental mechanisms of corrosion.
- Study the means of preventing corrosion.
- Determine the usefulness of new materials in various environments.
- Select the most suitable material for a particular environment and estimate its life.
- Determine the effects on materials of contaminants from corrosion products.
- Find the cause of plant equipment failures.
- Observe the effect of changes in composition or treatment in developing corrosion resistant materials.
- Serve as a quality control in materials production.

In order to design and use corrosion tests intelligently you have to consider the characteristics of the environment—whether it be an actual service or a simulated environment. Naturally, unless you are making some fundamental studies, the simulated environment should match the actual environment as closely as possible. Next, you have to consider the characteristics of the materials under test to establish their reproducibility and to insure that their condition in test corresponds to the condition in which they will be used in service. Finally, during and after the test you have to have some means of appraising and measuring corrosion damage.

## Simulating the environment

A corrosive environment is composed of many different and important elements. In either laboratory or field testing you have to consider:

1. Composition of the environment.
2. Volume or amount of test solution required to provide meaningful data.
3. Degree of immersion (e.g., total or partial immersion or exposure to vapors).
4. Length of exposure.
5. Amount of aeration or other oxidizing or reducing constituents.
6. Temperature of environment.
7. Velocity of testing media.

Because of the difficulty in duplicating all service

conditions simultaneously in the laboratory it is usually necessary to determine the effects of the individual controlling factors by varying them one at a time. Naturally, these factors are usually fixed if you are running a field corrosion test but even in this case it is important to know what effects individual factors have in order to interpret the results correctly.

**Simulate environment composition.** In corrosion tests it is important to use solutions that closely match those encountered in service. You should realize that laboratory-reagent-grade chemicals may not act the same as the solutions in service. Also, because the trace impurities found in service may have major effects on corrosion it is often desirable to add controlled amounts of impurities to the pure solution, or to use actual plant solutions. Close control of impurities can be especially important in running corrosion tests with liquid metals because trace amounts of oxygen or water can affect results.

If you are trying to establish the effects of different concentrations on corrosivity, you should cover the widest possible range of concentrations because some concentrations may be more corrosive than others. For example, a complete absence of water may increase corrosion considerably in some cases, whereas a trace of moisture may make other chemicals—such as chlorine and other halogens—more corrosive.

**Test with sufficient volume.** An insufficient volume of test solution can prematurely exhaust the corrosive constituents and provide low and misleading corrosion rates. Also, an accumulation of reaction products may either accelerate or stifle further attack. When testing the corrosive effects of liquid metals, a limited volume can become rapidly saturated by the corroding metal, thus stifling the reaction and producing only a small corrosion loss.

Naturally, in laboratory tests there is a practical limit to the volume of test solution that can be handled. The American Society for Testing and Materials recommends that a minimum of 250 ml of solution be used for each square inch of specimen area. However, it is good practice to replace the solution periodically when the effects mentioned above are known to exist and solution concentration is limited.

**Immerse to proper depth.** Test materials can be completely, partially, or alternately immersed in a corrosive medium and exposed to vapors.

*Total immersion* facilitates the greatest control of other environmental factors in corrosion and improves the reproducibility of test results. Even in total immersion, the depth to which the specimen is immersed can be important, as when field testing in natural waters and in soils. Small specimens exposed at different depths will not corrode in the same way as will long specimens extending through the same range of depth. For example, in measuring the corrosive behavior of metal pilings in sea water, short sections cannot be used; the sections must be continuous and long enough to extend through the total range from

This article was adapted from the chapter "Corrosion Testing," by F. L. LaQue which will appear in the new edition of *Corrosion Resistance of Metals and Alloys*, by McKay and Worthington, to be published by Reinhold Publishing Corp. in 1963.

above high tide to below low tide. This is necessary to allow for differential aeration and other possible concentration cells that can have a drastic effect on results. Wide variations can also occur between continuous and isolated specimens tested in various soils.

**Partial immersion** tests are usually conducted where you want to determine the effects of corrosion at liquid level lines. Localized attack frequently occurs with many metals along this line; it may be caused by concentration cells (differential aeration) and by differences in the nature and adhesion of corrosion product films at the waterline. Partial immersion tests are also useful to find out if the vapor above the liquid is more corrosive than the liquid itself.

**Alternate or cyclic immersion** tests may frequently simulate actual service conditions more closely than complete or partial immersion. Alternate wetting and drying (as well as aeration) can be provided by raising and lowering either the specimen or the solution container or, in a spray cabinet, by turning the spray off and on.

**How long to test?** Because corrosion rates usually vary with time, the length of exposure is an important factor in corrosion testing. Corrosion rates are usually higher at the beginning of exposure and tend to diminish as protective films or insoluble corrosion products build up. Thus, short-time tests will generally indicate higher rates of attack. For this reason, extrapolations of short-time data are usually conservative and may result in the selection of a better material or a thicker section than is actually needed.

A good rule of thumb to determine if a test has been run long enough is to multiply the corrosion rate in mdd (milligrams per square decimeter per day) by the number of test hours. If the resulting number exceeds 10,000 then you can usually assume that the test has run a sufficient length of time. For example, for a rate of 250 mdd a 40-hr test is adequate, and for a 25-mdd rate a 400-hr test is sufficient.

However, in some corrosive environments general rules cannot be used. For example, in most industrial atmospheres alloy steels should be tested for about four years. In marine and rural atmospheres even longer periods may be required before protective surface formations develop. In water and soil, tests should be allowed to run for three or more years.

**Simulate aeration.** Aeration can have an important effect on corrosion reactions and can be provided by bubbling air or oxygen into the solution.

If you need to study the effects of various degrees of aeration, it is better to vary the oxygen content of the saturating gas rather than vary the admission rate of the gas. If zero aeration is needed, then the test solution can be saturated with nitrogen or other inert gas.

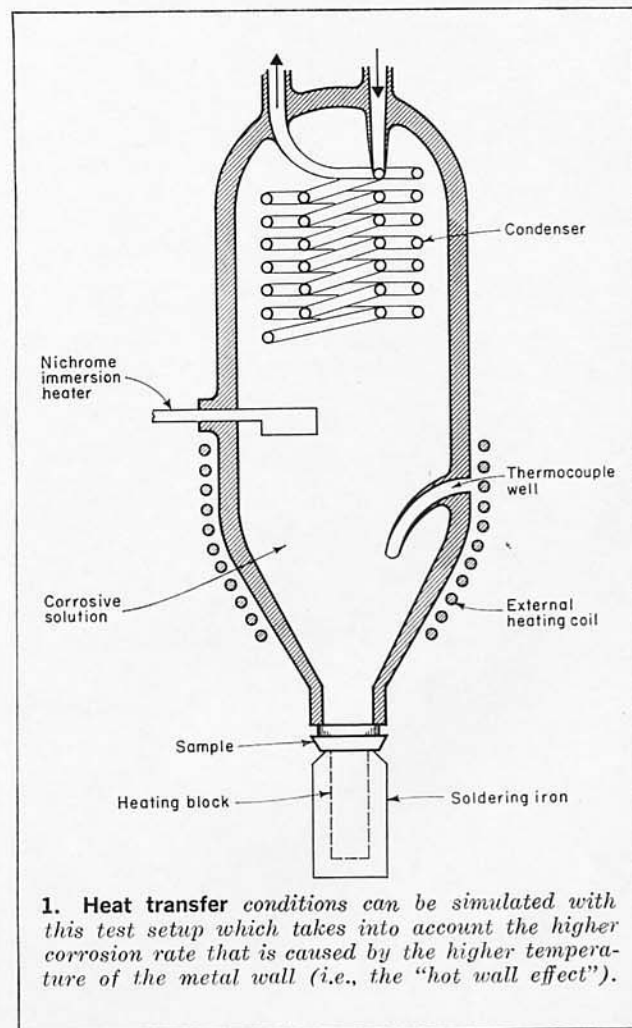
**Control temperature.** The effect of temperature is complex because it also influences other corrosion factors such as oxygen solubility, content of dissolved gases and film formation. Thus, it is difficult to extrapolate corrosion rates from one temperature to another.

Liquid metal corrosion tests require closer temperature control than most other tests. For example, a temperature differential of 5°C can produce a variation in corrosion rate several times greater than a differential of 0.5°C does.

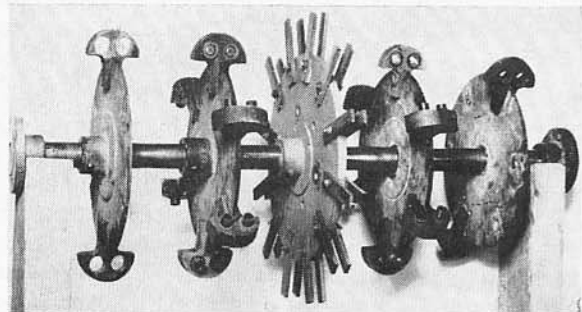
When testing a metal that is to be used in a heating coil or other heat transfer application, the metal must be tested under heat transfer conditions (Fig 1). Higher corrosion rates occur under heat transfer conditions because of the higher temperature of the metal wall. Thus, simple immersion of the specimens in the solution at the operating temperature may give low and misleading results, and even testing at higher solution temperatures does not simulate the "hot wall effect."

**Simulate velocity.** Corrosion generally increases with velocity. Unfortunately, it is difficult to study the effects of velocity on corrosion because laboratory tests rarely duplicate service conditions, especially flow rates.

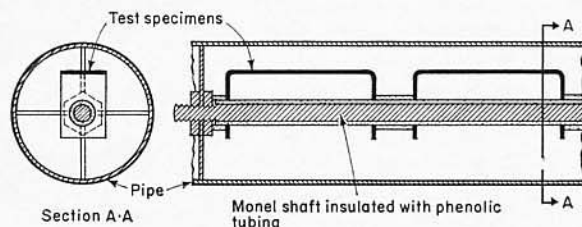
Another problem, of course, is that velocity causes several types of corrosion, such as uniform attack, impingement or corrosion erosion, and cavitation. Many tests have been developed to evaluate these forms of attack but practically no correlation exists from one test method to another.







**2. Velocity effects on corrosion** can be measured by mounting test specimens on periphery of wheels which rotate in test solution (above), or by installing specimens inside pipe carrying corrosive solution (below).



Zero velocity is about as difficult to control accurately as high velocity. Often it is mistakenly assumed that if neither the specimen nor the test liquid is moved the relative flow rate between them will be zero. However, even in this case velocity effects can be produced by convection currents and by agitation produced when corrosion products fall off the specimens. Thus, reproducible results are difficult to obtain under presumably quiet or stagnant conditions. In such cases it may be desirable to have some controlled movement to improve the reliability of the test even though velocity effects may not be of practical interest. Equipment is available for controlling velocity as low as 15 fpm.

Several different tests and devices are available for studying corrosion at high velocities. In a typical test a disk-shaped specimen is placed on the axis of a shaft and rotated at high velocity. A similar test, illustrated in the photo in Fig 2, can be made by attaching specimens to the periphery of a wheel which is rotated at high velocity in the corrosive medium. The sketch accompanying the photo shows a typical device for testing specimens in pipelines so that they will encounter velocity effects. Various other tests are available for measuring impingement attack or erosion.

Where you have to run velocity tests on pipe whose size is scaled down from the plant size to a model size it is important not to use the actual plant velocity when testing. The pipe affects turbulence (as measured by the Reynolds number) and it is the degree of turbulence rather than velocity that affects the corrosion rate. Therefore, to produce the same degree of turbulence in model piping systems the velocity should be changed in proportion to the decrease in

pipe size. Special equipment is available for measuring the rate of this type of corrosion for both liquid solutions and liquid metals. Cavitation erosion by liquids can also be measured with special devices.

## Testing for corrosion

At the outset of making a corrosion test you should be sure that the test material is in a standard condition and that it will provide reproducible results. Such factors as surface condition, heat treatment, method of support and internal stresses can have a marked effect on corrosion results.

**Surface preparation.** The surface condition of materials has to be controlled carefully in order to obtain high reproducibility in corrosion testing. An important way to improve reproducibility is to make sure that surfaces are uniform. For example, ASTM recommends that metal surfaces be abraded with grade 120 emery before total immersion tests. Also, before testing, the metal specimens should be cleaned to remove any dirt, oil or grease that might affect the inception or distribution of corrosion. Subsequent water spotting after cleaning can be prevented by dipping in alcohol and then in acetone. In some cases it may be desirable to chemically treat (pickle) the surface to eliminate mechanical effects.

Because cut or sheared edges often act as focal points for preferential attack and can give misleading results, they should be machined or ground to remove torn or fissured surfaces. Edge effects can also be held to a minimum by using specimens with a large surface-to-edge area ratio.

When testing metals it is sometimes desirable to treat them chemically to insure a certain level of initial activity or passivity. For example, in some cases you may want to start with a metal that is passive, as in the case of stainless steel treated in nitric acid. On the other hand, you may want a metal that is initially active to see if it will become passive or remain active.

**Effect of heat treatment.** Certain heat treatments and heat effects (as in welding) can seriously reduce the corrosion resistance of metals. The lowered corrosion resistance of some alloys is caused by the precipitation of separate phases in or around grain boundaries which leads to localized attack. A good example of this is the intergranular corrosion of stainless steels arising from the precipitation of chromium carbides or sigma phase at grain boundaries.

However, some heat treatments may improve corrosion resistance, e.g., homogenizing heat treatments on castings which eliminate "coring," improve the uniformity of the cast structure or redissolve harmful precipitates. Stress relief heat treatments may also help prevent stress corrosion cracking in certain alloys, but in others may make them susceptible to intergranular corrosion unless they are stabilized against this effect.

Because of these factors you must take the heat treatment of metals into account when corrosion



testing. In initial corrosion screening tests, the specimens should be exposed in their most resistant condition or in the condition which will be used in service. Then, after making a preliminary selection, you can run additional tests to study possible detrimental heat effects, such as those produced by welding. Specimens with welds cannot be relied upon in determining a metal's susceptibility to intergranular corrosion because the degree of sensitization can be affected by the rate of welding, size of the specimen and skill of the welder. Thus, separate tests should also be run on unwelded specimens which are given a controlled sensitizing or detrimental heat treatment.

**Testing for stress corrosion.** The object of a stress corrosion test is to find out how a metal will behave in a corrosive environment when it is stressed. If the purpose of the test is simply to find out if a material will resist cracking in an environment under the most severe internal stress, a suitable specimen can be prepared by taking a cold drawn tube and subjecting it to further cold work by flattening a portion of it.

However, in more complex applications the environment, magnitude and direction of stress have to be properly controlled. Naturally, if controlled external stresses are to be applied, any internal stresses should be eliminated by stress relief annealing to obtain proper results.

In designing a test for stress-corrosion cracking the metal can be stressed for either a constant deformation or a constant load. When cracking occurs in the constant deformation test the stresses are reduced and the rate of cracking slows down. However, in the constant load test, cracking increases the stress on the unaffected metal and therefore accelerates failure.

Many detailed tests have been developed to determine stress-cracking susceptibility. Following are some typical testing environments that have been developed for specific metals:

Steels: caustic embrittlement, hydrogen embrittlement, hydrogen sulfide.

Stainless steel: magnesium chloride solution (austenitic stainless); acid solutions with selenium compounds (chromium stainless).

Brass: mercurous nitrate solutions; mixtures of ammonia, water, oxygen and carbon dioxide.

Aluminum alloys: mixtures of sodium chloride and hydrogen peroxide.

Magnesium alloys: sodium chloride solutions with or without chromate additions.

Naturally, in any test where you are measuring the basic corrosion resistance of a metal you should support the metal so as to minimize crevice and galvanic effects. You can do this by minimizing the contact area of the supports and by insulating the specimens. In laboratory tests specimens can be simply supported on glass rods or hooks, or by handling them on Teflon cord. However, a more rugged system is usually required for actual plant tests. In such cases the specimens can be electrically insulated from the metal supporting rod by sliding a plastic

tube over the rod and by using plastic spacers between the specimens. A typical insulating procedure is covered in ASTM A224. Special devices for mounting specimens in pipelines so that they will encounter velocity effects have also been developed.

**Testing for corrosion fatigue.** The rate of failure under the combined action of corrosion and fatigue is always greater than that for either fatigue or corrosion applied separately. Naturally, it is difficult to simulate corrosion fatigue in laboratory tests because it is difficult to apply cyclic stresses and simultaneously maintain a corrosive environment around the stressed area. One way you can do this is to modify the conventional rotating beam fatigue test to allow a corrosive solution to circulate around the test specimen. The corrosive agents can also be applied by a pad or wick or by allowing the liquid to drip slowly on a rotating specimen. Tests have also been performed by flexing flat specimens while they were periodically immersed in the corrosive solution, and by rotating wire arcs in the test solution.

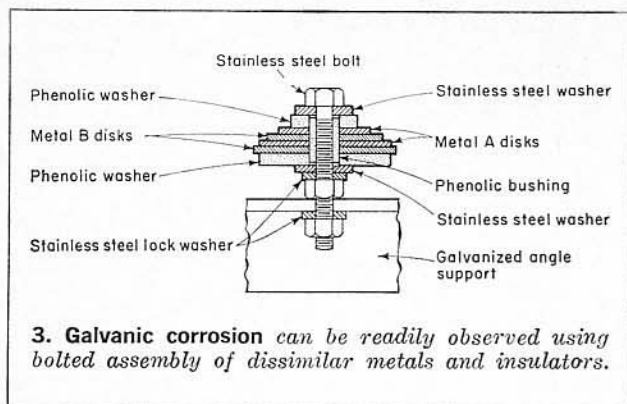
**Testing for crevice corrosion.** Crevice corrosion attack is caused by the formation of either oxygen or metal ion concentration cells in or around partially shielded areas. Various ways have been developed to deliberately create crevices on test metals. For example, in salt water testing, a material's resistance to crevice corrosion or "deposit attack" can be measured by observing the incidence and extent of corrosion under a small pile of sand placed on the surface of the immersed specimen. Another way to create crevices is to wind a wick around the test specimen.

The extent of crevice attack frequently depends on the ratio between the area freely exposed and the area within the crevice. For example, crevice corrosion tests in sea water show that the extent and depth of attack are directly proportional to the area of the surface freely exposed outside the crevice. Such effects should be taken into account.

**Testing for galvanic corrosion.** In designing a galvanic corrosion test you should take into account the following factors:

1. Potential relationship between the metals and their polarization characteristics.
2. Relative areas of anode and cathode.
3. Internal and external resistances in the galvanic circuit.

Galvanic contact between the specimens can be made through insulated wires extending outside the solution, or the metals can be put in direct contact. The wire method is preferred in laboratory tests because it allows you to make potential and current measurements. However, the direct contact method is preferred in plant or field testing where it would be difficult to use circuitry. A typical test of this type—an atmospheric galvanic couple test—is shown in Fig 3. In this standard ASTM test each of the two dissimilar metals has a specimen of the other metal on each side of it, but only the condition of the two middle materials specimens is measured during actual corrosion testing.



**Testing for spray resistance.** Several spray (or fog) and modified tests have been standardized by ASTM. These tests are most commonly used to evaluate various metal, organic and other coatings, and to make accelerated quality control tests on them. The standard ASTM tests are:

**Salt spray (fog) test, ASTM B117.** The salt spray test was developed to simulate sea coast atmospheres but it has subsequently been used to make other evaluations—for many of which it is not suited. Although the standard ASTM test sets the solution (5% sodium chloride at a pH of 6.5-7.2) and its temperature, many variations can result from the differences in fog characteristics caused by variations in nozzle design, brine pressure, and panel exposure angles. Thus, caution is required in comparing results from one cabinet to those from another.

**Acetic acid-salt spray test, ASTM B287.** This test was developed to reproduce the type of blistering frequently encountered on chromium-plated zinc die castings exposed to the atmosphere. Like the above test, it makes use of a 5% sodium chloride solution except that its pH is adjusted to between 3.1 and 3.3 by adding acetic acid.

**Copper-accelerated acetic acid-salt spray test,** also known by its initials as the CASS test. This test is a more corrosive modification of the acetic acid salt spray test and is reported to provide a good correlation with the performance of plated parts in service. The standard solution (as described in ASTM B368) contains the same amount of acetic acid and sodium chloride as the standard acetic acid salt spray test plus 1 gm of cupric chloride per gallon of test solution.

Chromium is virtually unattacked by the CASS solution. Nickel, however, corrodes at a rate of about 2.8 mils per yr; its sensitivity to the solution is caused by the copper ions which tend to maintain nickel in an active state. Thus, the CASS test will accelerate galvanic corrosion of nickel at any discontinuity in the chromium layer above the nickel layer.

**Corrodokote test, ASTM B380.** This test differs from the above three tests in that it is not a salt spray test but makes use of a corrosive slurry which is spread over the test metal. The slurry contains cupric nitrate, ferric chloride, ammonium chloride, kaolin

and distilled water. It is allowed to dry on the specimens prior to placing them in a humidity (80 to 90% RH) cabinet at 100 F.

This accelerated test is designed to simulate the action of melted street slush containing dirt, salts, etc., on chromium-plated automobile trim. One 20-hr cycle of the test will predict which coatings will not endure exposure for one winter in a typical city that uses salt to de-ice its streets. Several cycles are usually required to evaluate performance over a period of several years. Although the test will reveal unsatisfactory electroplates it cannot actually predict the life of good coatings.

## Evaluating corrosion damage

The extent and progress of corrosion damage can be evaluated by noting such features as:

1. Weight change in the material after corrosion.
2. Depth of pitting.
3. Change in mechanical strength.
4. Change in electrical properties.
5. Consumption of oxygen.
6. Evolution of hydrogen.

The optimum method depends on the type of test or on the particular type of corrosion being evaluated. In general, more than one method is used in evaluating the degree of corrosive attack.

**Measuring weight change.** This is one of the most common methods of evaluating corrosion. It is especially useful in oxidation studies of metals at high temperatures, where precise measurements can be obtained continuously with micro-balances.

The change in weight from corrosion can be either a weight loss or weight gain. In most cases, however, a weight gain has little quantitative significance unless you can tell how much of the corroded metal is in the corrosion products.

In general, it is much better to determine metal weight loss by weighing what is left after all adherent corrosion products have been removed. Naturally, any metal that is lost in the cleaning process should be accounted for; the amount that is lost can be calculated by measuring how much is lost when cleaning an identical blank or control specimen. Many satisfactory cleaning methods have been developed to provide exceptionally low weight loss. Steels, for example, can be cleaned so that the loss from cleaning is only about 0.01%.

Corrosion rates based on weight loss are commonly expressed in milligrams loss per square decimeter of exposed surface per day (mdd). Because it is difficult to visualize the depth of attack in mdd, this unit is frequently converted to other units that indicate depth of penetration, such as inches per year (ipy), mils per year (mpy), or inches per month (ipm). The basic formula for converting weight change to penetration is:

$$\text{ipy} = \text{mdd} (0.001437) \div d$$

where  $d$  is the density of the metal in gm per cu cm. A curve of this equation is shown in Fig 4. Knowing



specific gravity, you can use this curve to convert the mdd of a material into its penetration rate in ipy.

When using depth-of-penetration rates you should realize that they imply that corrosion has occurred at a constant rate or is completely uniform. Actually, most corrosion rates diminish with time and frequently corrosion in the form of pitting may be severe. Therefore, in reporting corrosion rates you should state the duration of the test as well as the nature and location of any localized attack, such as pitting or crevice attack. Also you should be aware that weight loss measurement will not disclose the extent of intergranular corrosion which can produce an almost complete loss of strength or ductility and go almost undetected in weight loss measurements.

**Measuring thickness directly.** In some cases you may desire to measure thickness directly. As mentioned above, you should also report any unusual or localized corrosion, as well as the frequency, distribution and shape of pits.

If a large number of pits are present then it is common practice to measure the maximum and average depth of the ten deepest pits. Large pits may be measured with a point micrometer (some will measure as small as 0.1 mil) or with a needle-point indicating depth gage. If more precise measurements are required you can use a microscope or examine the cross section of the metal with a metallograph.

**Using strength measurements.** In many cases you can use mechanical strength tests such as bending, tension, fatigue and impact tests to reveal internal weaknesses that are not apparent from weight loss measurements. For example, intergranular corrosion and stress corrosion cracking, and dezincification of brass, and graphitic corrosion of cast iron, can be more readily evaluated by one or more mechanical tests.

Whenever you use mechanical evaluations you should also provide a set of control specimens so that you can compare properties before and after corrosion. Naturally, the control specimens should be carefully selected to insure that they are representative of all specimens. It is possible for variations in mechanical properties to occur from specimens cut from the same metal or from different sheets or sections. Also, to eliminate any property differences they should be stored under the same temperature conditions.

**Using electrical measurements.** Because corrosion is essentially an electrochemical process, it is not surprising that many evaluation techniques involve measurement of changes in electrical properties. For example:

**Electrical resistance.** You can make quantitative corrosion measurements by measuring the change in electrical resistance of a metal in a corrosive medium. For example, since the resistance of a wire varies inversely with its cross-sectional area, the resistance of the wire (strips and small diameter tubes can also be used) increases as diameter decreases. Therefore, the resistance of a wire specimen will increase as it

corrodes in a solution.

This method has very good sensitivity and can pick up dimensional changes as small as 0.0001 mil. Instruments are available that translate the change in resistance directly to loss of thickness or cross sectional area.

The technique is particularly useful for monitoring the corrosiveness of a process stream and for measuring the effectiveness of corrosion inhibitors. Its main disadvantage is that the measurement assumes uniform attack; the severity of pitting or other localized attack cannot be determined.

**Potential measurements.** You can use measurements of electrical potential to evaluate galvanic corrosion tendencies, or to follow the development or loss of passivity over a period of time as a result of some systematic change in the conditions of exposure. Potential measurements can also disclose the appearance of a new phase resulting from thermal treatment, or measure the "breakdown voltage" of passive films in stainless steels and tin.

Potentials are measured between the test metal and an appropriate reference electrode by means of potentiometers, vacuum tube voltmeters or millivoltmeters. However, in the case of galvanic corrosion, much more information can usually be obtained by measuring the magnitude of the galvanic current rather than the open circuit potential between the metals.

Potential measurements can be used to plot anodic and cathodic polarization curves. These curves, particularly the anodic curves, provide a fast method of evaluating the relative corrosion resistance of new alloys and the effect of heat treatment on their corrosion resistance. The curves can be used to measure intergranular corrosion as well as to study anodic protection.

**Other measurements.** There are several other methods you can use to measure the progress of corrosion. One of these is to measure the change in reflectivity of polished surfaces. This method is a sensitive way of following corrosion in its very early stages in laboratory studies. Metal corrosion can also be detected by an ellipsometer which measures the increase in thickness of corrosion products without disturbing the specimens.

Corrosion can also be evaluated by making a chemical analysis of the test solution before and after testing. This method can be used when the primary problem is solution contamination rather than destruction of the metal. Although weight loss may also be used to estimate contamination, it does not take into consideration the effect of soluble and insoluble corrosion products of the test solution.

Chemical analysis may be required to detect other changes in test solution composition as corrosion progresses. For example, in theoretical studies the consumption rate of oxygen has been used to measure corrosion progress. Measuring the volume of hydrogen generated in a corrosive reaction is also useful, particularly in comparing the characteristics of different lots of steel in "tin" can corrosion studies. ■



# What We Do and Don't Know About Corrosion

By F. L. LaQue, Vice President, International Nickel Co., Inc.

## WHAT WE DO KNOW

## WHAT WE DON'T KNOW

### ELECTROCHEMICAL THEORY

- Presence of anodes and cathodes on corroding surfaces.
- Relation between current flow and corrosion.
- Corrosion potentials of many metals and alloys.
- Effects of polarization and resistance to current flow.

- Mechanism by which a metal atom leaves its lattice and becomes a hydrated ion in solution.
- Nature and extent of overvoltage factors (i.e., oxygen reduction and hydrogen evolution overvoltages) which influence the behavior of metal surfaces when they are acting as cathodes.

### STRESS CORROSION

- Some of the metals and environments where stress corrosion can be expected, e.g., brass in ammonia, steel in caustic, and stainless steels in chlorides.

- The mechanism of stress corrosion cracking in most systems, especially when the cracks are transcrystalline and there is no definable path along which corrosion and cracking might be expected to develop. Some present theories are: 1) an anodic boundary phase, as in aluminum alloys; 2) stress-induced precipitation of corrodible phases, e.g., nitrides in steels or martensite in austenitic steels; 3) rupturing of protective films by plastic deformation which allows development of anodic surfaces at tips of advancing cracks.
- Role of hydrogen in stress corrosion cracking, and why presence of hydrogen sulfide is such a potent stimulator of hydrogen embrittlement.
- What distinguishes an environment that causes cracking from one that does not. Why some environments cause intercrystalline cracking while other very similar environments cause transcrystalline cracking.

### PITTING

- Electrochemical aspects of pit propagation.
- Physical circumstances that favor pitting.

- Why a pit starts at one point rather than another.
- Why some ions such as chloride ions are more active than others in starting pitting.
- The mechanisms by which some alloying elements, such as molybdenum, improve resistance to pitting.

### IMPINGEMENT ATTACK

- Relative merits of different alloys in resisting impingement attack.
- Probable mechanisms that are involved.

- What determines the ability of an alloy to form an adherent protective film.
- What determines the protective film repair rate.
- How aluminum improves protective films on brass, and iron improves protective films on cupro-nickels.

### CAVITATION EROSION

- In a general way, the circumstances under which cavitation damage may occur.
- Relative merits of different alloys in resisting cavitation erosion.
- How to solve some problems by changing design or by controlling corrosivity of environment, as with inhibitors.

- Exact mechanism of cavitation damage.
- Relative importance of mechanical and chemical factors.
- Mechanism by which cathodic currents reduce cavitation damage.
- How to make an accelerated test that will rate materials properly.

### CATHODIC PROTECTION

- How to protect metals in some applications, e.g., underground pipes and ship hulls.
- How to monitor cathodic protection by potential measurements.

- Exact mechanism by which cathodic protection is achieved.
- Significance of potential measurements used to monitor cathodic protection.

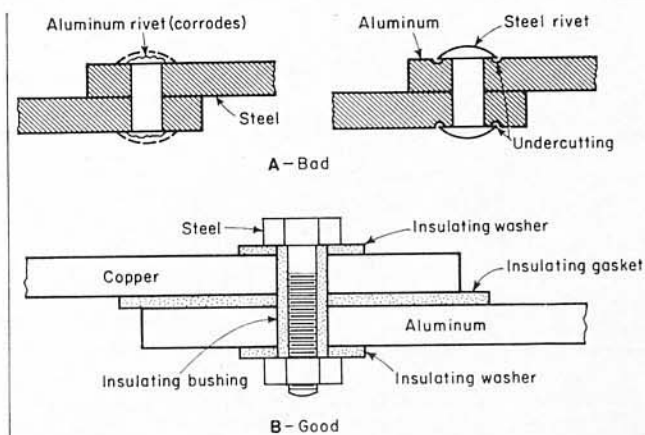
### ATMOSPHERIC CORROSION

- That there is a great spread in corrosivities of atmospheres at different locations and that this spread is due largely to atmospheric pollution.
- How to measure pollution, humidity, temperature, etc., quantitatively.

- How to use measurements of pollution and other factors to estimate the probable corrosivity of a particular atmosphere. ■ ■

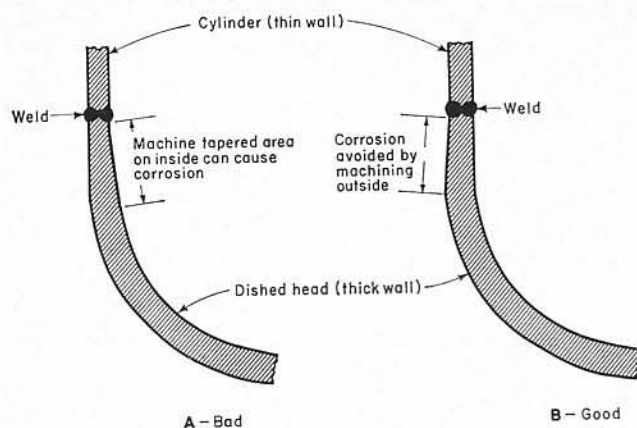
## Designing to Prevent Corrosion

*Here are eight design suggestions—follow them and you will minimize corrosive attack*



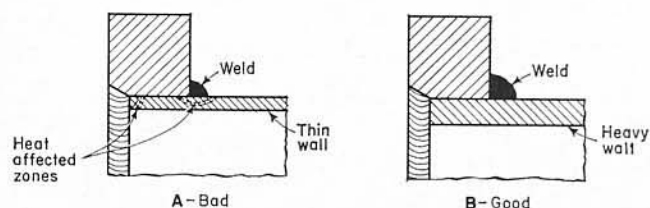
### 1. Insulate dissimilar metals.

Sketch A shows two examples of galvanic corrosion. Corrosion of an aluminum rivet can be expected when it is used to fasten steel sheets together. Similarly, if a steel rivet is used to fasten aluminum sheets, then undercutting galvanic corrosion of the aluminum sheet will result in loose rivets, slipping and possible structural damage. Corrosion of this type can be prevented by applying a nonhardening insulating joint compound in the area where the sheet and the rivet or bolt are in contact. Another approach is to apply a zinc chromate primer to all contacting surfaces and then coat the primed area with an aluminum paint. Where the fasteners are not subject to high stresses the contact points can be insulated with plastics or other nonmetallic sleeves, shims, washers and similar parts, as shown in sketch B.



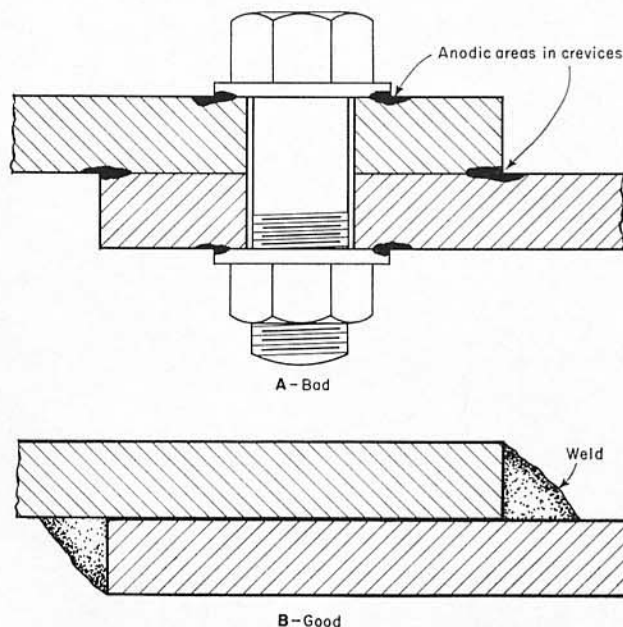
## 2. Prevent surface damage or marking.

Areas that have been damaged or marked are potential sources of corrosion. Fortunately, such areas are usually passivated quickly in a mild environment; however, they can be a source of severe corrosion in an aggressive environment. Wherever possible you should avoid internal machining. For example, in the vessel shown the heavy wall of a dished head had to be machine tapered down so that it could be butt welded to a thinner-walled cylinder. If the machining is done on the inside (A), then there is a chance that the machined area will become heavily corroded if it is exposed to an aggressive environment. Corrosion can be prevented by annealing the head after machining or by machine tapering the outside of the head while still providing a flush internal wall (B).



## 3. Avoid excessive welding heat.

Corrosion can occur in aggressive solutions at areas where variations in grain size are produced by the heat from welding. Corrosion rates vary according to the heat input of the welding method and the geometry of the joint. For example, in welding a thin section to a flange—such as the nozzle shown in sketch A—corrosion can occur in the areas indicated. Here the grain structure is changed by high temperatures caused by the inability of heat to dissipate. The possibility of corrosion in these areas can be avoided by making the wall heavier so that the heat is dissipated more rapidly, as shown in B.



## 4. Eliminate crevices.

Crevices are a potential source of concentration cell corrosion. They are frequently encountered in sections such as shown in sketch A where two plates are bolted together in a corrosive solution. No matter how much torque is applied to the bolt it is practically impossible to eliminate crevices into which the solution gradually penetrates and becomes stagnant. The difference in concentration between a solution in a crevice and the surrounding solution sets up a concentration cell wherein the crevice becomes anodic to the larger areas of surrounding metal and causes corrosion. Crevices can be avoided by using welds (B) instead of mechanical fasteners, or by using fluorocarbon gaskets between surfaces that are machined parallel. If this is not practical, then corrosion tests should be performed to select the most resistant alloy.

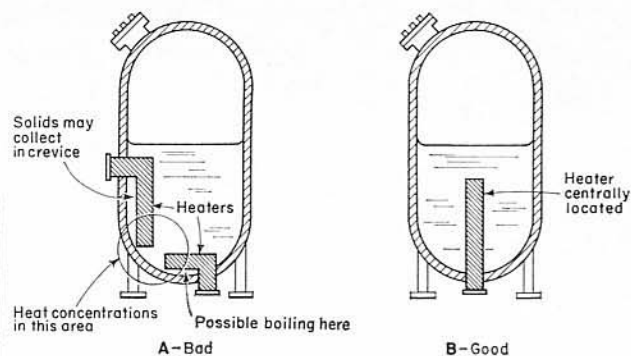
*For four more rules, turn page*

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"Designing to Prevent Corrosion," delivered by Mr. Coburn, Boston, 1961.

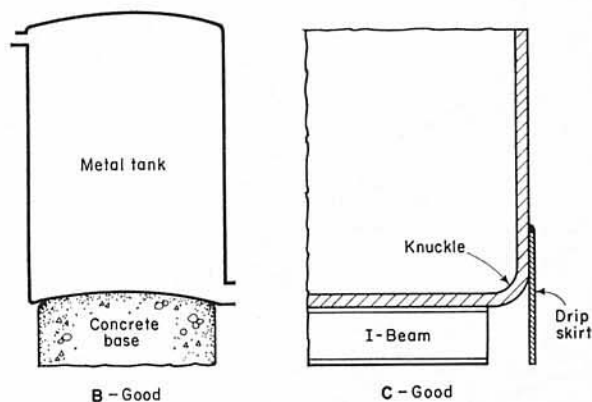
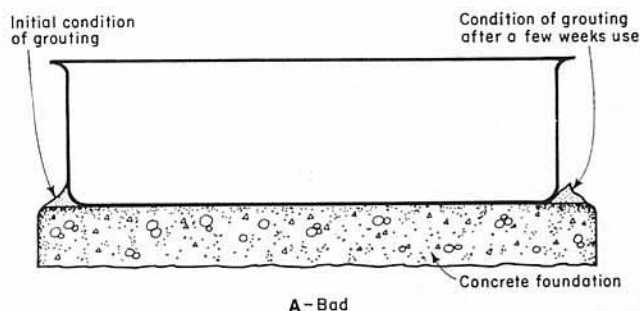
"Designing Corrosion Out of Process Equipment," delivered by Mr. Burton under the co-sponsorship of NACE and Ohio State University, Columbus, Ohio, 1960.





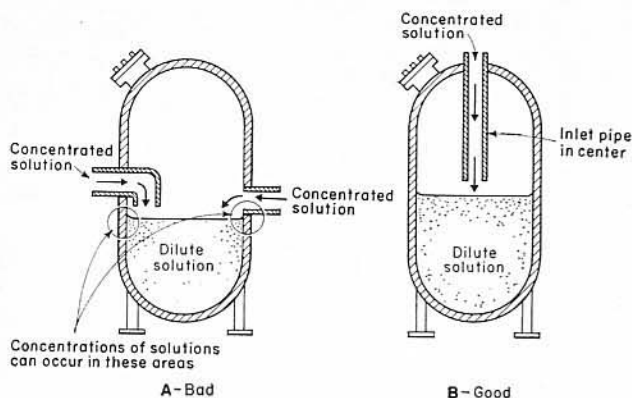
## 5. Avoid local hot spots.

Improper placement of heaters in tanks can cause local hot spots that accelerate corrosion (A). Corrosion can be minimized by locating the heater centrally, as shown in sketch B, and by avoiding ledges and crevices that might accumulate solids. If it is necessary to heat the tank externally then the heating units should be distributed over as large a surface area as possible. If the heat is applied to a small area it can cause internal corrosion.



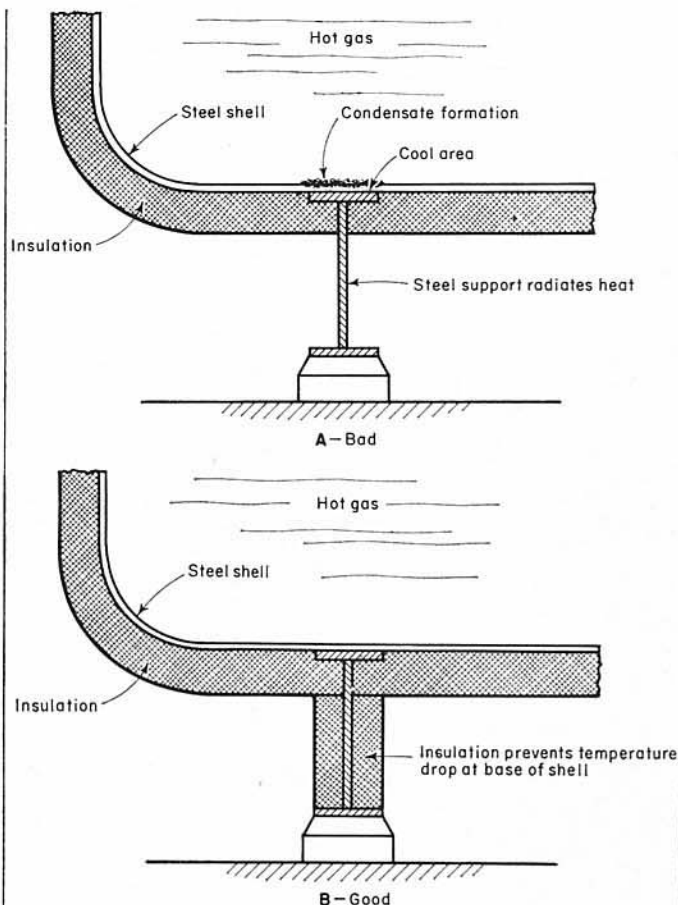
## 6. Keep corrosives away from structure.

Tank supports are often attacked by spilled corrosives and water which collect at the crevice formed where the tank floor or wall meets the support structure. This problem is especially liable to occur when the tank bottom is flat (A) and it may be avoided by using a curved construction on the bottom of the tank (B). Accumulation of corrosives can also be minimized to some extent by cutting the structure back (as shown by the recessed I-beam in sketch C), but the best solution is to weld a drip skirt to the wall to keep corrosives away from the structure.



## 7. Keep concentrates away from walls.

When a concentrated solution is introduced through the side of a tank it can cause corrosion by forming concentration cells along the tank wall (A) which may be accelerated by the heat evolved when the concentrated solution mixes with the main body of liquid. A better design is to have the concentrated solution enter at the center, as shown in sketch B. Also, the material for the tube should be carefully selected because when a cold solution is introduced through the tube into a hot tank there is danger that the temperature difference can produce a corrosion cell in which the cooler inlet tube may be attacked.



## 8. Prevent condensation.

It is possible for a metal to be unaffected by a gas, but corrode drastically in a liquid condensate of the gas. The accompanying sketch shows a typical example of the formation of a corrosive condensate. This is a section of an insulated metal vessel for a hot gas which rests on a steel support. It is possible for the support to act as a cooling fin at the contact area and lower the vessel wall temperature below the dew point of the gas so that it condenses into a severe corrosive (A). In this particular case condensation can be prevented by insulating the support right down to the ground level (B). Similarly, you can often prevent condensation on gas storage tank roofs by insulating the top so that the dew point is not reached when the tank cools after sunset. ■ ■

## Coatings to Prevent Corrosion

*A quick rundown of metallic and nonmetallic coatings useful in controlling corrosion*

by L. H. Seabright, Electrochemical Research Laboratory, Amphenol-Borg Electronics Corp.  
and Robert J. Fabian, Associate Editor, Materials in Design Engineering.

De Vilbiss Co.



*Sprayed organic coatings are one answer to corrosion.*

PROTECTIVE COATINGS are principally used to upgrade the corrosion resistance of ferrous metals (and some nonferrous metals) and avoid the necessity for using more costly alloys. Thus, they can both improve performance and reduce cost.

Protective coatings fall into two main categories: those that act as a physical barrier against the environment, and those that corrode preferentially and save the base metal from attack. Aside from zinc and cadmium coatings, which fall into the sacrificial category, most coatings are of the barrier type.

### **Metallic coatings**

Following is a summary of the most important types of metallic coatings you can use. These coatings can be applied by electrodeposition, flame spraying, hot

dipping, cladding and other techniques.

*Zinc and cadmium* coatings both are less noble than steel under most conditions. Thus, they can be used to cathodically or galvanically protect iron and steel. In the process the coatings are consumed preferentially and the base metal remains intact. A further advantage of the coatings is that they cause little difficulty from the standpoint of dissimilar metal contact when they adjoin aluminum or magnesium alloys.

*Nickel coatings*, unlike cadmium and zinc, are more noble than iron and steel and do not provide sacrificial protection. To protect the base metal they must provide an impervious, nonporous barrier. Electroplated coatings can be used in thicknesses up to 80 mils and, for added adhesion, they are usually applied over a very thin layer of copper. Nickel can also be applied by electroless plating and by cladding. The electroless coatings are particularly useful in areas that cannot be reached by electrodeposition and where a heavy duty coating is needed, as for tank cars handling corrosive liquids.

*Chromium electroplates* are especially useful where tarnish resistance combined with hardness, wear resistance and/or a low coefficient of friction is needed. They are most frequently used to preserve the appearance of nickel electroplates.

*Silver electroplates* can be useful in many corrosive applications. They are immune to attack by most dry and moist atmospheres and, although attacked by ozone, they resist the effects of oxygen at high temperatures. Most halogen gases will attack silver



(bromine is more corrosive than chlorine) but the initial film that is formed inhibits further attack. Moist ammonia is corrosive to the coatings but dry ammonia has no effect. Carbon monoxide, hydrogen, fluorine and nitrogen have no effect at ordinary temperatures. However, as is well known, the coatings will tarnish when subjected to most sulfur-bearing compounds.

*Precious metal coatings* such as gold, platinum and rhodium are mostly used to preserve good surface appearance by preventing discoloration and to prevent the formation of surface corrosion products which could interfere with the function of a part. Gold, for example, is widely used in electrical applications to preserve good conductivity and on costume jewelry and novelties. Platinum and rhodium coatings can be used for similar applications.

*Other metal coatings* such as aluminum, tin, lead, monel, stainless steel and various hard facings are frequently used to protect iron and steel against corrosion. Hot dipped aluminum coatings are especially useful where a combination of heat and corrosion is encountered and they have high resistance to corrosive condensates which form when a heated part cools down. Tin, of course, is widely known for its use on corrosion resistant food containers. Lead coatings are noted for their ability to form a film of environmental reaction products, such as lead sulfate, which are highly resistant to corrosion.

#### Nonmetallic coatings

High corrosion resistance can also be provided by organic coatings, rust preventives, ceramic and glass linings, and by porcelain enamels which are highly resistant to water, acids and chemicals.

Chemical conversion coatings may also be used alone or under an organic coating. Zinc, manganese and iron phosphate coatings, for example, are commonly used to retard corrosion and serve as a good

base for organic coatings. The tendency of zinc to form white corrosion products can be prevented by using a chromate conversion coating which, in the presence of water, hydrolyzes to form inhibitive ions. Special chemical and electrochemical treatments such as anodizing are also available for protecting aluminum and magnesium against corrosion.

Many specialized organic coatings have also been developed to resist atmospheric corrosion and direct chemical attack. Following is a summary of the major corrosion resistant coatings and their important properties:

*Bituminous* coatings have high resistance to water, outdoor atmospheres and underground exposure.

*Chlorinated polyether* coatings have high resistance to chemicals and are used to protect metal surfaces in chemical and food processing equipment.

*Cellulosic* coatings, such as cellulose acetate butyrate and heavy coatings applied by the fluidized bed, are noted for outstanding resistance to weathering.

*Epoxy* coatings have excellent resistance to many chemicals. Several classes of materials are available of which the epoxy-phenolics have the best chemical and solvent resistance. The recently developed 100% solids epoxy coatings, which can be applied in heavy thicknesses, are also noted for their resistance to water and chemicals.

*Fluorocarbon* coatings probably have higher chemical resistance than any other organic coating and most metallic coatings. Several types are available.

*Phenolic* coatings have excellent resistance to chemicals, solvents, oil and water.

*Polyamide* coatings, especially thermosetting blends, have high resistance to chemicals and solvents. Polyamide-phenolic coatings are noted for their excellent resistance to the passage of water.

*Polyester* coatings, especially 100% solids coatings, have excellent outdoor durability, good resistance to water and salt spray, and high resistance to many chemicals.

*Polyethylene* coatings and linings have very low water absorption, and excellent resistance to some chemicals, particularly strong oxidizing acids.

*Rubber* coatings and linings can be formulated with a wide range of properties such as high resistance to chemicals, water and weathering. Typical lining materials you can use are: natural rubber, neoprene, nitrile and butyl rubber and chlorosulfonated polyethylene. Polyvinyl chloride, while not an elastomer by definition, is also widely used as a lining material.

*Silicone* coatings have excellent resistance to moisture, salt spray and acids, particularly at high temperatures. Clear silicone coatings are available where high tarnish resistance is needed in decorative applications.

*Styrene-butadiene* primers have excellent rust-inhibiting and chemical resistance properties.

*Urethane* coatings are especially noted for their resistance to water and outdoor weathering, and can be formulated with a high degree of chemical resistance. ■ ■

#### Need More Data on Coatings?

M/DE has published several articles and manuals in recent years covering the whole field of protective coatings. For further data on the types and properties of corrosion resistant coatings, see:

"Bituminous Coatings," Aug '59, p 100.

"Chromate Conversion Coatings," Aug '60, p 116.

"Clear Silicone Coatings for Metals," Sept '62, p 11.

"Fluidized Bed: Heavy Coatings Applied In One Dip," Feb '61, p 91.

"Furane Coatings," Oct '59, p 100.

"Guide to Electroplated Coatings," Feb '62, p 95.

"New Protection for Magnesium," July '62, p 90.

"Organic Coatings for Metal Products," Mar '59, p 113.

"Picking a Coating to Resist Water Corrosion," May '61, p 149.

"Polyester Coatings for Metals," Oct '61, p 11.

"Properties of Porcelain Enamels," July '60, p 97.

"Tough, Chemical Resistant Urethane Coatings," June '59, p 80.

# Corrosion Resistance Data

on over 90 materials are given in this reference, especially prepared for M/DE readers.

by Robert J. Fabian, Associate Editor, Materials in Design Engineering

IN THE FOLLOWING PAGES you will find one of the most comprehensive guides to the corrosion resistance of materials ever published. Intended as an initial selection guide, it summarizes the behavior of more than 90 engineering materials in almost 70 of the most common atmospheres, waters, acids, solvents and

chemicals your product is likely to encounter in service. Almost all of the information is based on data especially prepared for M/DE by the major materials producers. Five groups of materials are covered in order: metals, plastics, elastomers, other nonmetals, and coatings and linings.

## Key to Abbreviations: Corrosive Media Covered in This Survey

<b>ATMOSPHERES (Atm)</b>	<b>SB</b> —Salt brine	<b>Chl sol</b> —Chlorinated solvents <sup>b</sup>	<b>Chl</b> —Chlorine	<b>Pot car</b> —Potassium carbonate
<b>HHA</b> —High humidity	<b>ACIDS</b>	<b>Est</b> —Esters <sup>c</sup>	<b>Det</b> —Detergents	<b>Pot dic</b> —Potassium dichromate
<b>IA</b> —Industrial	<b>Ac A</b> —Acetic acid	<b>Hyd</b> —Hydrocarbons <sup>d</sup>	<b>Eth ac</b> —Ethyl acetate	<b>Pot hyd</b> —Potassium hydroxide
<b>MA</b> —Marine	<b>Ars A</b> —Arsenic	<b>Ket</b> —Ketones <sup>e</sup>	<b>Eth chl</b> —Ethyl chloride	<b>Ros</b> —Rosins
<b>RA</b> —Rural	<b>Bor A</b> —Boric	<b>OTHER CHEMICALS</b>	<b>Glyc</b> —Glycerol	<b>Sod ac</b> —Sodium acetate
<b>SS</b> —Salt spray	<b>Chr A</b> —Chromic acid	<b>Acet</b> —Acetaldehyde	<b>Hyd per</b> —Hydrogen peroxide	<b>Sod bis</b> —Sodium bisulfate
<b>WATER</b>	<b>Cit A</b> —Citric acid	<b>Ac anh</b> —Acetic anhydride	<b>Hyd sul</b> —Hydrogen sulfide	<b>Sod chl</b> —Sodium chloride
<b>NFW</b> —Natural fresh	<b>Fat A</b> —Fatty	<b>Amm</b> —Ammonia	<b>Iso alc</b> —Isopropyl alcohol	<b>Sod hyd</b> —Sodium hydroxide
<b>DW</b> —Distilled	<b>For A</b> —Formic	<b>Amm nit</b> —Ammonium nitrate	<b>Mag car</b> —Magnesium carbonate	<b>Sod nit</b> —Sodium nitrate
<b>HPW</b> —Highly purified	<b>HCl</b> —Hydrochloric	<b>Anhyd amm</b> —Anhydrous ammonia	<b>Mag chl</b> —Magnesium chloride	<b>Sul diox</b> —Sulfur dioxide
<b>BFW</b> —Boiler feed	<b>HF</b> —Hydrofluoric	<b>But alc</b> —Butyl alcohol, tertiary	<b>Mag sul</b> —Magnesium sulfate	<b>T oil</b> —Tall oil
<b>WW</b> —Well water	<b>Nit A</b> —Nitric	<b>Cal chl</b> —Calcium chloride	<b>Mag nit</b> —Magnesium nitrate	<b>Zn chl</b> —Zn chloride
<b>RW</b> —River water	<b>Ph A</b> —Phosphoric	<b>Cal hyd</b> —Calcium hydroxide	<b>Mal anh</b> —Maleic anhydride	<b>Zn sul</b> —Zinc sulfate
<b>BW</b> —Brackish water	<b>Sul A</b> —Sulfuric		<b>Phth anh</b> —Phthalate anhydride	
<b>SW</b> —Sea water	<b>SOLVENTS (Solv)</b>			
	<b>Alc</b> —Alcohols <sup>a</sup>			

<sup>a</sup> E.g., butanol, ethyl alcohol and methanol, unless otherwise specified.

<sup>b</sup> E.g., carbon tetrachloride (CCl<sub>4</sub>), perchloroethylene and tetrachloroethylene, unless otherwise specified.

<sup>c</sup> E.g., butyl acetate, unless otherwise specified. <sup>d</sup> E.g., benzene, toluene and xylene, unless otherwise specified.

<sup>e</sup> E.g., acetone, methyl ethyl ketone (MEK) and methyl isobutyl ketone (MIBK), unless otherwise specified.

# METALS

## ALUMINUM

Atm—high res to weathering; attack is self-stopping and, after 1-2 yr, max penet is <0.2 mpy in adverse atm (e.g., MA), and <0.1 mpy in normal atm. Some minor diff in corr rates between alloys. Alclad alloys have high res to weathering, resist perforation.

NFW—negl att in 4.5-8.5 pH range. DW—exc. HPW—exc. BFW—exc; steam containing car diox has no eff to 480 F. Other waters—fresh and salt water in 4.5-8.5 pH range negl att even at boil temp, but some cause pitting because contain heavy metal salts. Alclads prevent perforation under these cond, are recom with fresh or salt water.

Ac A—exc; <1 mpy at RT. Compatible with glacial acid at bp if trace of moist is pres. Ars A—negl att. Bor A—negl att. Chr A—mod att, depend on conc and temp. Cit A—exc. Fat A—exc at RT; completely anhyd acids are sev corr, but att can be prev by presence of trace of water. For A—no att by uncontaminated sol at RT. HCl—att, but att in dil sol is reduced by inhibitors. HF—att. Nit A—negl att by conc >82%, incl red fuming. Ph A—att. Sul A—OK with very dil sol at RT; coating reqd with 15% during continuous contact. Alc—butyl: res at RT and also at bp if trace of moist is pres; methyl: res at RT; ethyl: res to bp. Chl sol—CCl<sub>4</sub>: res at RT and severe att at high temp can be prev by inhibitors; perchl: res. Est—res but acet at RT. Hyd—benz: res; tol: res; xyl: res. Ket—acet: negl att even at bp; MEK: res.

Acet—res. Ac Anh—res to at least 120 F; minor att at bp but is usable. Amm—res to gas; low corr rate with moist amm and all conc to 120 F. Res to amm-steam mix if car diox is pres in ratio of >2.5 parts. Amm nit—res. Cal chl—sl att by sol at RT. OK with Cr-inhib Cal chl brines; att by molten Cal chl. Cal hyd—some att but can be inhib with silicates. Chl—no att by dry to 260 F; pres of water causes sev corr. Eth ac—res; minor att if mineral acid or heavy metal contam is pres. Hyd per—exc. Mag car—exc. Mag chl—<1% sol stains at RT; dil sol >1% (by wt) cause mod pitting. Mag sul—exc. Mal anh—res to molten. Phth anh—res to molten. Pot car—att by some sol; dil sol may be inhib by silicates or colloidal matter. Pot dic—exc. Pot hyd—att by sol. Ros—exc. Sod ac—negl eff at RT. Sod bis—sl eff at RT. Sod chl—exc. Sod hyd—att by sol. Sod nit—negl eff by sol. Sul diox—no eff when dry but att in presence of water. T oil—res. Urea—negl att. Zn chl—mild pitting at RT. Zn sul—some att by sol.

## CAST IRONS/GRAY IRON\*

HHA—sl corr at low and med RH, but increases at 70+% RH. IA—5 mpy max. MA—good res; between IA and RA. RA—exc; 1 mpy max. SS—normally good. NFW—res; prot scale of calc carb forms. DW—exc, but less than NFW. HPW—exc, but less than NFW. WW—exc. RW—exc if not polluted. BW—good; corr higher in acid than alk cond. SW—rel low; 5-10 mpy. SB—good. Ac A—good in conc mix, less in dil. Ars A—good. Chr A—good. Cit A—poor in dil aerated sol. Fat A—good; dil sol may accel att. HCl—poor. Nit A—fair in conc; poor in intermed and dil sol. Ph A—poor, unless acid cont inhib impur such as arsenic. Sul A—good above

\* For ductile iron, corrosion resistance is similar to that of gray iron, the only difference being the effect of the graphite structure. For example, the flake graphite structure of gray iron is detrimental in resisting attack in oxidizing solutions, but in electrolytic corrosion the graphite is unattacked and can aid in holding the formed scale together and help resist further attack. In contrast, the spherulitic type of graphite present in ductile iron has little effect on corrosion resistance. A fine pearlitic structure provides the most corrosion resistance in both gray and ductile irons.

64% (by wt); poor below 60%.

Alc—good. Chl sol—good in CCl<sub>4</sub>. Hyd—good. Ket—good in acetone. Acet—good. Amm—good. Amm nit—good. Chl—poor. Eth ac—good. Eth chl—poor. Glyc—poor. Hyd sul—poor. Mag chl—poor. Mag sul—good. Pot car—good. Pot hyd—good. Sod bis—poor. Sod chl—good. Sod hyd—good. Sod nit—good. Zn chl—poor.

## CAST IRONS/HIGH NICKEL\*

Atm—res. Waters—res. Ac A—5%: 0.04 ipy at RT; 50%: 0.08 ipy at RT; conc: 0.02 at RT. Ars A (50%)—0.37 ipy at 80-120 F for 21 days. Cit A (5%)—0.09 ipy at RT. Fat A—res. HCl (5%)—0.01 ipy at RT; conc: 0.37 at RT. HF (10%)—0.001 ipy at RT for 1 mo. Nit A—5%: 0.83 ipy at RT; 10%: 2.36 ipy at RT; conc: 0.75 ipy at RT. Ph A (25%)—0.39-0.76 ipy at 190 F for 20-24 hr. Sul A—5%: 0.02 ipy at RT for 20 hr; 0.81 ipy at 195 F for 20 hr; 80%: 0.02 ipy at RT for 20 hr; 0.5 ipy at 195 F for 20 hr. Solv—res.

Amm (conc sol)—no att. Cal chl (5%)—0.005 ipy at RT. Cal hyd (sat sol)—sl wt gain after 20 hr at RT. Hyd sul (moist)—0.01 ipy after 7 days at 200 F. Pot hyd (92%)—0.01 ipy after 36 hr at 515 F. Sod chl (sat)—high res. Sod hyd (50%)—high res. Zn chl (30-70%)—0.08 ipy after 30 days boil.

\* Ni-Resist.

## CAST IRONS/HIGH SILICON\*

Atm—res. Waters—res to all to bp; Cr addition recom where chlorides are pres, as in BW, SW and SB. Ac A, Ars A, Bor A, Chr A, Cit A, Fat A, For A—res all c & t. HCl—Cr addition pref. Res dil conc to 175 F; intermed conc to 150 F; high conc to 125 F. Formation of fer chl inhib corr. HF—not res. Nit A—res all c & t, except weak at high temp. Ph A—res all c & t; pres of fluoride-containing cmpds accel corr. Sul A—res all c & t to bp. Alc, Hyd, Ket—res all c & t.

Acet, Ac anh, Amm, Amm nit, Anhyd amm, But alc—res all c & t. Cal chl—res all c & t; Cr addition pref when HCl or other constituents pres. Cal hyd—res dil sol at mod temp; not rec for conc sol or high temp. Chl—res to dry; Cr-cont alloy satis for wet. Det, Eth ac, Glycols, Glyc, Eth chl—res all c & t. Hyd per—low corr rate; depends on spec appl. Hyd sul—lim use. Iso alc—res all c & t. Mag car—res all c & t. Mag chl—res all c & t; Cr cont alloy pref when HCl or other constituents pres. Mag sul, Mag nit—res all c & t. Mal anh—res. Phth anh—res. Pot car—res all c & t. Pot dic—res all c & t. Pot hyd—res dil sol to mod temp; not rec for conc sol or high temp. Ros—res. Sod ac, Sod bis—res all c & t. Sod chl—res all c & t. Cr cont alloy pref when HCl or other const pres. Sod hyd—res dil sol at mod temp; not rec for conc sol or high temp. Sod nit—res all c & t. Sul diox—lim use. T oil—res. Urea—res all c & t. Zn chl—res all c & t; Cr-cont alloy pref when HCl or other const pres. Zn sul—res all c & t.

\* Duriron. "All c & t" means all conc and temp.

## CAST IRONS/MALLEABLE

Atm—exc. Waters—v good. Other chem—resistance prop of standard (ferritic) malleable generally same as those of unalloyed cast iron. Corr res of ferritic and pearlitic types can be improved by alloying with Cu.

## COBALT-BASE SUPERALLOY\*

Atm, Waters—NNR. Ac A—<0.001 ipy for all conc and temp. Cit A—NNR. For A—<0.02 ipy for all conc and temp. HCl—<0.03 ipy at RT. HFl A—>0.03 ipy at RT. HF—<0.02 ipy to 45% at RT. Nit A—no penet at RT; <0.02 ipy at 150 F; <0.02 ipy to 50% boil. Ph A—<0.004

\* Haynes 25. NNR means exc res but alloy is not normally reqd for environment.



ipy to 50% boil. Sul A—no penet at RT; <0.03 ipy to 60% at 150 F; useful to 5% boiling. Solv—NNR. Amm, Anhyd amm, But alc—NNR. Chl—<0.0001 ipy in wet or dry gas. Det, Eth ac, Glyc, Glycols, Hyd per, Iso alc, Ros—NNR. Sod hyd—no penet with 57% to boil, or with 50% to 150 F.

### COLUMBIUM

Atm, Waters—no att. HCl—dil (hot or cold): no att; conc (210 F): 0.0005-0.005 ipy (embrittles). HF—att. Nit A—no att. Ph A (85%)—<0.0005 ipy at 70 F (embrittles). Sul A—dil: <0.0005 ipy at 210 F; conc: >0.01 ipy at 210 F (embrittles). Solv, Anhyd amm, Cal chl—no att. Cal chl—unsatis. Chl—cold: no att; hot (above 390 F): att. Hyd per (30%)—0.001 ipy at 70 F; no embrittlement, oxide film forms. Pot hyd (5%)—att and embrittled at 210 F. Sod hyd (conc)—att (>0.01 ipy) at 70 to 210 F.

### COPPER\*

IA, MA, RA—v good. NFW—v good. SW—good. SB—good. Ac A—good. Bor A—v good. Chr A—unsatis. Cit A—v good. For A—v good. HCl—fair. HF—fair. Nit A—unsatis. Ph A—good. Sul A—good. Alc—v good. Chl sol—CCl<sub>4</sub> dry: v good; moist: good. Trichl dry: v good; moist: good. Hyd (pure)—v good. Ket (acet)—v good.

Ac anh—good. Amm—dry: v good; moist: unsatis. Amm nit—unsatis. But alc—v good. Cal chl—good. Cal hyd—v good. Chl—dry: v good; moist: fair. Eth ac—v good. Eth chl—good. Hyd sul—dry: v good; moist: unsatis. Mag chl—good. Mag sul—v good. Pot car—v good. Pot hyd—good. Ros—v good. Sod bis—good. Sod chl—good. Sod hyd—good. Sod nit—good. Sul diox—dry: v good; moist: good. Zn chl—fair. Zn sul—good.

\* Electrolytic tough pitch.

### COPPER ALLOYS/ALUMINUM BRONZE\*

IA, MA, RA—v good. NFW, SW—v good. SB—good. Ac A—good. Bor A—v good. HCl—fair. HF—fair. Nit A—unsatis. Ph A—good. Sul A—good. Alc—v good. Chl sol—CCl<sub>4</sub> dry: v good; moist: good. Trichl dry: v good; moist: good. Hyd (pure)—v good. Ket (acet)—v good.

Ac anh—good. Amm—dry: v good; moist: unsatis. Amm nit—unsatis. But alc—v good. Cal chl—good. Cal hyd—v good. Chl—dry: v good; moist: fair. Eth ac—v good. Eth chl—good. Hyd sul—dry: v good; moist: unsatis. Mag chl—good. Mag sul—v good. Pot car—v good. Pot hyd—good. Ros—v good. Sod bis—good. Sod chl—good. Sod hyd—good. Sod nit—v good. Sul diox—dry: v good; moist: good. Zn chl—fair. Zn sul—good.

\* 95% Cu.

### COPPER ALLOYS/BERYLLIUM COPPER

IA-MA, NFW—good. SW—good at RT, limited at 140 F. SB—good. Ac A—good in up to 1% at RT, limited in 2.5-10% at RT. Bor A—good. Chr A—poor. Cit A—good. HCl—limited in 0.5% at RT, poor in over 5% at RT and in 10% at 140 F. Nit A—poor. Ph A—limited in 3-95% at RT to 212 F. Sul A—limited in <10% at RT, poor in 10% at 140 F. Alc, Chl solv (CCl<sub>4</sub>), Hyd, Ket—good. Cal chl—good. Chl—dry: good; moist: poor at high temp, limited at RT. Hyd sul—dry: good; moist: poor. Sod chl—good. Sod hyd—limited in 1-10% at RT. Sul diox—dry: good; moist: limited.

### COPPER ALLOYS/COPPER-SILICON\*

IA, MA, RA—v good. NFW—v good. SW—good. SB—good. Ac A—good. Bor A—v good. Chr A—unsatis. Cit A—v good. For A—v good. HCl—fair. HF—fair. Nit A—unsatis. Ph A—good. Sul A—good. Alc—v good. Chl sol—CCl<sub>4</sub> dry: v good; moist: good. Trichl dry: v good; moist: good. Hyd (pure)—v good. Ket (acet)—v good.

\* 95.8% Cu.

Ac anh—good. Amm—dry: v good; moist: unsatis. Amm nit—unsatis. But alc—v good. Cal chl—good. Cal hyd—v good. Chl—dry: v good; moist: fair. Eth ac—v good. Eth chl—good. Hyd sul—dry: v good; moist: unsatis. Mag chl—good. Mag sul—v good. Pot car—v good. Pot hyd—good. Ros—v good. Sod bis—good. Sod chl—good. Sod hyd—good. Sod nit—good. Sul diox—dry: v good; moist: good. Zn chl—fair. Zn sul—good.

### COPPER ALLOYS/CUPRO-NICKEL\*

IA, MA, RA—v good. NFW, SW, SB—v good. Ac A—good. Bor A—v good. Chr A—unsatis. Cit A—v good. For A—v good. HCl—fair. HF—good. Nit A—unsatis. Ph A—good. Sul A—good. Alc—v good. Chl sol—CCl<sub>4</sub> dry: v good; moist: v good. Trichl dry: v good; moist: v good. Hyd (pure)—v good. Ket (acet)—v good.

Ac anh—good. Amm—dry: v good; moist: fair. Amm nit—fair. But alc—v good. Cal chl—v good. Cal hyd—v good. Chl—dry: v good; moist: good. Eth ac—v good. Eth chl—good. Hyd sul—dry: v good; moist: fair. Mag chl—good. Mag sul—v good. Pot car—v good. Pot hyd—v good. Ros—v good. Sod bis—v good. Sod chl—v good. Sod hyd—v good. Sod nit—v good. Sul diox—dry: v good; moist: fair. Zn chl—fair. Zn sul—good.

\* 30% Ni.

### COPPER ALLOYS/MUNTZ METAL\*

IA—good. MA—good. RA—v good. NFW—fair. SW—fair. SB—not suit. Ac A—unsatis. Bor A—good. Chr A—unsatis. Cit A—fair. For A—fair. HCl—unsatis. HF—unsatis. Nit A—unsatis. Ph A—unsatis. Sul A—unsatis. Alc—v good. Chl sol—CCl<sub>4</sub> dry: good; moist: fair. Hyd (pure)—v good. Ket (acet)—v good.

Ac anh—unsatis. Amm—dry: v good; moist: unsatis. Amm nit—unsatis. But alc—v good. Cal chl—unsatis. Cal hyd—good. Chl—dry: v good; moist: unsatis. Eth ac—good. Eth chl—fair. Hyd sul—dry: v good; moist: fair. Mag chl—unsatis. Mag sul—fair. Pot car—good. Pot hyd—fair. Ros—v good. Sod bis—unsatis. Sod chl—unsatis. Sod hyd—fair. Sod nit—fair. Sul diox—dry: v good; moist: unsatis. Zn chl—fair. Zn sul—good.

\* 60 Cu-40% Zn.

### COPPER ALLOYS/NICKEL SILVER\*

IA—v good. MA—good. RA—v good. NFW—v good. SW—v good. SB—v good. Ac A—good. Bor A—v good. Chr A—unsatis. Cit A—v good. For A—v good. HCl—fair. HF—fair. Nit A—unsatis. Ph A—good. Sul A—good. Alc—v good. Chl sol—CCl<sub>4</sub> dry: v good; moist: good. Trichl dry: v good; moist: good. Hyd (pure)—v good. Ket (acet)—v good.

Ac anh—good. Amm—dry: v good; moist: unsatis. Amm nit—unsatis. But alc—v good. Cal chl—v good. Cal hyd—v good. Chl—dry: v good; moist: fair. Eth ac—v good. Eth chl—good. Hyd sul—dry: v good; moist: fair. Mag chl—good. Mag sul—v good. Pot car—v good. Pot hyd—v good. Ros—v good. Sod bis—v good. Sod chl—v good. Sod hyd—v good. Sod nit—v good. Sul diox—dry: v good; moist: fair. Zn chl—fair. Zn sul—good.

\* 18% Ni.

### COPPER ALLOYS/PHOSPHOR BRONZE\*

IA, MA, RA—v good. NFW—v good. SW—good. SB—good. Ac A—good. Bor A—v good. Chr A—unsatis. Cit A—v good. For A—v good. HCl—fair. HF—fair. Nit A—unsatis. Ph A—good. Sul A—good. Alc—v good. Chl sol—CCl<sub>4</sub> dry: v good; moist: good. Trichl dry: v good; moist: good. Hyd (pure)—v good. Ket (acet)—v good.

Ac anh—good. Amm—dry: v good; moist: unsatis. Amm nit—unsatis. But alc—exc. Cal chl—good. Cal hyd—v good. Chl—dry: v good; moist: fair. Eth ac—v good. Eth chl—good. Hyd sul—dry: v good; moist: unsatis. Mag

\* 94.5% Cu.

## Key to Abbreviations

ATMOSPHERES (Atm)	ACIDS	Est—Esters	Phth anh—Phthalate anhydride	Pot car—Potassium carbonate
HHA—High humidity	Ac A—Acetic acid	Hyd—Hydrocarbons	Eth ac—Ethyl acetate	Pot dic—Potassium dichromate
IA—Industrial	Ars A—Arsenic	Ket—Ketones	Eth chl—Ethyl chloride	Pot hyd—Potassium hydroxide
MA—Marine	Bor A—Boric	OTHER CHEMICALS	Glyc—Glycerol	Ros—Rosins
RA—Rural	Chr A—Chromic acid	Acet—Acetaldehyde	Hyd per—Hydrogen peroxide	Sod ac—Sodium acetate
SS—Salt spray	Cit A—Citric acid	Ac anh—Acetic anhydride	Hyd sul—Hydrogen sulfide	Sod bis—Sodium bisulfate
WATER	Fat A—Fatty	Amm—Ammonia	Iso alc—Isopropyl alcohol	Sod chl—Sodium chloride
NFW—Natural fresh	For A—Formic	Amm nit—Ammonium nitrate	Mag car—Magnesium carbonate	Sod hyd—Sodium hydroxide
DW—Distilled	HCl—Hydrochloric	Anhyd amm—Anhydrous ammonia	Mag chl—Magnesium chloride	Sod nit—Sodium nitrate
HPW—Highly purified	HF—Hydrofluoric	But alc—Butyl alcohol, tertiary	Mag sul—Magnesium sulfate	Sul diox—Sulfur dioxide
BFW—Boiler feed	Nit A—Nitric	Cal chl—Calcium chloride	Mag nit—Magnesium nitrate	T oil—Tall oil
WW—Well water	Ph A—Phosphoric	Cal hyd—Calcium hydroxide	Mal anh—Maleic anhydride	Zn chl—Zinc chloride
RW—River water	Sul A—Sulfuric	SOLVENTS (Solv)		Zn sul—Zinc sulfate
BW—Brackish water	Alc—Alcohols	Alc—Alcohols		
SW—Sea water	Chl sol—Chlorinated solvents	Chl—Chlorine		
SB—Salt brine		Det—Detergents		

chl—good. Mag sul—v good. Pot car—v good. Pot hyd—good. Ros—v good. Sod bis—good. Sod chl—good. Sod hyd—good. Sod nit—good. Sul diox—dry: v good; moist: good. Zn chl—fair. Zn sul—good.

### COPPER ALLOYS/RED BRASS\*

IA, MA, RA—v good. NFW—v good. SW—good. SB—good. Ac A—good. Bor A—v good. Chr A—v good. Cit A—v good. For A—v good. HCl—fair. HF—fair. Nit A—unsatis. Ph A—good. Sul A—good. Alc—v good. Chl sol—CCl<sub>4</sub> dry: v good; moist: good. Trichl dry: v good; moist: good. Hyd (pure)—v good. Ket (acet)—v good. Ac anh—good. Amm—dry: v good; moist: unsatis. Amm nit—unsatis. But alc—v good. Cal chl—good. Cal hyd—v good. Chl—dry: v good; moist: fair. Eth ac—v good. Eth chl—good. Hyd sul—dry: v good; moist: unsatis. Mag chl—good. Mag sul—v good. Pot car—v good. Pot hyd—good. Ros—v good. Sod bis—good. Sod chl—good. Sod hyd—good. Sod nit—good. Sul diox—dry: v good; moist: good. Zn chl—fair. Zn sul—good.

\* 85 Cu-15% Zn.

### COPPER ALLOYS/TOBIN BRONZE\*

IA—good. MA—good. RA—v good. NFW—fair. SW—good. SB—fair. Ac A—unsatis. For A—good. Chr A—unsatis. Cit A—fair. For A—fair. HCl—unsatis. HF—unsatis. Nit A—unsatis. Ph A—unsatis. Sul A—unsatis. Alc—v good. Chl sol—CCl<sub>4</sub> dry: v good; moist: unsatis. Trichl dry: v good; moist: fair. Hyd (pure)—v good. Ket (acet)—v good.

Ac anh—unsatis. Amm—dry: v good; moist: unsatis. Amm nit—unsatis. But alc—v good. Cal chl—fair. Cal hyd—good. Chl—dry: v good; moist: unsatis. Eth ac—good. Eth chl—fair. Hyd sul—dry: v good; moist: fair. Mag chl—unsatis. Mag sul—fair. Pot car—good. Pot hyd—fair. Ros—v good. Sod bis—fair. Sod chl—fair. Sod hyd—fair. Sod nit—fair. Sul diox—dry: v good; moist: unsatis. Zn chl—unsatis. Zn sul—unsatis.

\* 60 Cu-39.25 Zn-0.75% Sn.

### IRONS/INGOT\*

Atm—rusts. Waters—can be used in most waters; behaves like carbon steel. Acids—not normally used with acids; known to be OK with conc sul. Solv—not norm used. Other chem—not norm used.

\* Other irons are covered under Cast Irons.

### IRONS/WROUGHT

HHA—mild corr; prot coating recom. IA—satis except where excessive acid vap pres. MA—good. RA—exc;

superficial corr only. SS—good. NFW—good, except with soft or where signif quant of carb diox or hyd sul gases are pres. DW—good where diss oxygen is not excess and iron contam is not crit. HPW—diss oxy will cause corr. BFW—good if diss oxy is removed. WW—good except where excess quant of hyd sul and carb diox are pres. RW—good, except where pH is unusually low due to indust wastes. BW—good, except where acid condn is present. SW—good; corr rates higher in tropical temp. SB—v good. Solv—little if any eff. Ac A, Cit A, For A—satis only at low conc. HCl, HF, Nit A, Ph A—unsatis. Sul A—satis >85%; performance also depends on temp.

Amm—exc. Amm nit—satis. Cal chl—exc at higher conc and in inhib sol; corr affected by certain impurities. Cal hyd—good. Chl—satis only in absence of moist. Det—satis. Eth ac—same as Chl. Eth chl—satis only in absence of mois and acidic impurities. Glyc—good. Hyd per—unsatis. Hyd sul—satis to dry only. Mag car—good. Mag chl, Mag sul, Mag nit—fair. Pot car—good. Pot dic—satis only at certain conc and under controlled pH. Pot hyd—satis. Sod ac—good in neutral and alkaline sol. Sod bis—unsatis. Sod chl—generally good; corr dep on conc and temp. Sod hyd, Sod nit—good. Sul diox—good dry, fair moist. Zn sul—unsatis.

### LEAD

Atm, Waters—res all because of formation of protective oxide film. Ac A—mod att, greatly accel at high veloc and temp. Ars A—mod att; acid forms lead salts. Chr A—mod att. Cit A—fair res. Fat A—fair res in absence of aeration or air-liquid interface. For A—some as Ac A. HCl—not res, but has been used with >30% conc. HF—fair res to 60% cold. Nit A—not res, but tolerable res with 50-70% acid at RT. Ph A—fair res to 80%, under 200 F. Sul A—res to 96% at RT, and 85% to 430 F. Alc—res. Chl sol—corr varies from sl to sev depend on breakdown to HCl and pres of org acids. Est—good to exc provided low mol wt organic acids absent; sl tendency to catalyze gum formation with some hyd. Hyd, Ket—see Est.

Acet—see Ac A. Amm—res to liq and dry gas. Amm nit—good res. Anhyd amm—good res. But alc—good res. Cal chl—not res with fused salt; otherwise fairly res. Cal hyd—reduces corr when added to soft water, but corrodes lead in "green" cement in presence of moist and oxy. Chl—res at mod conc; fair at 100%. Det—good except where free alkali pres. Eth ac—good. Glyc, Glycols—practically res. Hyd per—catalyzes decomp of peroxide into water. Hyd sul—res to dry gas but corr in wet. Iso alc—good res. Mag car—good res. Mag chl—mod corr. Mag sul—good res. Pot car—res to dil sol. Pot dic—good res. Pot



hyd—corr greatly accel by diss oxy. Ros—good res. Sod ac—fair res except in acid sol. Sod bis—res. Sod chl—good res in dil sol at ord temp. Sod hyd—good res to 30% at 75 F, 10% at 195 F. Sod nit—not res. Sul diox—good res. T oil—good res. Urea—satis to 375 F. Zn chl—satis. Zn sul—res, partic in acid sol.

#### MAGNESIUM

HHA, IA—v good; tarnishes. MA—prot reqd. RA—v good; tarnishes. SS—exc if prot; poor unprot. NFW—v good. DW—v good below bp. WW—poor to v good, depend on comp. RW—poor to v good. BW—not recom, except as anode in cath prot. SW, SB—same as BW. Ac A—not rec. Bor A—att. Chr A—not att. Cit A—not rec. Fat A—not rec. For A—not rec. HCl—not rec. HF—<5%: slight att; >5% no att. Nit A—not rec. Ph A—not rec. Sul A—not rec. Alc—no att, except for meth. Chl sol—exc, except not rec for CCl<sub>4</sub> fire ext. Est—exc. Hyd—exc. Ket—exc.

Acet—not rec. Ac anh—not rec. Amm nit—good; nitrates inhib corr. Anhyd amm—v good. But alc—exc. Cal chl—not rec. Cal hyd—no att. Chl—not recom. Det—v good. Eth ac—exc. Eth chl—good w/o water, otherwise hydrolysis; causes att. Glyc—exc. Glycols—exc. Hyd per—not rec. Hyd sul—v good; tarnishes. Iso alc—exc. Mag car—exc. Mag chl—not recom. Mag sul—v good. Mag nit—v good. Mal anh—poor. Phth anh—poor. Pot car—v good. Pot dic—exc. Pot hyd—exc. Ros—exc. Sod ac—mild att. Sod bis—poor. Sod chl—poor. Sod hyd—exc. Sod nit—v good. Sul diox—dry; v good; wet: att. T oil—exc. Urea—v good. Zn chl, Zn sul—not recom; will displace Zn.

#### MOLYBDENUM

IA—little reac. MA—little reac; 10-yr test gave 0.5 mdd 80 ft from ocean, 0.3-1.1 mdd 800 ft from ocean. RA—res. SW—wt loss of 21.7 mdd after 34 day high-speed galvanic test. Ac A—exc to 10% at RT, good to 10-80% at RT. Chr A—good in hot. For A—exc to 10% at RT, good to 80% at RT. HCl—good to v good if no oxid agents pres; 0.9 mpy in 20% boiling. HF—good to v good if no oxid agents pres; 2.3 mpy in 49% at 212 F. Nit A—rapid att, except in conc acid at RT when passiv occurs. Ph A—good to v good; 1.5 mpy in 50% boil. Sul A—v good to exc up to 60% and at least 400 F.

Alc—res. Chl sol—res. Hyd—good to 2000 F; some carburization at longer periods, higher temp. Amm—exc to 2000 F; superfic nitride case may form at longer periods, will form at higher temp. Chl—dry: good to 450 F, poorer at higher temp; wet: poor. Det—res. Hyd per—may accel decomp of perox. Hyd sul—good to 1650 F in reduc atm; at higher temp, thin adh sulfide film forms in reduc atm. Pot car—good in 10 and 50% sol at 212 F; poor in fused salt. Sod hyd—good in 10 and 50% sol at 212 F; poor in fused salt. Sul diox—good to 1200 F; fair with oxid at higher temp.

#### NICKEL

Atm—high res; rate of att extremely slow; becomes dull, tends to acq v thin corr prod of basic sulfate. NFW—high res; <0.0001 ipy. DW—high res; 0.000001 ipy. Ac A—corr by air-sat acid at high temp, but corr consid less in air-free acid. Fat A (stearic, oleic)—res. For A—see Ac A. HCl—satis within proper limits of conc, temp, aeration. Nit A—unsatis except below 0.5% at RT. Ph A—lim usefulness; unsatis in hot conc. Sul A—fair corr res; <0.05 in <80% cold; max corr occurs at 5% and decr uniformly to 80%; >80% perf is erratic. Solv—res. Amm (aq)—res. Anhyd amm—no att. Cal chl—res. Chl—dry: no att; wet: att. Sod chl—res; <0.005 ipy. Sul diox—dry: res; wet: att. Zn chl—res; 0.02 ipy in boil conc sol.

#### NICKEL ALLOYS/NICKEL-CHROMIUM

Atm—exc to all; may tarnish in sul atm. Waters—exc. Ac A—fair. For A—fair. HCl—mod corr in dil; not res

\* Inconel.

with hot or conc. Nit A—<0.005 ipy at conc over 20%, but corr may be high (>0.2 ipy) in dil (e.g., 5%). Sul A—fair. Chl—dry: no att; wet: att. Mag chl—exc res in strong hot sol (<0.001 ipy).

#### NICKEL ALLOYS/NICKEL-COPPER\*

Atm—exc to all; gradually discolor in IA. Waters—exc. Ac A—exc, <0.004 ipy. Fat A—res to stearic and oleic at high temp. HCl—good res to dil; usually res with air-free conc <20% at RT; heat incr corr rate. HF—exc. Nit A—lim use; usually below 1% and 80 F. Ph A (85%)—0.0015 ipy at 205 F. Sul A—OK for boil sol to 20%; low corr rates (e.g., 0.005 ipy) below 80%; avoid hot air-sat sol. Solv—exc.

Amm—dry: res; wet: not res. Anhyd amm—res. Cal chl—high res. Chl—dry: res to 800 F; wet: not res. Eth ac—res. Sul diox—not res wet. Sod chl—high res. Zn chl—res. Zn sul—res.

\* Monel.

#### NICKEL ALLOYS/NICKEL-IRON CHROMIUM\*

Ac A—high res incl boil conc. HCl—not res except to v dil. Nit A—res att all conc and temp up to boil 65%. Ph A—res to pure at all conc and temp up to boil 85%. Sul A—res up to: 40% boil; 60% to 175 F; all conc RT to 150 F. Amm—res under most cond. Pot hyd—res. Sul diox—res to wet.

\* Ni-o-nel.

#### NICKEL ALLOYS/HASTELLOY B\*

Atm—NNR; <0.02 ipy in SS. Waters—NNR; <0.002 ipy in sea water. Ac A—<0.02 ipy for all conc and temp. Bor A—<0.002 ipy for all conc and temp. Chr A—Hastelloy C norm preferred. Cit A (10%)—<0.02 ipy to 180 F. Fat A—<0.002 ipy to 600 F. For A—<0.02 ipy for all conc and temp. HCl—max rate is 0.024 ipy for 20% boiling. HF—<0.005 ipy up to 45% at RT. Nit A—not rec. Ph A—max rate of 0.028 ipy in conc boiling. Sul A—<0.015 ipy in 60% boil; above 60% max use temp is 300 F. Solv—NNR.

Ac anh—0.02 ipy at all conc and temp. Amm—<0.02 ipy to 600 F. Anhyd amm—NNR. But alc—NNR. Cal chl—<0.02 ipy at all conc and temp. Chl—not recom. Det, Eth ac—NNR. Eth chl—<0.02 ipy for all conc and temp. Glyc, Glycols—NNR. Hyd per—NNR. Hyd sul—Hastelloy C preferred. Iso alc—NNR. Mag car—<0.02 ipy to 10% boiling. Mag chl—<0.002 ipy to all conc and temp. Mag sul—<0.002 ipy to 50% boil. Mal anh—<0.002 ipy at 400-545 F. Pot car—<0.02 ipy at all conc and temp. Pot hyd—<0.02 ipy at all conc and temp. Sod bis—<0.02 ipy at all conc and temp. Sod hyd—no meas penet by 5% boil or with 50% to 150 F. T oil—<0.02 ipy to 550 F. Zn chl—<0.02 ipy to all conc and temp. Zn sul—<0.02 ipy to 40% to boil.

\* Nickel-base superalloy. NNR means exc res but alloy is not normally reqd for environment.

#### NICKEL ALLOYS/HASTELLOY C\*

Atm—NNR; <0.002 ipy in MA. Waters—NNR; <0.002 ipy in SW, and in sat SB at 140 F. Ac A—<0.002 ipy for all conc and temp. Bor A—<0.002 ipy for all conc and temp. Chr A—<0.002 ipy to 20% and 150 F; <0.02 ipy to bp. Cit A—0.02 ipy to 58% and 170 F. Fat A—<0.002 ipy to 600 F. For A—<0.002 ipy for all conc and temp. HCl—<0.003 ipy at RT; good res to all conc to 120 F. HF—<0.006 ipy to 45% at RT. Nit A—<0.001 ipy at RT; <0.023 ipy at 150 F; useful to about 10% at boil. Ph A—<0.004 ipy to 50% boil; <0.045 ipy to 85% boil. Sul A—<0.05 ipy to 20% boil. Solv—NNR.

Acet—<0.002 ipy at 98% and 135 F. Ac anh—<0.002 ipy at all conc and temp. Amm—<0.02 ipy to 600 F. Amm

\* Nickel-base superalloy. NNR means exc res but alloy is not normally reqd for environment.



# Key to Abbreviations

ATMOSPHERES (Atm)	ACIDS	Est—Esters	Eth ac—Ethyl acetate	Pot car—Potassium carbonate
HHA—High humidity	Ac A—Acetic acid	Hyd—Hydrocarbons	Eth chl—Ethyl chloride	Pot dic—Potassium dichromate
IA—Industrial	Ars A—Arsenic	Ket—Ketones	Glyc—Glycerol	Pot hyd—Potassium hydroxide
MA—Marine	Bor A—Boric	OTHER CHEMICALS	Hyd per—Hydrogen peroxide	Ros—Rosins
RA—Rural	Chr A—Chromic acid	Acet—Acetaldehyde	Hyd sul—Hydrogen sulfide	Sod ac—Sodium acetate
SS—Salt spray	Cit A—Citric acid	Ac anh—Acetic anhydride	Iso alc—Isopropyl alcohol	Sod bis—Sodium bisulfate
WATER	Fat A—Fatty	Amm—Ammonia	Mag car—Magnesium carbonate	Sod chl—Sodium chloride
NFW—Natural fresh	For A—Formic	Amm nit—Ammonium nitrate	Mag chl—Magnesium chloride	Sod hyd—Sodium hydroxide
DW—Distilled	HCl—Hydrochloric	Anhyd amm—Anhydrous ammonia	Mag sul—Magnesium sulfate	Sod nit—Sodium nitrate
HPW—Highly purified	HF—Hydrofluoric	But alc—Butyl alcohol, tertiary	Mag nit—Magnesium nitrate	Sul diox—Sulfur dioxide
BFW—Boiler feed	Nit A—Nitric	Cal chl—Calcium chloride	Mal anh—Maleic anhydride	T oil—Tall oil
WW—Well water	Ph A—Phosphoric	Cal hyd—Calcium hydroxide	Phth anh—Phthalate anhydride	Zn chl—Zinc chloride
RW—River water	Sul A—Sulfuric	Chl—Chlorine		Zn sul—Zinc sulfate
BW—Brackish water	SOLVENTS (Solv)	Det—Detergents		
SW—Sea water	Alc—Alcohols			
SB—Salt brine	Chl sol—Chlorinated solvents			

nit—<0.002 ipy at RT. Anhyd amm—NRR. But alc—NRR. Cal chl—<0.002 ipy at all conc and temp. Cal hyd—<0.002 ipy at all conc and temp. Chl—<0.0001 ipy in wet or dry gas. Det, Eth ac—NRR. Eth chl—<0.02 ipy for all conc and temp. Glyc, Glycols, Hyd per—NRR. Hyd sul—<0.002 ipy to 160 F. Iso alc—NRR. Mag car—<0.02 ipy to 10% boil. Mag chl—<0.002 ipy to all conc and temp.

Mag sul—<0.02 ipy to 50% boil. Mal anh—<0.002 ipy at 400-545 F. Pot car—<0.02 ipy at all conc and temp. Pot dic—<0.02 ipy at 25% and 100 F. Pot hyd—<0.02 ipy at all conc and temp. Ros—<0.002 ipy to 570 F. Sod ac—<0.02 ipy at 10% and 75 F. Sod bis—<0.02 ipy at all conc and temp. Sod chl—<0.002 ipy at 550 F. Sod hyd—no att with 57% to boil, or 50% to 150 F. Sod nit—<0.02 ipy at 30% and RT. Sul diox—<0.002 ipy at 180 F in moist gas. T oil—<0.002 ipy to 650 F. Urea—<0.02 ipy with 28% and 360 F. Zn sul—<0.02 ipy to 40% boil.

## PLATINUM\*

Atm, Waters—1 in all. Ac A—1 to all conc and temp. Ars A—causes embrittle when heated. Bor A—not suit in pres of reduc substances (e.g., tartaric acid). Chr A, Cit A, Fat A, For A—1. HCl—1, some wt loss above 85 F. HF, Nit A—1 to bp. Ph A—1 to 210 F, but 4 above 570 F. Sul A—1 to 390 F. Alc—1. Chl sol—1 to CCl<sub>4</sub>. Est—1. But Acet. Hyd—1 to Benz, ac, Tol. Ket—1 to Acetone.

Acet—1. Ac anh—1 to all conc and temp. Amm—1 in aq sol. Amm nit—1. But alc—1. Cal chl—1. Cal hyd—1, but strong oxid agents and v high temp lead to attack. Chl—1. Det—prob 1. Glyc—1. Hyd per—1 to 70 F (hyd per is catalytically decomposed by finely divided metals. Hyd sul—1 to 2000 F, but darkens. Mag chl—1 normally, but 4 in pres air at high temp. Mag sul, Pot car, Pot hyd, Sod A—1. Sod bis—1 with sol. Sod chl—res all pure sol and melts, att by fusions in mixtures with amm salts. Sod hyd—1 to aq sol, fusions cause sl att which inc in pres of oxid subst. Sod nit—1 to sol, but 4 in fusions in mix with nitrates. Sul diox—1 to 2200 F. Zn chl—1 to 70 F, but 4 at 750 F. Zn sul—1 to sol.

\* Key: 1 = practically resistant, 2.4 gm/sq m/day; 2 = fairly res, up to 24 gm/sq m/day; 3 = not particularly res but usable, up to 72 gm/sq m/day; 4 = unusable, over 72 gm/sq m/day.

## STAINLESS STEELS/304

HHA, IA—exc. MA—good to exc. RA—exc. SS—fair to good. NFW, DW, HPW—exc. WW—good to exc. BW, RW—fair to exc. SW—unsatis to good. SB—unsatis to exc. Ac A—poor to exc. Bor A—good to exc. Chr A—poor to exc. Cit A—good to exc. Fat A—poor to exc. For A—unsatis to exc. HCl, HF—unsatis. Nit A—exc. Ph A,

Sul A—unsatis to exc. Solv—exc to all, except Chl solv if HCl is present.

Acet—exc. Ac anh—good to exc. Amm, Amm nit, Anhyd amm, But alc—exc. Cal chl—subject to pitting. Cal hyd—exc. Chl—subject to pitting unless dry. Det, Eth ac, Eth chl, Glyc, Glycols, Hyd per, Hyd sul, Iso alc, Mag car—exc. Mag chl—subject to pitting. Mag sul, Mag nit—exc. Phth anh—unsatis to exc. Pot car, Pot dic—exc. Pot hyd—unsatis to exc. Ros, Sod ac—exc. Sod bis—poor to exc. Sod chl—subject to pitting. Sod hyd—unsatis to exc. Sod nit—exc. Sul diox—poor to exc. T oil—unsatis to good. Urea—fair to exc. Zn chl—subject to pitting. Zn sul—unsatis to exc.

## STAINLESS STEELS/316

HHA, IA, MA, RA—exc. SS—good to exc. NFW, DW, HPW—exc. WW—good to exc. RW—exc. BW—good to exc. SW—good to exc if no marine fouling. SB—unsatis to exc. Ac A—good to exc. Bor A—exc. Chr A—poor to exc. Cit A—exc. Fat A—fair to exc. For A—poor to exc. HCl, HF—unsatis. Nit A—exc. Ph A, Sul A—unsatis to exc. Solv—exc to all, except Chl solv if HCl is present.

Acet, Ac anh, Amm, Amm nit, Anhyd amm, But alc—exc. Cal chl—subject to pitting. Cal hyd—exc. Chl—subject to pitting unless dry. Det, Eth ac, Eth chl, Glyc, Glycols, Hyd per, Hyd sul, Iso alc, Mag car—exc. Mag chl—subject to pitting unless dry. Det, Eth ac, Eth chl, Glyc, Glycols, Hyd per, Hyd sul, Iso alc, Mag car—exc. Mag chl—subject to pitting. Mag sul—good to exc. Mag nit—exc. Phth anh—poor to exc. Pot car, Pot dic—exc. Pot hyd—unsatis to exc. Ros, Sod ac, Sod bis—exc. Sod chl—subject to pitting. Sod hyd—unsatis to exc. Sod nit—exc. Sul diox—good to exc. T oil—fair to exc. Urea—exc. Zn chl—subject to pitting. Zn sul—fair to exc.

## STAINLESS STEELS/430

HHA—exc. IA—exc but thin protective rust film may form. MA—fair to good. RA—exc. SS—subject to pitting. NFW, DW, HPW, BFW—exc. WW, RW—fair to exc. BW—fair to good. SW, SB—unsatis to poor. Ac A—poor to fair. Bor A—fair to exc. Chr A—poor. Cit A—unsatis to exc. Fat A—unsatis to good. For A—unsatis to poor. HCl, HF—unsatis. Nit A—exc. Ph A—unsatis to exc. Sul A—unsatis. Solv—exc to all except poor with Chl solv if HCl is present.

Ac anh—unsatis to poor. Amm, Amm nit—good to exc. Anhyd amm—fair to exc. Cal chl—subject to pitting. Cal hyd—poor to fair. Chl—poor. Det—exc. Eth ac—good. Eth chl, Glyc, Glycols—exc. Hyd per—fair to exc. Hyd sul—poor to fair. Iso alc, Mag car—exc. Mag chl—subject to pitting. Mag sul—good to exc. Mag nit—exc. Pot car—

good. Pot dic—exc. Pot hyd—unsatis to exc. Ros, Sod ac—good. Sod bis—unsatis to good. Sod chl—subject to pitting. Sod hyd—unsatis to exc. Sod nit—good to exc. Sul diox—good when dry. Zn chl—subject to pitting. Zn sul—unsatis to exc.

### STEELS, CARBON\*

HHA—unaff at low RH; rust develops at crit RH of about 65%. Cor at 1.5 mpy at 82% RH. IA—depends on ext of pollution and length of wetness; typ corr rate: 0.7 mpy. MA—depends on salt contam and length of exposure to wetness; typ rate: 1.2 mpy. RA—depends on pollution and length of wetness; typ rate: 0.6 mpy. SS—sev corr; typ rate: 16.2 mpy.

NFW—v good, depends on temp, diss oxy, and whether water is scale-forming (hard) or not (soft). In soft more corr because no prot scale forms; typ rate: 2-6 mpy. DW—no apprec att in air-free but not ordin used when aerated. HPW—suitable under cert cond; behavior depends on temp, chem content and diss gas. BFW—dep on diss oxy cont and temp; OK with deaerated. WW—OK if prot calcareous coatings form. RW—if uncontaminated performs same as FW; high corr if contam with acid mine-drainage. BW—dep on temp, veloc, oxy content; OK in deaerated to 250 F. SW—same as BW. Steel piling cor at 2 mpy 1st yr, 1 mpy thereafter. SB—dep on temp, veloc, oxy content; res 10% air-free, but rate when aerated incr to 12 mpy.

Bor A—usually not suit, but sometimes used if high corr rate can be toler and acid contam not import. Chr A—gen OK. Cit A—same as Bor A. Fat A—see Bor A. For A—same as Bor A. HCl—not res with liq; OK with hyd chl gas to 400 F, and with moist vap at temp high enough to prev cond. HF—OK >75-80%, <150 F; not res <70% and at low temp or with anhydrous acid <150 F. Nit A—not res <75%; corr decreases >75% and sometimes used with >95% at RT. Ph A—rapid att by all conc and crude cont <50% phos pentoxide (69% Ph A). Sometimes OK with conc crude contain impur (arsenic) which inhib corr. Sul A—not res up to 80%; conc acid is much less corr and steel OK for 90-100% (oleum) provided avoid agitation.

Alc—gen satis; some corr in pres water and air. Chl sol—OK with dry CCl and others to bp; sev corr in pres of water. Est—OK with acetates; poss corr in pres of impur and/or water. Hyd—OK with benz, tol, xyl and pet solv; poss corr in pres impur and/or water. Ket—OK; poss corr in pres impur and/or water.

Acet—same as Ket. Ac anh—usually not suit but used where prod contam unimp. Amm—OK dry to 700 F; poss corr in pres impur and/or water. Amm nit—OK with dry; prot coating reqd in pres moist which incr att. Conc sol can cause str-corr crack at high temp. Anhyd amm—satis air contam can cause str-corr crack. But alc—OK; some corr and discol in pres water and air. Cal chl—OK with dry to 600 F; water can cause sev corr. Cal hyd—OK with dry and wet. Chl—OK with dry to 400 F; unsatis with wet. Eth ac—OK; poss corr in pres impur and/or water. Eth chl—OK with dry to 700 F; sev corr in pres water. Glyc—same as But Alc. Glycols—same as But Alc.

Hyd per—not suit. Hyd sul—OK dry to 600 F; pres of water causes sev corr. Can cause str-corr. Iso alc—same as But Alc. Mag car—OK dry and wet. Mag chl—OK dry; moist can cause heavy corr. Mag sul—same as Mag chl. Mag nit—same as Mag chl. Mal anh—OK dry; poss sev corr at high temp or with moist. Phth anh—same as Mag chl. Pot car—same as Mag chl. Pot dic—OK dry and wet. Pot hyd—high res, but poss sev att at high temp in pres moist. Sol may cause str-corr at high temp. Ros—mod att

\* Data on atmospheric corrosion apply to structural carbon steel with low residual copper content. Structural carbon steel containing 0.2% copper is about twice as resistant as ordinary structural carbon steel, and the addition of small amounts of other alloying elements in certain high strength, low alloy steels results in atmospheric corrosion resistance 4 to 6 times greater than that of ordinary structural carbon steel. Other steels are covered under Stainless steels.

at RT; sev att at high temp. Sod ac—high res to dry at RT, poss sev corr in pres moist. Sod bis—OK dry at RT (<2 mpy); apprec corr in pres moist. Sod chl—high res to dry at RT; moist incr corr.

Sod hyd—high res, but sev corr at high temp and conc with diss oxy; hot sol may cause str-corr crack (caustic embr). Sod nit—OK with dry to 1000 F; sev att in pres of moist. T oil—OK to 200 F; sev att at higher temp. Urea—OK with pure; sev corr in pres water and air. Zn chl—OK dry to 300 F; moist incr corr. Zn sul—same as Mag chl.

### TANTALUM\*

Atm, Waters, Ac A, Bor A—NNR. Chr A—<0.002 ipy for all conc and temp. Cit A—NNR. Fat A—<0.002 ipy for all conc and temp. For A—NNR. HCl—<0.002 ipy for all conc and temp. HF—not recom. Nit A—<0.002 ipy for all conc and temp. Ph A—<0.002 ipy for all conc and temp; may be att if acid is contam with fluorides. Sul A—<0.002 ipy for all conc and temp. Solv—NNR.

Ac, anh, Amm, Amm nit, Anhyd amm, But alc, Cal chl, Cal hyd—NNR. Chl—<0.001 ipy in wet or dry gas. Det, Eth ac, Eth chl, Glyc, Glycols, Hyd per, Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Pot car, Pot dic—NNR. Pot hyd—not rec >57%. Ros, Sod ac, Sod bis, Sod chl—NNR. Sod hyd—not rec >5%. Sod nit—NNR. Sul diox—not recom. T oil, Urea, Zn chl, Zn sul—NNR.

\* NNR = exc res but metal is not norm reqd for environment.

### TIN, GRADE A

HHA—slow oxid prod yellow discol with negl metal loss. IA—slow corr prod adh gray layer; penet rate in NYC of 0.052 mpy. MA—faster corr than IA, e.g., 0.074 mpy. RA—init loss brightness, then slow corr, e.g., 0.019 mpy. SS—same as MA but more pitting. NFW—res but poss less pitting if chloride pollution is high and water is stagnant. DW, HPW—res under all cond, oxide film thickens into yellow film at high temp. BFW—liable to etch. WW—res but may be att under scale depos or in crev; may pit with high chloride content. BW—initial pitting which may chg to slow corr at higher salt cont. SW, SB—slow corr.

Ac A—res cold sol to 0.3% vapors above sol to 1%, and all air-free sol; otherwise att at rate depend on oxy conc and temp. Bor A—res. Chr A—res; forms passive film. Cit A—res oxy-free acid; diss otherwise. Fat A—res to 165 F; slow att likely at higher temp. For A—res oxy-free acid; diss otherwise. HCl, HF—slow att, depend on oxy supply up to 0.5N; faster attack at higher conc and temp. Nit A—vigorous att. Ph A—slow, declining attack up to 0.1N cold; more vigorous att at higher conc and temp. Sul A—sim to HCl but slower att rate. Alc—usually res. Chl sol—res to dry stable compounds. Poss sl corr in pres water and acidic breakdown products. Est—immune in cold stable cmpds; poss sl corr hot espec if hydrolysis can occur. Hyd—res. Ket—res pure liquids; acidic impur may cause sl etching.

Acet—res. Ac Anh—att at all temp. Amm—res in sol up to 1 gm/l, and above 200 gm/l; att in intermed range depend on oxy supply. Lower conc limit falls with temp rise. Amm nit—local pitting in stagnant dil sol but prob res to moving sol; strong solv (espec hot) may att. Anhyd amm—res. But alc—poss att in hot anhyd; otherwise res. Cal chl—local pitting in stag dil sol, but less likely in moving solns; sl att by stronger sol. Cal hyd—slow att. Chl—rapid att. Det—etched by more alkaline materials, depend on oxy supply and temp; str stag sol may pit. Glyc—res to pure, but poss slow att by crude prod. Glycols—res at ord temp; uncertain at higher. Hyd per—res. Hyd sul—res to 210 F, slow react poss at higher temp. Iso alc—res; poss att by hot anhydrous. Mag car—res. Mag chl, Mag sul, Mag nit—local pitting in stag dil sol; att prob in stronger, esp hot, sol. Mag sul—same as mag chl. Mag nit—same as mag chl. Pot car—res cold



## Key to Abbreviations

<b>ATMOSPHERES (Atm)</b>	<b>ACIDS</b>	<b>Est—Esters</b>	<b>Eth ac—Ethyl acetate</b>	<b>Pot car—Potassium carbonate</b>
<b>HHA—High humidity</b>	<b>Ac A—Acetic acid</b>	<b>Hyd—Hydrocarbons</b>	<b>Eth chl—Ethyl chloride</b>	<b>Pot dic—Potassium dichromate</b>
<b>IA—Industrial</b>	<b>Ars A—Arsenic</b>	<b>Ket—Ketones</b>	<b>Glyc—Glycerol</b>	<b>Pot hyd—Potassium hydroxide</b>
<b>MA—Marine</b>	<b>Bor A—Boric</b>	<b>OTHER CHEMICALS</b>	<b>Hyd per—Hydrogen peroxide</b>	<b>Ros—Rosins</b>
<b>RA—Rural</b>	<b>Chr A—Chromic acid</b>	<b>Acet—Acetaldehyde</b>	<b>Hyd sul—Hydrogen sulfide</b>	<b>Sod ac—Sodium acetate</b>
<b>SS—Salt spray</b>	<b>Cit A—Citric acid</b>	<b>Ac anh—Acetic anhydride</b>	<b>Iso alc—Isopropyl alcohol</b>	<b>Sod bis—Sodium bisulfate</b>
<b>WATER</b>	<b>Fat A—Fatty</b>	<b>Amm—Ammonia</b>	<b>Mag car—Magnesium carbonate</b>	<b>Sod chl—Sodium chloride</b>
<b>NFW—Natural fresh</b>	<b>For A—Formic</b>	<b>Amm nit—Ammonium nitrate</b>	<b>Mag chl—Magnesium chloride</b>	<b>Sod hyd—Sodium hydroxide</b>
<b>DW—Distilled</b>	<b>HCl—Hydrochloric</b>	<b>Anhyd amm—Anhydrous ammonia</b>	<b>Mag sul—Magnesium sulfate</b>	<b>Sod nit—Sodium nitrate</b>
<b>HPW—Highly purified</b>	<b>Nit A—Nitric</b>	<b>But alc—Butyl alcohol, tertiary</b>	<b>Mag nit—Magnesium nitrate</b>	<b>Sul diox—Sulfur dioxide</b>
<b>BFW—Boiler feed</b>	<b>Ph A—Phosphoric</b>	<b>Cal chl—Calcium chloride</b>	<b>Mal anh—Maleic anhydride</b>	<b>T oil—Tall oil</b>
<b>WW—Well water</b>	<b>Sul A—Sulfuric</b>	<b>Cal hyd—Calcium hydroxide</b>	<b>Phth anh—Phthalate anhydride</b>	<b>Zn chl—Zinc chloride</b>
<b>RW—River water</b>	<b>SOLVENTS (Solv)</b>	<b>Chl—Chlorine</b>		<b>Zn sul—Zinc sulfate</b>
<b>BW—Brackish water</b>	<b>Alc—Alcohols</b>	<b>Det—Detergents</b>		
<b>SW—Sea water</b>	<b>Chl sol—Chlorinated solvents</b>			
<b>SB—Salt brine</b>				

sol to 1%, gen att by hot and more conc sol depend on oxy supply. Pot dic—res; hot sol prod passive film. Pot hyd—att. Ros—res. Sod chl—pitting in stag dil sol esp in crev and in contact with more noble metal. Att may spread in strong hot sol. Sod hyd—att. Sod nit—pitting in stag dil sol. Sul diox—res sol to 0.1 gm/l; stained by 0.1-1 gm/l; etched by stronger sol. Res in low conc in air but att at higher conc from yellow color, to black stain, to gen etch. Att by liquid sul diox. Zn chl—pitting in dil col sol; att in stronger hot sol or fused salt. Zn sul—pits in dil cold sol.

### TITANIUM\*

Atm—high corr res. Waters—high corr res. Ac A—<5 mpy in 5, 25, 50, 75, 99.5% boil. Chr A—<5 mpy in 10% boil, 36.5% at 195 F. Cit A—aerated: <5 mpy in 10, 25, 50, 90% at 212 F; nonaerated: <5 mpy in 10% boil. HCl—<5 mpy to >50 mpy, dep on conc and temp. HF—>50 mpy to 1% at RT. Nit A—<5 mpy in 10, 20, 30, 40, 50, 60, 70% at 212 F, and 65% boil. Ph A—<5 mpy in 5, 10, 20, 30% at 95 F; 5-50 mpy in 35-85% at 95 F, 5-35% at 140 F, 5% at 212 F, and 10% at 175 F. Sul A—<5 mpy in 5% at 95 F; 5-50 mpy in 10% at 95 F and 60-70% at 95 F; >50 mpy in 20-50% at 95 F, and 70% at 95 F. Solv—<5 mpy.

Ac anh—<5 mpy in 99% at RT. Anhyd amm—<5 mpy in 100% at 105 F. Cal chl—<5 mpy in 5, 10, 25% at 212 F. Chlorine—dry: >50 mpy at 86 F; wet: <5 mpy at 165 F. Mag chl—<5 mpy in 5, 20, 42% boil. Pot hyd—<5 mpy in 10% boil. Sod chl—<5 mpy in 20% and sat boil. Sod hyd—<5 mpy in 10% boil and 40% at 175 F. Sul diox (water-sat)—<5 mpy at 160 F. Zn chl—<5 mpy in 5, 10, 20% boil.

\* Commercially pure. Key: <5 mpy = high corr res; 5-50 mpy = may be satis for noncritical parts where some corr can be tolerated.

### ZINC\*

IA—about 0.0002 ipy. MA—about 0.0002 to 0.0006 ipy. RA—very low corr; <0.0004 ipy. DW, HPW—corr rate higher than SW, RW or tap water due to absence of salts which normally form prot layers. BFW, WW, RW—low corr rate; att is function of temp, gases present, pressure, hardness. BW—corr rate similar to, but less than SW. SW—0.001 ipy. SB—att dep on conc and oxygen present; max att at 0.5% NaCl, less att at 3%. Acids—att at pH <6.5. Alc—no att in anhydrous form. Chl solv—att in presence of mois. Est, Hyd, Ket—no att.

Amm—severe att at 600 F. But alc—no att if water-

\* In general, corr res prop of zinc coatings are quite similar to prop of zinc and its alloys listed here.

free. Cal chl—mild att initially; rate decreases due to formation of prot layer of slightly soluble salt. Cal hyd—low att <12.5 pH; aggressive att >12.5 pH. Chl—dry: no att; wet: att. Det—no att if nonalkaline or if conc is low. Glyc—no att if high purity and water-free. Hyd sul—harmless because nonsoluble zinc sulfide forms. Iso alc—no att if water-free. Mag chl—aggressive att initially, but decreases due to build-up of prot layer of sparingly soluble compds. Mal anh, Phth anh—no att. Pot car—heavy att. Pot dic—no att (chromates and dichromates are corr inhibitors for zinc). Pot hyd—high corr rate. Ros—negligible att if acid-free. Sod chl—same as SB; corr rate decr in more conc sol because oxygen solubility decreases. Sod hyd—high corr rate. Sod nit—slight att. Sul diox—severe att. Zn chl—aggressive att because hydropscopic salts form. Zn sul—less than Zn chl.

### ZIRCONIUM

Atm—not normally used. Waters—<5 mpy. Ac A—<5 mpy to most conc boil. For A (50%)—<5 mpy at 212 F. Chr A—<5 mpy in 10% boil, 20% at RT. Cit A (50%)—<5 mpy at 212 F. For A—<5 mpy in 10, 25, 50, 90% at 212 F. HCl—<5 mpy at most conc and temp. HF (48%)—>50 mpy at RT. Nit A—<5 mpy at most conc and temp. Ph A—<5 mpy in 5-30% at RT and 40% at 212 F; 5-50 mpy in 35-85% at RT and 85% at 100 F. Sul A—<5 mpy in 70% at 212 F. Solv—<5 mpy.

Acet—<5 mpy at 150 F. Ac anh—<5 mpy at RT. Amm (50%)—<5 mpy at 190 F. Cal chl (28%)—<5 mpy in boil. Eth ac—<5 mpy at 212 F. Hyd per (50%)—<5 mpy at 140 F. Mag sul (37%)—<5 mpy at 200 F. Pot hyd (50%)—5 mpy in boil. Sod chl (sat)—<5 mpy in boil. Sod hyd—<5 mpy in 10, 25% boil, 40% at 175 F. Zn chl (20%)—<5 mpy at 212 F.

## PLASTICS

### ABS\*

Atm, Waters—no att. Ac A (5%)—no att. Bor A—no att. Chr A (6%)—sl att, some stain. Cit A (10%), Fat A, For A (10%), HCl (10%)—no att. HF—10%: no att; conc: att. Nit A (10%)—sl att. Ph A (conc)—no att. Sul A (10%)—no att. Alc—sl att by meth and 95% eth. Chl sol—gen att. Est—att. Hyd—solv in tol. Ket—gen solv. Acet—att. Amm nit—no att. Anhyd amm (gas or liq)—att. But alc—no att. Cal chl—no att. Cal hyd—no att. Chl (anhyd or liq)—att. Det—no att. Eth ac—att. Glyc,



Glycols (ethyl glycol), Hyd per, Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Pot car, Pot dic, Pot hyd (10%), Sod ac, Sod bis, Sod chl (10%), Sod hyd (10%) Sod nit—no att. Sul diox (anhyd and sol)—sl att; stains. T oil, Zn chl, Zn sul—no att.

\* Acrylonitrile-butadiene-styrene. Sl att indicates slight surface crazing or checking; att indicates severe crazing or plastic becomes softened or unusable by end of test; solv indicates medium acts as solvent. Test time at least 1 week at 70 F.

### ACETALS

Atm, Waters—exc, except fair to good res to IA. Ac A—fair. Ars A—poor. Bor A—exc. Chr A—poor. Cit A, Fat A—good. For A, HCl, HF, Nit A, Ph A, Sul A—poor. Alc, Chl sol, Est, Hyd, Ket—exc.

Acet—exc. Ac anhyd—good. Amm—poor. Amm nit—fair. Anhyd amm—poor. But alc—exc. Cal chl—exc. Cal hyd—exc. Chl—poor. Det—fair to exc. Eth ac, Eth chl, Glyc, Glycols—exc. Hyd per—poor. Hyd sul—wet gas: fair; dry gas: good. Iso alc, Mag car, Mag chl, Mag sul, Mag nit—exc. Mal anh, Phth anh, Pot car—good. Pot dic—poor. Pot hyd—fair to poor. Ros—exc. Sod ac—exc. Sod bis—good. Sod chl—exc. Sod hyd—fair to poor. Sod nit—good. Sul diox—dry: exc; wet: good. T oil—exc. Urea—exc. Zn chl, Zn sul—fair.

### ACRYLICS\*

Atm, Waters—exc to all. Ac A—weak (15%): good; strong: poor. Ars A—good. Bor A—exc. Chr A—unsatis. Cit A—exc. Fat A—exc. HCl—weak (30%): good; strong: unsatis. Nit A—weak (30%): good; strong: unsatis. Ph A—weak (65%): good; strong: unsatis. Sul A—weak (60%): good; strong: unsatis. Alc—eth alc (50%): satis; meth alc (60%): satis. Chl sol, Est, Hyd, Ket—unsatis.

Acet, Ac anhyd—unsatis. Amm (aq)—good. Amm nit—exc. Anhyd amm—yellows. Cal chl—exc. Cal hyd—exc. Chl—dry: good; moist: unsatis. Det—dil: exc; as recd: gen good. Eth ac—unsatis. Eth chl—unsatis. Glyc, Glycols—exc. Hyd per—good to 50%. Hyd sul—exc. Iso alc—good to 50%. Mag car, Mag chl, Mag sul, Mag nit, Pot car, Pot dic, Pot hyd, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit—exc. Sul diox—dry: good; moist: unsatis. Zn chl, Zn sul—exc.

\* Data for sheet and moldings. Acid conc are approx; resistance ratings depend on temperature and stress levels.

### ALKYDS\*

Atm—no eff by sunlight. Water—0.15-0.8% water abs (ASTM D570). Weak acids—no att. Str acids—att. Alkalis—att. Org solv—no att.

\* Mineral-filled.

### CELLULOSE ACETATE BUTYRATE\*

Atm—no att, except: IA—swells v slightly but does not soft. Waters—no att. Ac A—5%: +3%; 10%: +5%; 30%: +14%. Bor A (5%)—+1.3%. Chr A (6%)—+2% after 8 days at 100 F. Cit A (10%)—+1.6% after 4 mo at 140 F. Fat A (oleic)—+2.3%. HCl (10%)—+1.4%; att surf slight in 1 yr. HF (10%)—+10%. Nit A (10%)—decomp in 8 mo. Ph A—30%: +1.3%; 50%: +1.6%; 75%: att in 2 mo. Sul A—10%: +1.5%; 20%: sl att surface after 1 yr. Alc—+2 to 15%. Chl solv—swell badly or diss. Est—diss. Hyd—diss by some; aliphatic have little or no eff. Ket—diss.

Ac Anhyd—diss. Amm nit—solid: +0.2%; 10% aq: +1.7%. But alc—+3.6%. Cal chl (aq)—2.5%: +1.5%; 40%: +0.4%. Cal hyd (sat aq)—+1.7%. Chl—+8%. Det—no att. Eth ac—diss. Glyc—+0.03%. Glycols—0.8%. Hyd per (aq)—3%: +1.7%; 5%: +1.4%. Hyd sul—moist gas: +3%; sat aq: +6%. Iso alc—>20%. Sod ac (3% aq)—+1.3% after 3 days at 100 F. Sod bis (1%

\* All figures are % wt change; tests run at 73 F for 1 mo, unless otherwise noted.

aq)—same as Sod Ac. Sod chl—10%: +1.3%; sat aq: +0.8%. Sod hyd (aq)—1%: +1%; 10%: +1.4%, embrittles in 8 mo. Sod nit—solid: +0.08%; 10% aq: +1.5%; sat aq: +0.9%. Sul diox (gas)—>20%, Zn chl (sat aq)—+1.6%.

### CHLORINATED POLYETHER

HHA—exc. IA—exc to indust acid and alk fumes. MA—res fungus growth. RA—exc. SS—exc. NFW—res to 250 F. DW—res to 250 F. HPW—res to 250 F. BFW, WW, RW, BW, SW—exc. SB—exc to 250 F; supersat brines could cause some abrasive wear at high solids and flow rates.

Ac A—res to all conc to 250 F. Ars A—res to 250 F. Bor A—res to 250 F. Chr A—mixed results; should be tested. Cit A—exc to 250 F. Fat A—exc to 250 F. For A—exc to 90% to 250 F. HCl—exc to 50% to 250 F. HF—exc to 30% to 220 F and to 60% to 150 F. Nit A—exc to 10% to 220 F and to 70% to 80 F. Ph A—exc to all conc to 250 F. Sul A—exc to 80% to 250 F, 90% to 220 F, 96% to 150 F; do not use above 98%.

Alc—exc to 220 F. Chl sol—exc with CCl<sub>4</sub> to 220 F; exc to trichl and perchl to 150 F. Est—exc to 150 F. Hyd, Ket—exc to 150 F; higher temp OK when dil sol pres in aqueous sys. Acet—res to 150 F. Ac anhyd—res to 220 F. Amm—res to gas and aqueous to 220 F. Amm nit—exc to 250 F; res to most amm cmpds. But alc—res to 220 F. Cal chl—exc to 250 F. Cal hyd—exc to 250 F. Chl—res to wet and dry to 250 F; pretesting recom. Det—exc to 250 F. Eth ac—res to 150 F. Eth chl—res to 220 F. Glyc—res to 220 F. Glycols—res to 220 F. Hyd per—res to 90% to 150 F; used to 35% to 212 F. Hyd sul—res to dry and aqueous to 220 F. Iso alc—exc to 220 F. Mag car—exc to 250 F; Mag chl—exc to 250 F. Mag sul—exc to 250 F. Mag nit—exc to 250 F. Mal anh—exc to 250 F. Pot car—exc to 250 F. Pot dic—exc to 250 F. Pot hyd—exc to 250 F. Ros—exc to 250 F. Sod ac—exc to 250 F. Sod bis—exc to 220 F. Sod chl—exc to 250 F. Sod hyd—exc to 70% to 250 F. Sod nit—exc to 250 F. Sul diox—no data but expect oxid react. T oil—exc to 220 F. Urea—exc to 250 F. Zn chl—exc to 220 F. Zn sul—exc to 250 F.

### DIALLYL PHTHALATE\*

Atm—exc. Waters—exc to all, including boiling NFW; 0.9% wt chg in DW after 1 mo. Ac A—exc, incl hot. Chr A—+1.2% at 160 F. Cit A (3%)—+1.2% at 160 F. Nit A (10%)—+1.29% after 1 mo. Sul A (30%)—+0.48% after 1 mo. Alc—exc; +0.2%. Chl sol—fair to good; -0.06%. Est—exc; +0.3%. Hyd—exc; -0.025%. Ket—sl well; -0.02%. Amm—exc in 1.2% aq sol. Det—exc. Eth ac—exc. Pot hyd—exc in 5% aq sol but att by hot alcoholic sol. Sod hyd (20%) exc; -2.26% at 160 F.

\* Unless otherwise noted, figures refer to % wt chg.

### EPOXY, GLASS-REINFORCED

Water—exc. Ac A—10%: exc in cold, fair in hot. 75%: fair in cold, not res in hot. Bor A—exc in cold and hot. Chr A—exc in cold, fair in hot. Cit A—exc in cold, good in hot. Fat A—exc in cold, good in hot. For A (50%)—good in cold. HCl—exc in cold, fair in hot. Nit A—5%: fair in cold, not res in hot; 20%: poor in cold, not res in hot. Ph A—exc in cold, good in hot. Sul A—10%: exc in cold, good in hot; 70%: exc in cold, not res in hot. Alc (amyl and benzyl)—exc in cold, fair in hot. Hyd—benz: good in cold, poor in hot. Tol—good in cold, fair in hot. Ket—acet: exc in cold, fair in hot; MEK: exc in cold, fair in hot.

Amm nit—exc. Cal chl—exc. Cal hyd—exc in cold, good in hot. Chl—dry: exc in cold, not res in hot; wet: poor in cold, not res in hot. Hyd per—not res. Mag car—exc. Mag chl, Mag sul—exc in cold, good in hot. Pot car—exc. Sod ac—exc in cold, good in hot. Sod bis—exc. Sod chl—exc. Sod nit, Zn sul—exc in cold, good in hot.

# Key to Abbreviations

<b>ATMOSPHERES (Atm)</b>	<b>ACIDS</b>	<b>Est—Esters</b>	<b>Eth ac—Ethyl acetate</b>	<b>Pot car—Potassium carbonate</b>
<b>HHA—High humidity</b>	<b>Ac A—Acetic acid</b>	<b>Hyd—Hydrocarbons</b>	<b>Eth chl—Ethyl chloride</b>	<b>Pot dic—Potassium dichromate</b>
<b>IA—Industrial</b>	<b>Ars A—Arsenic</b>	<b>Ket—Ketones</b>	<b>Glyc—Glycerol</b>	<b>Pot hyd—Potassium hydroxide</b>
<b>MA—Marine</b>	<b>Bor A—Boric</b>	<b>OTHER CHEMICALS</b>	<b>Hyd per—Hydrogen peroxide</b>	<b>Ros—Rosins</b>
<b>RA—Rural</b>	<b>Chr A—Chromic acid</b>	<b>Acet—Acetaldehyde</b>	<b>Hyd sul—Hydrogen sulfide</b>	<b>Sod ac—Sodium acetate</b>
<b>SS—Salt spray</b>	<b>Cit A—Citric acid</b>	<b>Ac anh—Acetic anhydride</b>	<b>Iso alc—Isopropyl alcohol</b>	<b>Sod bis—Sodium bisulfate</b>
<b>WATER</b>	<b>Fat A—Fatty</b>	<b>Amm—Ammonia</b>	<b>Mag car—Magnesium carbonate</b>	<b>Sod chl—Sodium chloride</b>
<b>NFW—Natural fresh</b>	<b>For A—Formic</b>	<b>Amm nit—Ammonium nitrate</b>	<b>Mag chl—Magnesium chloride</b>	<b>Sod hyd—Sodium hydroxide</b>
<b>DW—Distilled</b>	<b>HCl—Hydrochloric</b>	<b>Anhyd amm—Anhydrous ammonia</b>	<b>Mag sul—Magnesium sulfate</b>	<b>Sod nit—Sodium nitrate</b>
<b>HPW—Highly purified</b>	<b>HF—Hydrofluoric</b>	<b>But alc—Butyl alcohol, tertiary</b>	<b>Mag nit—Magnesium nitrate</b>	<b>Sul diox—Sulfur dioxide</b>
<b>BFW—Boiler feed</b>	<b>Nit A—Nitric</b>	<b>Cal chl—Calcium chloride</b>	<b>Mal anh—Maleic anhydride</b>	<b>T oil—Tall oil</b>
<b>WW—Well water</b>	<b>Ph A—Phosphoric</b>	<b>Cal hyd—Calcium hydroxide</b>	<b>Phth anh—Phthalate anhydride</b>	<b>Zn chl—Zinc chloride</b>
<b>RW—River water</b>	<b>Sul A—Sulfuric</b>	<b>Chl—Chlorine</b>		<b>Zn sul—Zinc sulfate</b>
<b>BW—Brackish water</b>	<b>SOLVENTS (Solv)</b>	<b>Det—Detergents</b>		
<b>SW—Sea water</b>	<b>Alc—Alcohols</b>			
<b>SB—Salt brine</b>	<b>Chl sol—Chlorinated solvents</b>			

## ETHYL CELLULOSE

HHA—exc. IA—good. MA—good. RA—exc. SS—good. NFW, DW, HPW, BFW, WW, RW—exc. BW, SW, SB—good. Ac A—dil: good; conc: poor. Chr A—poor. Fat A—softened but not att. HCl—good. Nit A—fair. Ph A—fair. Alc, Chl solv, Est, Hyd, Ket—poor.

Acet—poor. Ac anh—fair. Amm—exc. Anhyd amm—exc. But alc—poor. Cal chl—good. Cal hyd—exc. Det—exc. Eth ac—poor. Eth chl, Glyc, Glycols, Iso alc—poor. Mal anh—fair. Phth anh—fair. Pot car, Pot hyd, Ros, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit—exc. T oil—poor. Urea—exc.

## FLUOROCARBONS/CFE

Atm, Waters—exc to all. Ac A, Ars A, Bor A, Chr A, Cit A, Fat A, For A, HCl, HF—exc. Nit A, Ph A, Sul A, Alc—exc. Chl sol, Est—v good. Hyd, Ket—exc.

Acet, Ac anh, Amm, Amm nit, Anhyd amm, But alc, Cal chl, Cal hyd—exc. Chl—mod. Det—exc. Eth ac—v good. Eth chl, Glyc, Glycols, Hyd per, Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh, Pot car, Pot dic, Pot hyd, Ros, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit, Sul diox, T oil, Urea, Zn chl, Zn sul—exc.

## FLUOROCARBONS/TFE\*

Atm—exc to all. Waters—exc to all. HCl—0 wt ch in 10 and 20%. Nit A (10%)—0 wt ch at 75 F; +0.1% at 160 F. Sul A (30%)—0 wt ch at 75 and 160 F for 12 mo; +0.1% at 390 F for 8 hr. Alc (95% eth alc)—0 wt ch at 120 F for 12 mo, +0.3% at 390 F for 8 hr. Chl sol (CCl<sub>4</sub>)—+0.6% at 75 F for 12 mo, +3.7% at 390 F for 8 hr. Hyd—benz; +0.5% at 175 F for 4 days, +1% at 390 F for 8 hr. Tol: +0.3% at 75 F for 12 mo, +0.6% at 160 F for 2 weeks.

Eth ac—+0.5% at 75 F for 12 mo, +0.6% at 160 F for 2 weeks. Sod hyd—0 wt ch for most conc and temp. Zn chl—exc to mp. Other chem—TFE fluorocarbons are inert to nearly all chem and solv, except those cont fluorine or metallic sodium and other alkali metals.

\* Unless otherwise noted, figures refer to % wt chg; values cited are considered to be negligible. FEP fluorocarbons, because of closed molecular structure approaching crystallinity, also have outstanding corr res; prop are similar to those cited above.

## FLUOROCARBONS/VINYLDENE FLUORIDE

Atm, Waters—exc to all. Ac A—good. Ars A—v good. Bor A—exc. Chr A—v good. Cit A—exc. Fat A—exc. For A—exc. HCl—good. HF—v good. Nit A—good. Ph A—v good. Sul A—good. Alc—exc. Chl sol—exc. Est—good. Hyd—exc. Ket—fair (acetone partially diss).

Acet—good. Ac anh—good. Amm—v good. Amm nit—v good. Anhyd amm—v good. But alc—v good. Cal chl—exc. Cal hyd—v good. Chl—v good. Det—v good. Eth ac—good. Eth chl—good. Glyc, Glycols, Hyd per—exc. Hyd sul—v good. Iso alc, Mag car, Mag chl, Mag sul, Mag car—exc. Mag anh, Phth anh—v good. Pot car, Pot dic—exc. Pot hyd—v good. Ros—exc. Sod ac, Sod bis—v good. Sod chl—exc. Sod hyd—v good. Sod nit—exc. Sul diox—v good. T oil—exc. Urea—v good. Zn chl, Zn sul—exc.

## MELAMINE\*

Atm—no att except HHA may cause dimens chg after long exp. Waters—no att. Chr A (5%)—sl att after 4 hr at 75 F. Cit A (10% water sol)—no att after 7 days at 75 F. Fat A—no att. For A, HCl—no att at low conc. Sul A—no att in 1% after 7 days at 75 F. Alc, Est, Hyd—no att. Ket—no att after 7 days at 75 F. Chl—att after long exp. Det—no att. Pot hyd—may discol. Sod chl—no att. Sod hyd (10% sol)—no att after 7 days at 75 F. Urea—no att.

\* Alpha cellulose-filled molding compound.

## NYLONS\*

Atm—exc for long exp in sun, but water stab grades recom. Water—exc; however, because water plasticizes nylon and changes dimen, 6/10 nylons are recom where dimen crit. Ac A—poor. Bor A—fair. Chr A—poor. Cit A—fair. Fat A—exc. For A—poor. HCl—poor. HF—poor. Nit A—poor. Ph A—fair to poor. Sul A—poor. Alc—absorbed by nylon but does not att; plasticizing action can change dimen. Chl sol—exc to perchlorinated sol; others absorbed in varying deg. Est, Hyd, Ket—exc.

Acet—exc. Ac anh—poor. Amm, Amm nit, Anhyd amm—good. But alc—exc. Cal chl—good but solv action at high conc. Cal hyd—exc. Chl—poor. Det, Eth ac, Eth chl—exc. Glyc, Glycols—absorbed but does not att. Hyd per—fair. Hyd sul—exc. Iso alc—absorbed but does not att. Mag car, Mag chl, Mag sul, Mag nit, Pot car—exc. Pot dic—poor. Pot hyd—good. Ros—exc. Sod ac, Sod chl—exc. Sod hyd—good. Sod nit—exc. Sul diox—good. T oil—exc. Urea—exc. Zn chl—solv action at high temp. Zn sul—exc.

\* High molecular wt 6/10 nylons have best res to acids.

## PHENOLICS\*

Water (except BW, SW and SB)—1.06. Ac A (5%)—0.98. Cit A—10%: 0.655. HCl (10%)—1.49. Nit A (10%)—1.97. Sul A (30%)—0.98. Alc (95% eth alc)—0.041.

\* All data given as % wt gain unless otherwise noted; exposure is based on 7 days at room temp.

Chl sol (CCl<sub>4</sub>)—0.006. Hyd (tol)—0.016. Ket (acet)—0.086. Anhyd amm—0. Cal chl (5%)—1.04. Eth ac—0.8. Hyd per (3%)—1.04. Sod chl—5%: 1.05; 10%: 0.524. Sod hyd—1%: 0.85; 10%: 2.78. Sul diox—0 at RT for 72 hr.

### PHENOXIES

HHA—exc, unaff after 2000 hr at 100% and 120 F. IA, MA, RA—satis when prop compounded. SS—exc; unaff after 2000 hr in 5% at 95 F. NFW, DW, HPW, BFW, WW, RW, BW—exc; 0.28% wt gain after immersion 7 days. No meas dimen chg. SW—0.33% wt gain after 7 days in 10% at RT; 0.1% chg in width.

Ac A—glacial: swells; 10%: 0.32% wt gain in 7 days with 0-0.25% dimen incr. Ars A, Bor A, Chr A, Cit A—no att. Fat A—may stress crack. HCl (conc)—0.16% wt gain with 0-0.36% dimen incr. HF—not recom. Nit A—10%: 0.25% wt incr; conc: disintegrates. Ph A—not att. Sul A (38%)—0.21% wt gain and 0.15 and 0.1% incr in width and length after 7 days. Alc (95% eth)—4.3% wt gain in 7 days. Chl sol (CCl<sub>4</sub>)—0.09% wt gain and 0.05-0.36% dimen incr. Est—swells. Hyd—tol: 8.2% wt gain; zyl: 0.58% wt gain; aliphatics: no att. Ket—swelling.

Amm nit—no att. Anhyd amm—no att. But alc—stress crack. Cal chl, Cal hyd—no att. Chl—not recom. Det—0.26% wt incr in 8.4% Tide sol. Stress crack. Eth ac—swell. Eth chl—not recom. Glyc—0.12% wt gain. Glycols—0.03% wt gain and 0-0.15% dimen incr. Hyd per—0.34% wt gain and 0-0.1% dimen incr. Hyd sul—no att. Iso alc—stress crack. Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh, Pot car, Pot dic, Pot hyd, Ros, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit, Sul diox—no att. T oil—stress crack. Urea, Zn chl, Zn sul—no att.

### POLYALLOMER\*

Atm, Waters—no att. Ac A (5%)—+0.1%. Cit A (10%)—+0.1%. Fat A (oleic)—+0.4-0.7%. HCl (10%)—+0.1%. Nit A (70%)—+0.7% (yellows). Sul A (30%)—+0.01. Alc—+0.1%. Chl sol—+10-20%. Est—+6-10%. Hyd—+20% in some; +1-20% in aliphatic. Ket—+2-3%. Cal chl (40% aq)—+0.1%. Glyc, Glycols—+0.1%. Hyd per (30%)—+0.1%. Sod chl (10% aq)—+0.02%. Sod hyd (10% aq)—+0.01%.

\* All figures are % wt change; tests run at 73 F for 1 mo, unless otherwise noted.

### POLYCARBONATES\*

Atm, Waters—no att. Ac A (5%), Ars A, Bor A, Chr A, Cit A (5%), Fat A (10%), For A—no att. HCl—no att to 20%. HF—no att but sl etch to 25%. Nit A—no att to 75%. Ph A (10%)—no att. Sul A—no att to 75%. Alc—meth alc: att, crystallizes; eth alc: no att. Chl sol (CCl<sub>4</sub>)—crazing, stress crack. Hyd—dimeth eth: no att; benz and tol: att, crazing, hazing. Ket (acet)—att, crystallizes.

Acet—att. Ac anh—att, crystallizes. Amm—att. Amm nit—no att. Anhyd amm—att. But alc—no att. Cal chl—no att. Cal hyd—att when wet. Chl—no att. Det—no att in 2% sol. Eth ac, Eth chl—att. Glyc, Glycols, Hyd per (30%), Hyd sul, Iso alc, Mag chl, Mag sul—no att. Pot car—att. Pot dic—no att. Pot hyd—att. Sod bis, Sod chl—no att. Sod hyd (10%)—att. Sod nit (10%)—crazing, stress crack. Sul diox, Urea, Zn chl, Zn sul—no att.

\* Data applicable only at room temp and in unstressed condition.

### POLYESTERS, GLASS-REINFORCED\*

Atm—exc. Waters—OK with all except BFW because of its high temp. Ac A—good to 160 F and 75%. Bor A—exc to 160 F; fair to 212 F. Chr A—fair to good. Cit A—

\* Except for epoxies, covered elsewhere in this section, space limitations do not permit presentation of data on other reinforced plastics. Materials such as asbestos-reinforced phenolics and furanes should not be overlooked where high corrosion resistance is needed.

good to exc. Fat A—good. For A—fair. HCl—fair. HF—not recom. Nit A—fair to 20%. Ph A—good. Sul A—fair to good to 50%. Alc—good. Chl sol, Est, Hyd, Ket—fair.

Amm nit—good. Cal chl—good. Chl—good. Det—good. Glyc—exc. Glycols—good. Hyd per—not recom above 30% and 160 F. Mag car, Mag chl, Phth anh, Pot car, Pot dic—good. Pot hyd—not recom. Sod ac, Sod bis, Sod chl—good. Sod hyd—not recom. Sod nit—good. Sul diox—fair. Zn chl, Zn sul—good.

### POLYETHYLENE\*

Atm, Waters—no att. Ac A—very sl swell. Ars A (conc), Bor A (sat), Chr A (50%), Cit A, Fat A, For A—no att. HCl—faint discol. HF—no att. Nit A (conc)—severe crazing, sl discol, sl swell. Ph A—no att. Sul A—mod discol. Alc—no att. Chl sol—mod to sev swell. Est—sl swell. Hyd—mod etching, sl to sev swell, sev crazing. Ket—sl to mod swell, mod etching.

Acet—no att. Ac anh—very sl swell. Amm—sl swell. Amm nit—no att. Anhyd amm—no att. But alc—sl discol and swell. Cal chl—no att. Cal hyd—sl discol. Chl—sev embrittle. Eth acet—sl swell. Eth chl—sl swell. Glyc, Glycols, Hyd per—no att. Hyd sl—very sl discol. Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh, Pot car, Pot dic—no att. Pot hyd—sl discol. Sod ac—very sl swell. Sod bis, Sod chl—no att. Sod hyd—sl discol. Sod nit, Sul diox, T oil, Urea, Zn chl, Zn sul—no att.

\* Most tests cond by immersing 1/8 by 2-in. disk in reagent in sealed container for 1 mo at 125 F. No agitation applied and specimens not stressed; thus, data cannot be used for predicting performance under stress.

### POLYPROPYLENE

Atm, Waters—Exc to all. Ac A—res to 100% acetic, and to glacial to 68 F; res to 40% sol to 68 F and 10% to 140 F. Chr A—res 1% to 140 F, partly res 10% to 140 F. Cit A—res 10% aq sol to 140 F. For A—res 100% conc to 68 F, and 10% aq sol to 140 F. HCl—res 30% aq to 140 F and 2% to 212 F; partly res 10% to 212 F. HF—res 38-40% aq to 68 F. Nit A—not res fuming, res 50% aq to 140 F. Ph A—res 85% aq to 212 F. Sul A—res 2-10% aq to 212 F, partly res 98% to 140 F, destr by 100%. Alc—exc res to 100% methanol to 140 F. Chl sol—not res to CCl<sub>4</sub>. Est—not res to 100% butyl acetate. Hyd—partly res 100% benz to 68 F, not res 100% xyl at 68 F. Ket—res to 100% acetone to 133 F.

Amm—exc to 30% at 68 F, res to other conc and temp unknown. Det—exc at 120 F, res at higher temp unknown. Eth ac—partly res (3 to 8% swelling after 6 mo at 68 F, 140 F). Glyc—exc to 100%, 212 F. Glycols—exc to 100%, 140 F, res at higher temp unknown. Hyd per—exc at 30%, 68 F; destr at 212 F. Iso alc—exc. Pot hyd, Sod hyd—exc.

### POLYSTYRENES/GENERAL PURPOSE\*

Atm, Waters—no att. Ac A—5%: no att; 25%: no att; glacial (100%): att. Bor A—no att. Chr A (20%)—no att. Cit A—10%: no att; 20%: sl att. Fat A—no att. For A (90%)—sl att. HCl—10%: no att; 38%: sl att. HF—1%: sl att; 48%: att. Nit A (20 and 70%)—att. Ph A (50%)—no att. Sul A—10 and 50%: sl att; conc: att. Alc—no att by eth alc. Chl sol—CCl<sub>4</sub>: solv; perchlor: att; tetrachloroethylene: solv. Est—but acet: solv. Hyd—benz, tol and xyl are solv. Ket—att by acet; MEK and MIBK are solv.

Amm nit—no att. Anhyd amm—no att. But alc—no att. Cal chl, Cal hyd—no att. Chl (sat sol)—att. Det—gen no att. Eth ac—solv. Ethl chl (gas and liq)—att. Glyc, Gly-

\* Gen purp polystyrenes generally have res equal to or greater than rubber-modified polystyrenes. Sl att indicates slight surface crazing or checking; att indicates severe crazing or plastic becomes softened or unusable by end of test; solv indicates medium acts as solvent to plastic. Test time at least 1 week at 70 F.



# Key to Abbreviations

<b>ATMOSPHERES (Atm)</b>	<b>ACIDS</b>	<b>Est—Esters</b>	<b>Eth ac—Ethyl acetate</b>	<b>Pot car—Potassium carbonate</b>
<b>HHA—High humidity</b>	<b>Ac A—Acetic acid</b>	<b>Hyd—Hydrocarbons</b>	<b>Eth chl—Ethyl chloride</b>	<b>Pot dic—Potassium dichromate</b>
<b>IA—Industrial</b>	<b>Ars A—Arsenic</b>	<b>Ket—Ketones</b>	<b>Glyc—Glycerol</b>	<b>Pot hyd—Potassium hydroxide</b>
<b>MA—Marine</b>	<b>Bor A—Boric</b>	<b>OTHER CHEMICALS</b>	<b>Hyd per—Hydrogen peroxide</b>	<b>Ros—Rosins</b>
<b>RA—Rural</b>	<b>Chr A—Chromic acid</b>	<b>Acet—Acetaldehyde</b>	<b>Hyd sul—Hydrogen sulfide</b>	<b>Sod ac—Sodium acetate</b>
<b>SS—Salt spray</b>	<b>Cit A—Citric acid</b>	<b>Ac anh—Acetic anhydride</b>	<b>Iso alc—Isopropyl alcohol</b>	<b>Sod bis—Sodium bisulfate</b>
<b>WATER</b>	<b>Fat A—Fatty</b>	<b>Amm—Ammonia</b>	<b>Mag car—Magnesium carbonate</b>	<b>Sod chl—Sodium chloride</b>
<b>NFW—Natural fresh</b>	<b>For A—Formic</b>	<b>Amm nit—Ammonium nitrate</b>	<b>Mag chl—Magnesium chloride</b>	<b>Sod hyd—Sodium hydroxide</b>
<b>DW—Distilled</b>	<b>HCl—Hydrochloric</b>	<b>Anhyd amm—Anhydrous ammonia</b>	<b>Mag sul—Magnesium sulfate</b>	<b>Sod nit—Sodium nitrate</b>
<b>HPW—Highly purified</b>	<b>HF—Hydrofluoric</b>	<b>But alc—Butyl alcohol, tertiary</b>	<b>Mal anh—Maleic anhydride</b>	<b>Sul diox—Sulfur dioxide</b>
<b>BFW—Boiler feed</b>	<b>Nit A—Nitric</b>	<b>Cal chl—Calcium chloride</b>	<b>Phth anh—Phthalate anhydride</b>	<b>T oil—Tall oil</b>
<b>WW—Well water</b>	<b>Ph A—Phosphoric</b>	<b>Cal hyd—Calcium hydroxide</b>		<b>Zn chl—Zinc chloride</b>
<b>RW—River water</b>	<b>Sul A—Sulfuric</b>	<b>Chl—Chlorine</b>		<b>Zn sul—Zinc sulfate</b>
<b>BW—Brackish water</b>	<b>SOLVENTS (Solv)</b>	<b>Det—Detergents</b>		
<b>SW—Sea water</b>	<b>Alc—Alcohols</b>			
<b>SB—Salt brine</b>	<b>Chl sol—Chlorinated solvents</b>			

cols, Hyd per—no att. Hyd sul—att. Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Pot car, Pot dic—no att. Pot hyd—10 to 30%: no att; sat: sl att. Sod ac, Sod bis, Sod chl, Sod hyd, Zn chl, Zn sul—no att.

## POLYSTYRENES/FOAM\*

Atm, Waters—no att. Acet A—softens in glacial. Bor A—no att. Chr A—cell struct affected, mod abs. Cit A—cell struct affected, mod abs. Fat A—sl cracking of cell walls, sl abs. HCl, HF—cell struct affected, mod abs. Nit A—severe embrittle, high wt gain. Alc—very sl. Chl sol, Est, Hyd, Ketones—not rec.

Amm—no att at RT or below. Anhyd amm—no att at RT or below. But alc—sl cracking. Cal chl, Cal hyd—no att. Chl—sev embrittle. Det—some breakdown cell struct. Eth ac—not rec. Glyc, Glycols—no att. Iso alc—sl breakdown cell struct. Mag car, Mag chl, Mag sul, Mag nit, Phth anh, Sod bis, Sod chl, Sod nit, Zn chl, Zn sul—no att.

\* Tests conducted at 125 F, unless otherwise noted. Chem att is diff to rate because severe att ruptures cell walls, resulting in loss of buoyancy and high wt gains. Thus, data on chem att on base resin may, in many cases, provide better data.

## POLYVINYL CHLORIDE\*

Atm—res. Waters—not res. Ac A—10%: res; 80%: res at 72 F, not res at 140 F; glacial: res at 72 F, not res at 140 F. Ars A (80%)—res. Bor A—res. Chr A—10%: res at 72 F, not res at 140 F; 50%: not res. Cit A—res. Fat A—res. For A—res at 72 F, not res at 140 F. HCl—res to 35%. HF (50%)—res at 72 F, not res at 140 F. Nit A—res 10, 30 and 68%. Ph A—res up to 70% and 80%; not res 85%. Alc—res. Chl sol (CCl<sub>4</sub>)—not res. Est, Hyd, Ket—not res.

Acet—not res. Ac anh—not res. Amm—dry: res; liquid: not res. Amm nit, Anhyd amm, But alc, Cal chl, Cal hyd—res. Chl—not res. Det—res. Eth ac, Eth chl—not res. Glycols, Hyd per, Hyd sul, Mag car, Mag chl, Mag sul, Mag nit, Pot car, Pot dic, Pot hyd, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit—res. Sul diox—dry: res; wet: not res. T oil, Urea, Zn chl, Zn sul—res.

\* Normal impact grade. Unless otherwise specified, data apply at both 72 F and 140 F.

## POLYVINYLIDENE CHLORIDE\*

Atm—no att except sl discol in high IA. Waters—no att. Acetic (glacial)—no att after 3 mo; turns brown in 6 mo and dark brown in 1 yr. Slightly brittle. Ars A (conc)—

\* Rated at 125 F. Most tests conducted by immersing 1/8 by 2-in. disk in reagent in sealed container for 1 mo. No agitation applied and specs not stressed; thus, data cannot be used for predicting performance under stress.

no att. Bor A—no att. Chr A—no att. Cit A (crystals)—no att. Fat A—OK after 3 mo but becomes dark brown after 1 yr. For A—hardens and embrittles. HCl (35%)—within 1 yr becomes dark brown, v hard and brittle. HF (48%)—sl darkening after 1 yr, sl hardening. Nit A (65%)—after 3 mo embrittles and darkens; after 1 yr becomes dark brown, brittle and blisters. Ph A (85%)—no att. Sul A (98%)—blisters, darkens, becomes v brittle after 1 week. Alc—sl incr in hard. Chl sol—sl soft after 1 week; sl decomp after 1 yr. Est—v soft and pliable after 1 week exposure. Hyd, Ket—soft and pliable after 1 week exposure.

Ac anh—soft and pliable. Amm—no att. Amm nit (sat)—sl incr in hard after 1 mo. Anhyd amm—darkens. Cal chl (15%)—darkens and hardens. Cal hyd (sat)—no att after 6 mo. Chl—rapid att. Det—some discol. Eth ac—very soft and pliable in 1 week. Glyc, Glycols—no att. Hyd per—no att after 1 mo. Hyd sul, Iso alc, Mag car, Mag chl, Mag nit, Mal anh, Phth anh, Pot car, Pot dic—no att. Pot hyd (50%)—darkens and hardens after 1 week; embrittles in 3 mo; blisters and becomes v hard after 1 yr. Sod ac, Sod bis, Sod chl—no att. Sod hyd (50%)—same as Pot Hyd. Sod nit—no att. Sul diox (dry), Urea, Zn chl, Zn sul—no att.

## STYRENE-ACRYLONITRILE (SAN)\*

Atm, Waters—no att. Acet A (5%), Bor A, Chr A (6%), Cit A (10%), Fat A, For A (10%), HCl (10%), HF (10%), Ph A (conc), Sul A (30%)—no att. Alc—sl att by meth and 95% eth. Chl sol—gen att. Est—att. Hyd—solv in tol. Ket—gen solv.

Amm nit, But alc, Cal chl, Cal hyd, Det—no att. Eth ac—att. Glyc, Glycols (eth glyc), Hyd per (5%), Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Pot car, Pot dic, Pot hyd (10%), Sod ac, Sod bis, Sod chl (10%), Sod hyd (10%), Sod nit, T oil, Zn chl (10%), Zn sul—no att by these media.

\* Sl att indicates slight surface crazing or checking; att indicates severe crazing or plastic becomes softened or unusable by end of test; solv indicates medium acts as solvent. Test time at least 1 week at 70 F.

## UREA FORMALDEHYDE\*

HHA—may cause swell, crack after long exp. IA—no att. MA—not recom. RA—no att. SS—not recom for long exp. Waters—satis in short intermittent exp, but not recom for long exp. Bor A—no att. Chr A (5%)—shows att after 4 hr at 75 F. Cit A (10%)—att after 7 days at 75 F. HCl, HF, Nit A, Ph A—att after long exp in low conc. Sul A (1%)—att after 7 days at 75 F. Ket—no att after 7 days at 75 F.

\* Alpha cellulose-filled molding compound.

## URETHANE FOAMS\*

HHa—v slow hydrs; rate incr with temp; polyester type att more rapid than polyether type. IA—aff by oxides of nitrogen. MA—v slow hydrs. RA—no att. SS—v slow hydrs. NFW, DW, HPW—same as HHA. BFW—hydrs rate incr if alkaline. WW, RW, BW, SW, SB—v slow hydrs. Ac A—att at high conc. Ars A, Bor A—v slow hydrs. Chr A—att. Cit A—v slow hydrs. Fat A—slow att. For A—hydrs. HCl—complete hydrs at high conc. HF—comp hydrs. Nit A—att at high conc. Ph A, Sul A—complete hydrs at high conc.

Alc—swell when immersed but rel little perm eff if exposed cold and redried. Chl sol—same as Alc; no perm damage from std dry clean processes. Est—same as Alc. Hyd—sl swell. Ket—high swell; no perm damage if exposed cold and redried.

Acet—no eff from short exp; slow reac after long cont use. AcAnh—slow reac. Amm (aq)—slow att from hydrs. Amm nit—poss slow oxid. Anhyd amm—slow att. Cal chl—not att dry. Cal hyd—promotes hydrs in aq sol. Chl—att, partic polyether types, by oxid. Det (aq sol)—v slow hydrs on long exp; att accel in strong det or at high temp. Eth ac, Eth chl—same as Alc. Glyc, Glycols—no att cold. Hyd per—polyether type may be oxid. Hyd sul—poss v slow att. Iso alc—same as Alc. Mag car, Mag chl, Mag sul, Mag nit—no att dry. Mal anh, Phth anh—no signif att at RT. Pot car—catalyzes hydrs in aq sol. Pot dic—may be oxid by aq sol. Pot hyd—hydrs by aq sol. Ros—no att at RT. Sod ac, Sod bis, Sod chl—no att dry. Sod hyd—hydrs in aq sol. Sod nit, Sul diox—no att dry. T oil—slow att. Urea—no att. Zn chl, Zu sul—no att dry.

\* Hydrs means hydrolysis. All chem from Acet on are anhydrous unless otherwise noted. In general, urethane foams adversely aff by strong acids, bases and oxid agents. Of two main types, polyester type has less res to hydrs, but more res to oxid than polyether type.

## ELASTOMERS

### FLUOROELASTOMER\*

Atm—no att. NFW (158 F)—+9.8% after 6 mo; +16% after 24 mo. Ac A (glac)—+62% after 7 days at 75 F. HCl (37%)—+3.2% after 7 days at 158 F; +7.2 after 24 mo at 100 F. HF (48%)—+1.5% after 7 days at 75 F. Nit A (70%)—+2.7% after 7 days at 75 F; +38% after 12 mo at 100 F. Ph A (60%)—+4.2% after 28 days at 212 F. Sul A—60%: +0.5% (158 F) and +10% (250 F) after 28 days. Alc—sl to mod swell. Chl sol (CCl<sub>4</sub>)—+1.3% after 7 days at 75 F; +12% after 28 days at 158 F. Est—heavy swell. Hyd—benz: +20% after 7 days at 75 F; tol: +8% after 3 days at 75 F; xyl: +17% after 5 days at 122 F. Ket—acet: heavy swell; MEK: heavy swell; methyl isobutyl ketone: heavy swell.

Ac anh—+140 % after 7 days at 75 F. Anhyd amm—fuses and hardens. Det (1% bleach sol)—+2.6% after 30 days at 212 F. Phth anh—+42% after 1 day at 400 F. Sod hyd (46.5%)—+2.1% after 7 days at 75 F; -9.5% after 6 mo at 100 F.

\* Viton. All figures are % vol chg.

### BUTYL RUBBER\*

Waters—recom. Ac A—not recom in 80% and glacial. Ars A, Bor A—recom. Chr A—not recom in all. Cit A—recom. Fat A—lim recom. For A, HCl (muriatic), HF—recom. Nit A—not recom. Ph A—recom. Sul A—50% (100 F): recom; 79%: lim recom. Alc—recom. Chl solv—not recom.

\* Publication 61-13, NACE Technical Committee Report, National Assn. of Corrosion Engineers. Key: recom = recommended, good svc can be expected; lim recom = limited recommendation, good svc may be expected under some condn such as intermittent exposure; not recom = not recommended, svc poor or insuffic data available, but adequate svc often may be obt under special condn.

Est—lim recom. Hyd—not recom. Acet—100%: lim recom; 40%: recom. Amm, Amm nit, But alc, Cal chl, Cal hyd, Chl—recom. Eth ac—lim recom. Eth chl—not recom. Glyc, Glycols, Hyd per, Hyd sul (dry), Mag chl, Mag sul, Mag nit, Pot car, Pot dic, Pot hyd, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit—recom. Sul diox—lim recom wet. Urea, Zn chl, Zn sul—recom.

### NEOPRENE\*

Ac A—25%: satis; glacial (70 F): questionable. Ars A, Bor A—satis. Chr A—not recom in 50% at 70 F. Cit A—satis in 10% at 85 F. Fat A—satis. HCl—not recom. HF—not recom in 50% at 70 F. Nit A (70 F)—10%: satis; 35, 70%: not recom. Ph A—satis in 85%. Sul A—50%: satis; 95%: not recom. Alc—generally satis. Chl sol—not recom at 70 F. Amm, Amm nit, But alc, Cal chl—satis. Chl—dry (70 F): questionable; wet (100 F)—not recom. Eth ac, Eth chl—not recom. Hyd per—satis in 3% at 70 F. Hyd sul, Mag chl, Mag sul, Pot car, Pot dic, Pot hyd, Sod hyd—satis. Sul diox (liquid)—satis at 170 F. Zn chl, Zn sul—satis.

\* All ratings at 150 F unless otherwise noted. From "Elastomeric Linings," M/DE, Aug '57, p 94.

### NITRILE RUBBER

Atm—exc to all, except good to exc to IA. Waters—exc. to all, except good to exc in BFW and SB. Ac A—fair to good. Ars A—good. Bor A—exc. Chr A—poor to fair. Cit A—good. Fat A—exc. For A—fair to good. HCl—20%: exc at RT, good at 158 F; 37%: good at RT; fair to good at 158 F. HF—48%: good; 75%: not recom. Nit A—20%: exc at RT, fair at 158 F; 40%: fair to good at RT, not recom at 158 F; 50+ %: not recom. Ph A (20 and 40%)—exc at RT and 158 F. Sul A—17%: exc at RT; 30, 42 and 56%: good to exc at 158 F; 70%: fair to good at RT, not recom at 158 F. Alc—aliphatics: exc at RT, good to exc at 158 F; aromatics: poor. Chl sol—good to exc if complete H subst with Cl; poor to fair if unsubst H. Est—fair to good at RT and 158 F. Hyd—aliphatics: good to exc; oils—gen exc; aromatics: fair to good. Ket—poor.

Acet—fair; 50-60% vol swell. Ac anh—poor to fair. Amm—exc; 3-10% vol swell. Amm nit—exc. Anhyd amm—exc. But alc—2-6% vol swell. Cal chl—exc; 0-3% vol swell. Cal hyd—3-6% vol swell. Chl—good. Det—good to exc. Eth ac—not recom. Eth chl—fair to good. Glyc—exc; 0-4% vol swell. Glycols—gen good to exc. Hyd per (30%)—exc; 7-10% vol swell. Hyd sul—good at RT; not recommended at temperatures >212 F. Iso alc—exc; 2-8% vol swell. Mag car—good to exc. Mag chl (18%)—exc; 1-4% vol swell.

Mag sul, Mag nit—good to exc. Mal anh—good. Phth anh—fair to good. Pot car—exc; <5% vol swell. Pot hyd (30%)—exc; 0-5% vol swell. Ros—good. Sod ac—exc; <3% vol swell. Sod bis—good to exc. Sod chl—exc; 0-2% vol swell. Sod hyd—exc in 10, 20, 30, 40 and 50%. Sod nit—exc; 0-3% vol swell. Sul diox—fair. T oil—good to exc. Urea—poor. Zn chl—exc; 0-3% vol swell. Zn sul—0-3% vol swell.

### POLYSULFIDE RUBBER\*

Atm, Waters—satis. Ac A, Ars A, Bor A—satis. Chr A—unsatis. Cit A, Fat A—satis. For A—unsatis. HCl—satis. HF, Nit A, Ph A—unsatis. Sul A, Alc, Chl sol, Est, Hyd, Ket—satis. Acet, Ac anh, Amm, Amm nit, Anhyd amm, But alc, Cal chl, Cal hyd—satis. Chl—unsatis. Det, Eth ac, Eth chl, Glyc, Glycols—satis. Hyd per, Hyd sul—unsatis. Iso alc, Mag car, Mag chl, Mag sul, Mag nit—satis. Mal anh—unsatis. Phth anh, Pot car—satis. Pot dic—unsatis. Pot hyd, Ros, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit—satis. Sul diox—unsatis. T oil, Urea, Zn chl, Zn sul—satis.

\* Thiokol polysulfide polymer, Type FA.



## Key to Abbreviations

<b>ATMOSPHERES (Atm)</b>	<b>ACIDS</b>	<b>Est—Esters</b>	<b>Eth ac—Ethyl acetate</b>	<b>Pot car—Potassium carbonate</b>
HHA—High humidity	Ac A—Acetic acid	<b>Hyd—Hydrocarbons</b>	<b>Eth chl—Ethyl chloride</b>	<b>Pot dic—Potassium dichromate</b>
IA—Industrial	Ars A—Arsenic	<b>Ket—Ketones</b>	<b>Glyc—Glycerol</b>	<b>Pot hyd—Potassium hydroxide</b>
MA—Marine	Bor A—Boric	<b>OTHER CHEMICALS</b>	<b>Hyd per—Hydrogen peroxide</b>	<b>Ros—Rosins</b>
RA—Rural	Chr A—Chromic acid	<b>Acet—Acetaldehyde</b>	<b>Hyd sul—Hydrogen sulfide</b>	<b>Sod ac—Sodium acetate</b>
SS—Salt spray	Cit A—Citric acid	<b>Ac anh—Acetic anhydride</b>	<b>Iso alc—Isopropyl alcohol</b>	<b>Sod bis—Sodium bisulfate</b>
	Fat A—Fatty	<b>Amm—Ammonia</b>	<b>Mag car—Magnesium carbonate</b>	<b>Sod chl—Sodium chloride</b>
<b>WATER</b>	For A—Formic	<b>Amm nit—Ammonium nitrate</b>	<b>Mag chl—Magnesium chloride</b>	<b>Sod hyd—Sodium hydroxide</b>
NFW—Natural fresh	HCl—Hydrochloric	<b>Anhyd amm—Anhydrous ammonia</b>	<b>Mag sul—Magnesium sulfate</b>	<b>Sod nit—Sodium nitrate</b>
DW—Distilled	HF—Hydrofluoric	<b>But alc—Butyl alcohol, tertiary</b>	<b>Mag nit—Magnesium nitrate</b>	<b>Sul diox—Sulfur dioxide</b>
HPW—Highly purified	Nit A—Nitric	<b>Cal chl—Calcium chloride</b>	<b>Mal anh—Maleic anhydride</b>	<b>T oil—Tall oil</b>
BFW—Boiler feed	Ph A—Phosphoric	<b>Cal hyd—Calcium hydroxide</b>	<b>Phth anh—Phthalate anhydride</b>	<b>Zn chl—Zinc chloride</b>
WW—Well water	Sul A—Sulfuric	<b>Chl—Chlorine</b>		<b>Zn sul—Zinc sulfate</b>
RW—River water	<b>SOLVENTS (Solv)</b>	<b>Det—Detergents</b>		
BW—Brackish water	Alc—Alcohols			
SW—Sea water	Chl sol—Chlorinated solvents			
SB—Salt brine				

### SILICONE RUBBER\*

Atm—exc; highly res to ozone but gen more perm to gases than other mat. Waters—exc to all except those cont strong bases or oxid acids. Ac A, Cit A, Fat A—exc. HCl—good to dil. HF—att. Nit A—strong sol may att. Ph A—exc to weak; poor to exc when heated. Alc—exc. Chl sol—use fluorosilicones. Est—poor. Hyd—poor, but fluorosilicones good to exc. Ket—fair to good; fluorosilicones att.

Amm—fair to exc. Anhyd amm—fair to good. But alc—exc. Cal chl—exc. Cal hyd—good. Det—exc. Eth chl—poor. Glyc—exc. Glycols—exc. Hyd per—exc. Iso alc—good. Pot car—good to exc. Ros—exc. Sod ac—exc. Sod bis—good. Sod chl—exc. Sod hyd—weak sol: exc; strong sol: poor. Sul diox—exc. Urea—exc. Zn chl, Zn sul—good to exc.

\* Silicone resins somewhat more inert and res to chem att than silicone rubbers because of their greater crosslinking.

## OTHER NONMETALLICS

### GLASS\*

Atm—exc; only pres of water in atm produces any meas att. Waters—any corr involves ion exchange, hydration and selective attack. Corr increases sharply with temp, a factor of 10 for every 45°C. NFW—exc; <0.0002 ipy at <212 F. DW, HPW—exc; <0.0002 ipy at <212 F; minute amounts of sodium and boron are extracted, but rate of extraction falls off rapidly with time. BFW, WW, RW—exc; <0.0002 ipy at <212 F. BW—exc; <0.002 ipy at <212 F. SW, SB—exc; <0.002 ipy at <212 F; water with appreciable salt content corrodes somewhat more rapidly than pure water.

Acids—corr by most acids is very low below bp. Corr is not linear function of time and effect of conc is slight; effect of temp is also sl and corr rate doubles for about every 50°C rise. However, corr rate may be signif higher in superheated acids. Ac A, Ars A, Bor A, Chr A, Cit A, Fat A, For A, HCl—exc; <0.001 ipy at <212 F. HF—generally unsatis; conc HF is extremely corrosive (e.g., 48% at RT corrodes at 2000 ipy), however, rate drops off rapidly as conc decreases (e.g., 10% at RT corrodes at only 0.4 ipy). Nit A—exc; <0.001 ipy at <212 F. Ph A

\* Code 7740. Data apply to agitated liquids. Although data are given as depth of penetration, degradation of appearance and transparency sometimes occur. Molten aluminum, magnesium and other electropositive metals react with Code 7740 glass at high temp. Thus, use of glass is not recom with these metals for continuous use but is all right for short periods.

—exc; <0.001 ipy at <212 F; not unduly corrosive <212 F provided no fluorides are present; however, at higher temp, rate incr faster than for most other acids. Sul A—exc; <0.001 ipy at <212 F. Solv—exc; <0.0001 ipy; organic solv cause little corr but some solv may extract minute quant of soluble components such as sodium or boron.

Acet, Ac anh—exc; <0.0001 ipy at <bp. Amm, Anhyd amm—poor to exc; corr by strong alkalis is relatively higher but not excessive for many appl. Amm nit—exc; <0.002 ipy at <212 F. But alc—exc; <0.0001 ipy at <bp. Cal chl—exc; <0.002 ipy at <212 F. Cal hyd, Det, Mag car, Pot car—fair to exc; corr by strong alkalis is rel higher but not excessive for many appl. Eth ac—exc; <0.001 ipy at <bp. Eth chl—exc; <0.001 ipy at <bp; Hyd per, Hyd sul—exc; <0.001 ipy at <212 F. Iso alc—exc; <0.001 ipy at <bp. Mag chl, Mag sul, Mag nit—exc; <0.002 ipy at <212 F. Mal anh, Phth anh—exc; <0.0001 ipy at <bp. Pot dic—exc; <0.002 ipy at <212 F. Pot hyd, Sod hyd—unsatis to exc; corr by strong alkalis is relatively higher but not excessive for many appl. Ros—exc; <0.0001 ipy at <bp. Sod ac, Sod bis, Sod chl, Sod nit—exc; <0.002 ipy at <212 F. T oil, Urea—exc; <0.0001 ipy at <212 F. Zn chl, Zn sul—exc; <0.002 ipy at <212 F.

### GRAPHITE AND CARBON\*

Atm, Waters—no att. Ac A—res. Chr A—res 0-10% to 200 F. Cit A, Fat A, For A, HCl, HF—res. Nit A—res 0-10% to 185 F; 10-20% to 140 F; not res over 20%. Ph A—res. Sul A—res 0-90% at all temp; 90-96% to 480 F; above 96% at RT. Solv—res. Acet, Ac anh, Amm, Amm nit, Anhyd amm, But alc, Cal chl, Cal hyd—res. Chl (dry)—res to 3000 F. Det, Eth ac, Eth chl, Glyc, Glycols—res. Hyd per—res all conc at RT. Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh, Pot car, Pot dic, Pot hyd, Ros, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit, Sul diox, T oil, Urea, Zn chl, Zn sul—res.

\* Unless otherwise specified, res means res to all conc and temp. Carbon not recommended in environments cont air where temp of carbon exceeds 620 F. Graphite not recom in environments cont air where temp of graphite exceeds 720 F. (See also Graphite, Impervious.)

### GRAPHITE, IMPERVIOUS/CARBON-IMPREGNATED\*

Atm, Waters—no att. Ac A, Ars A, Bor A—res. Chr A—res 0-10% to 200 F. Cit A, Fat A, For A, HCl, HF—res. Nit A—see Carbon and graphite. Ph A—res. Sul A—res 0-90% at all temp; 90-96% to 480 F; above 96% at RT. Solv—res.

Acet, Ac anh, Amm, Amm nit, Anhyd amm—res. But alc, Cal chl, Cal hyd, Chl (dry), Det, Eth ac, Eth chl,

\* Unless otherwise specified, res means res to all conc and temp.



Glyc, Glycols—res. Hyd per—res all conc at RT. Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh, Pot car, Pot dic, Pot hyd, Ros, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit, Sul diox, T oil, Urea, Zn chl, Zn sul—res.

#### GRAPHITE, IMPERVIOUS/RESIN-IMPREGNATED\*

Atm, Waters—no att. Ac A, Ars A—res all conc to 340 F. Chr A—res 0-10%. Amm, Anhyd amm, Amm nit—res all conc to 340 F. But alc—see Chl sol. Cal chl, Cal hyd, Chl (dry), Det—res all conc to 340 F. Eth ac, Eth chl—see Chl sol. Gly, Glycols—res all conc to 340 F. Hyd per—res all conc at RT. Hyd sul—res all conc to 340 F. Iso alc—see Chl sol. Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh, Pot car, Pot dic—res all conc to 340 F. Pot hyd—res 6-67% to bp; 67-80% to 275 F. Ros, Sod ac, Sod bis, Sod chl—res all conc to 340 F. Sod hyd—res 6-67% to bp; 67-80% to 275 F. Sod nit, Sul diox, T oil, Urea, Zn chl, Zn sul—res all conc to 340 F. 200 F. Cit A, Fat A, For A, HCl—same as Ac A. HF—res 0-48% to boil; 48-60% to 185 F; not res over 60%. Nit A—see Carbon and graphite. Ph A—res 0-85% to 340 F. Sul A—res 0-70% to boil; 70-85% to 340 F; 85-90% to 300 F; 90-93% to 185 F; not res over 96%. Alc—same as Ac A. Chl sol, Est, Hyd, Ket, Acet, Ac anh—res all conc to bp.

\* Unless otherwise specified, res means res to all conc and temp.

#### STONEWARE

Atm, Waters—res all except for slight leaching of silica in hot DW, HPW and DW. Ac A—res all conc to at least 250 F. Ars A, Chr A, Cit A, Fat A, For A, HCl—res. HF—silica is att at any temp; OK if acid washed away quickly. Nit A—res. Ph A—res all conc to 150 F if HF not pres. Sul A—res all conc below 300 F. Solv—res all at any temp and conc. Acet, Ac anh, Amm nit, Anhyd amm, Amm, But alc, Cal chl, Cal hyd, Chl, Det, Eth ac, Eth chl, Glyc, Glycols, Hyd per, Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh—res. Pot car—sl att above 150 F. Pot dic—res. Pot hyd—slowly att but long life below 100 F; not res for long use above 125 F. Ros, Sod ac, Sod bis, Sod chl—res. Sod hyd—same as Pot Hyd. Sod nit, Sul diox, T oil, Urea, Zn chl, Zn sul—res.

## COATINGS AND LININGS

#### ALUMINUM COATINGS\*

HHA—exc. IA—exc. MA—good. RA—exc. SS—better than galvanized. Waters—not recom. Acids—not apt to be used with acids. Solv—not apt to be used with solv. Pot hyd—coating diss. Ros—OK. Sod hyd—coating diss. Other chem—Because hot dip aluminum coatings are primarily used for atm corr res, few data have been prepared on chem res.

\* Hot dip, type 2.

#### CADMIUM ELECTROPLATES

Atm—generally exc. Water—generally exc. No data on res to acids and chem.

#### CHROMIUM ELECTROPLATES\*

Atm, Water—gen exc. Ac A—0.015 ipy. Ars A—0.011 ipy. Cit A—0.007 ipy. For A—1.2 ipy. Nit A—0.012 ipy. Ph A—10%: 0.034 ipy; 85%: 0.002 ipy. Sul A—10%: 10 ipy; 100%: 0.069 ipy. Chl sol (CCl<sub>4</sub>)—dry: no att; wet: att. Cal chl, Mag chl, Sod chl, Sod hyd—no att. Zn chl—0.001 ipy.

\* Conc is 10% by vol for both solutes and liquids unless otherwise stated; test temp is 136 F. From *Corrosion Handbook*, Herbert H. Uhlig, John Wiley & Sons, Inc., New York, 1948.

#### CERAMIC LININGS\*

DW—<2 mpy to bp; 20 to 50 mpy at 350 F. Ac A—2 to 20 mpy with 20% at bp, and with 10% and 40% at 350 F. HF (20%)—2 to 20 mpy at bp; >50 mpy at 350 F. Sul A—2 to 20 mpy with 10, 50 and 70% at bp. Sod hyd—2 to 20 mpy with 5% at 150 F.

\* Nucelite.

#### CHLORINATED RUBBER COATINGS\*

NFW—DW, SW—res. Ac A—not res to 20% and conc. Chr A—5%: res; 40%: not res. Cit A—res. HCl—10%: res; conc: not res. HF—res 10 and 30%. Nit A—10%: res; conc: not res. Ph A—10%: res; conc: not res. Cal chl—res. Chl—res. Hyd per (30%)—not res. Sod ac, Sod chl—res. Sod hyd—res to dil and conc.

\* All values at 120 F.

#### EPOXY COATINGS

Atm, Waters—exc. Ac A—10%: exc; glacial: fails. HCl—exc. Nit A (30%)—att. Ph A—exc at 4 and 10%; poor at 43, 64 and 85%. Sul A—3%: exc; 70%: att. Ket (acet)—att. Eth ac—att. Sod hyd—exc at 1, 5, 20 and 50%. Sod chl (20%)—exc.

\* Solvent-free type. *Corrosion Technology*, May '61, p 135.

#### FURANE COATINGS

Atm, NFW, DW, HPW, BW, SW, SB—no att. Ac A—10%: no att on baked (275 F) coating; 99.5%—slight stain on RT-cured coat. Ar A, Bor A—no att. Chr A—slight stain and dull. Cit A, Fat A—no att. For A—baked: no att; RT-cured: stain. HCl—no att. Nit A—10%: no att; 25+ %: att. Ph A—no att. Sul A—50%: no att; 60-75%: OK baked at 275 F. Alc—no att. Chl sol (CCl<sub>4</sub>)—dulls RT-cured; no att on baked (275 F). Hyd—no att. Ket (MEK)—dulls RT-cured; no att on baked (275 F). Amm, Cal chl, Cal hyd, Det—no att. Eth ac—dulls RT-cured; no att on baked (275 F). Glyc, Glycols, Hyd per, Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh, Pot car, Pot hyd, Ros, Sod ac, Sod bis, Sod chl, Sod hyd, Sod nit, Sod diox, T oil, Urea, Zn chl, Zn sul—no att.

#### GLASS LININGS\*

Atm—exc, but primary use is on interior surfaces. DW—to 190 F: <2 mpy; 210-250 F: 2 to 20 mpy; 350 F (special glasses): 20 to 50 mpy; >350 F (standard glasses): >50 mpy. Other waters—generally same res as DW except for high (>10) pH waters at high (>150 F) temp, and high pur waters at high temp.

Ac A—<2 mpy at all conc to bp; <2 mpy with 50% at 300 F; 2 to 20 mpy with 10-40% at 350 F; >50 mpy with 5% at 400 F. Chr A—<2 mpy with 2-60% at RT. Cit A—<2 mpy with 2-66% at RT. Fat A—<2 mpy with 100% at 240 F. For A—<2 mpy with 2-86% at RT. HCl—<2 mpy at RT; 2 to 20 mpy with 14-37% at bp; 20 to 50 mpy with 5% at 325 F, 20% at 350 F, 37% at 400 F, and 5% at 425 F. HF—>50 mpy with 5 and 50% at RT. Nit A—<2 mpy with 100% at 175 F and 0.1-73% at bp; 2 to 20 mpy with 40% at 350 F. Ph A—<2 mpy with 60% at 200 F; 2 to 20 mpy with 60% at 250 F; >50 mpy with 60% at 350 F. Sul A—<2 mpy with 60% at 212 F; 2 to 20 mpy with 40 and 50% at 350 F; 20 to 50 mpy with 5 and 20% at 350 F. Solv—little data but high res can be expected.

Ac anh—<2 mpy with 100% at RT and 450 F. Amm (aq)—2 to 20 mpy with 10% at 160 F and 1-20% at bp. Amm nit—<2 mpy with 1-20% at bp. Cal chl—2 to 20 mpy with 1-20% at bp. Cal hyd—2 to 20 mpy with 7% at 212 F. Chl—<2 mpy with 100% wet at 100 and 212 F. Hyd per—<2 mpy with 90% at 150 F. Mag nit—

\* Glasteel. In general, corr rate up to 8 mpy indicates mtl is acceptable; 8 to 20 mpy indicates not res unless, of course, high rate can be tolerated for specific process.

# Key to Abbreviations

<b>ATMOSPHERES (Atm)</b>	<b>ACIDS</b>	<b>Est—Esters</b>	<b>Eth ac—Ethyl acetate</b>	<b>Pot car—Potassium carbonate</b>
HHA—High humidity	Ac A—Acetic acid	<b>Hyd—Hydrocarbons</b>	<b>Eth chl—Ethyl chloride</b>	<b>Pot dic—Potassium dichromate</b>
IA—Industrial	Ars A—Arsenic	<b>Ket—Ketones</b>	<b>Glyc—Glycerol</b>	<b>Pot hyd—Potassium hydroxide</b>
MA—Marine	Bor A—Boric	<b>OTHER CHEMICALS</b>	<b>Hyd per—Hydrogen peroxide</b>	<b>Ros—Rosins</b>
RA—Rural	Chr A—Chromic acid	<b>Acet—Acetaldehyde</b>	<b>Hyd sul—Hydrogen sulfide</b>	<b>Sod ac—Sodium acetate</b>
SS—Salt spray	Cit A—Citric acid	<b>Ac anh—Acetic anhydride</b>	<b>Iso alc—Isopropyl alcohol</b>	<b>Sod bis—Sodium bisulfate</b>
<b>WATER</b>	Fat A—Fatty	<b>Amm—Ammonia</b>	<b>Mag car—Magnesium carbonate</b>	<b>Sod chl—Sodium chloride</b>
NFW—Natural fresh	For A—Formic	<b>Amm nit—Ammonium nitrate</b>	<b>Mag chl—Magnesium chloride</b>	<b>Sod hyd—Sodium hydroxide</b>
DW—Distilled	HCl—Hydrochloric	<b>Anhyd amm—Anhydrous ammonia</b>	<b>Mag sul—Magnesium sulfate</b>	<b>Sod nit—Sodium nitrate</b>
HPW—Highly purified	HF—Hydrofluoric	<b>But alc—Butyl alcohol, tertiary</b>	<b>Mag nit—Magnesium nitrate</b>	<b>Sul diox—Sulfur dioxide</b>
BFW—Boiler feed	Nit A—Nitric	<b>Cal chl—Calcium chloride</b>	<b>Mal anh—Maleic anhydride</b>	<b>T oil—Tall oil</b>
WW—Well water	Ph A—Phosphoric	<b>Cal hyd—Calcium hydroxide</b>	<b>Phth anh—Phthalate anhydride</b>	<b>Zn chl—Zinc chloride</b>
RW—River water	Sul A—Sulfuric	<b>Chl—Chlorine</b>		<b>Zn sul—Zinc sulfate</b>
BW—Brackish water	<b>SOLVENTS (Solv)</b>	<b>Det—Detergents</b>		
SW—Sea water	Alc—Alcohols			
SB—Salt brine	Chl sol—Chlorinated solvents			

<2 mpy with conc at 350 F. Sod hyd—<2 mpy with 1-20% at 70 F; >50 mpy with 1-20% at 210 F.

## POLYESTER COATINGS\*

Atm—v good. Waters—exc. Ac A (50%)—no eff. Fat A (linseed), HCl (50%), Nit A (50%)—v sl discol. Sul A (50%)—no eff. Sod hyd (10%)—mod dull.

\* Low-luster protective polyester.

## PORCELAIN ENAMELS\*

HHA—no att. IA—sl eff on AR type after 20 yr; some non-AR types fade and lose gloss but metal not aff. MA, RA—no att on AR. SS—no att after 400 hr, v little thereafter. Waters—no att. Ac A, Ars A, Bor A—AR is highly res; other types etched. Fat A—no att. For A—same as Ac A. HCl—AR not att; other types attacked more than by Ac A. HF—att. Nit A—about same as Ac A. Ph A—slight less than HCl. Sul A—about same as HCl. Solv—no att.

Acet—no att. Ac anh—no att cold. Amm, Amm nit, Anhyd amm, But alc, Cal chl, Cal hyd, Chl—no att. Det—no att when cold but may show sl etch after long exp

\* AR means acid resistant type. All ord pore enamels have rel poor res to two types of environments: HCl and hot (>225 F) conc caustic alkali sol. All pore enamels gen unaff by org solv and resins, and by alk sol at RT. They are also inert to oxid and reduc sol. Acid resistant (AR) enamels can be prod to withstand prac all org and min acids, even at elev temp.

to hot; spec res enamels avail. Eth ac, Eth chl, Glyc, Glycols, Hyd per, Hyd sul, Iso alc, Mag car, Mag chl, Mag sul, Mag nit, Mal anh, Phth anh—no att. Pot car—same as Det. Pot dic—no att. Pot hyd—no att when cold; sev etch in hot conc sol. Ros—no att. Sod ac—att in cold sol. Sod bis, Sod chl—no att. Sod hyd—same as Pot Hyd. Sod nit, Sul diox, T oil, Urea, Zn chl, Zn sul—no att.

## URETHANE COATINGS

Atm—good to exc. Waters—fair to exc. Ac A, Bor A, Chr A—poor to v good. Cit A—good to exc. Fat A—fair to exc. For A, HCl, HF—poor to v good. Nit A—poor to good. Ph A—poor to v good. Sul A—poor to good. Ph A—poor to v good. Sul A—poor to good. Alc, Chl sol—poor to exc. Est—poor to v good. Hyd—fair to exc. Ket—poor to v good.

Ac anh—poor to good. Amm—fair to exc. Amm nit—good to exc. But alc—poor to exc. Cal chl—good to exc. Cal hyd—fair to exc. Chl—poor to v good. Det—poor to exc. Eth ac, Eth chl—poor to v good. Glyc, Glycols, Hyd per, Hyd sul, Iso alc—fair to exc. Mag car—good to exc. Mag chl—fair to exc. Mag sul, Mag nit—good to exc. Mal anh, Phth anh—good to exc. Pot car—poor to v good. Pot dic—fair to exc. Pot hyd—poor to v good. Ros, Sod ac, Sod bis, Sod chl—good to exc. Sod hyd—poor to v good. Sod nit—good to exc. Sul diox—poor to v good. T oil, Urea, Zn chl, Zn sul—good to exc. ■■

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# Corrosion Terms You Should Know

**Active potential.** An electric potential associated with the condition of corrosion, as contrasted with a condition of passivity.

**Anion.** A negatively charged ion or radical which migrates toward the anode under the influence of a potential gradient.

**Anode.** An electrode or portion of an electrode at which a net oxidation reaction occurs.

**Anodic protection.** The reduction or elimination of corrosion that can sometimes be obtained by making current flow from it to the solution, as by connecting it to the positive pole of a source of current. Under most conditions, as the potential of an initially active metal is gradually shifted in a more noble direction (as by potentiostatic means) the corrosion current gradually increases. However, with suitable combinations of metal and solution, a critical potential is soon reached. At somewhat higher values of the potential the current drops to a very low value, and the metal becomes passive. (See also Cathodic Protection.)

**Cathode.** An electrode or portion of an electrode at which a net reduction reaction occurs.

**Cathodic corrosion.** An increase in corrosion of a metal caused by making it cathodic.

**Cathodic protection.** Reduction or prevention of corrosion of a metal surface caused by making it cathodic; e.g., by using a sacrificial anode or impressed current. (See also Anodic Protection.)

**Cation.** A positively charged ion or radical which migrates toward the cathode under the influence of a potential gradient.

**Caustic embrittlement.** Stress-corrosion cracking in alkaline solutions.

**Cavitation damage.** Deterioration caused by the formation and collapse of cavities in a liquid.

**Cell.** A source of electric current responsible for corrosion. It consists of an anode and a cathode immersed in an electrolyte. The anode and cathode may be separate metals or dissimilar areas on the same metal. When the electrodes are in electrical contact with each other they develop a difference in potential which causes current to flow and produces corrosion at the anode. A cell involving an electrolyte in the corrosion process is referred to as an electrolytic cell.

**Concentration cell.** An electrolytic cell, the emf of which results from differences in the composition of the electrolyte at anode and cathode areas.

**Corrosion fatigue limit.** The maximum stress that a metal withstands without failing when cyclically stressed under corrosive conditions.

**Crevice corrosion.** Localized corrosion resulting from the crevices that are formed between a metal and a nonmetal, or between two metal surfaces.

**Critical humidity.** The value of relative humidity above which the atmospheric corrosion of a metal increases sharply.

**Dezincification.** A corrosion phenomenon resulting in parting of zinc from copper-zinc alloys.

**Electrolyte.** An ionic conductor.

**Fretting.** Deterioration resulting from repetitive slip at the interface of two materials. If this deterioration is increased by corrosion, it is referred to as fretting corrosion.

**Galvanic corrosion.** Corrosion associated with the current of a galvanic cell made up of dissimilar electrodes. Also known as a couple action.

**Galvanic series.** A list of metals and alloys arranged according to their relative potentials in a given environment.

**Graphitic corrosion.** Corrosion of gray cast iron in which the metal constituents are converted to corrosion products and the graphite is left intact.

**Intergranular corrosion.** Corrosion that occurs preferentially at grain boundaries.

**Ion.** An electrically charged atom or radical.

**Noble metal.** A metal which in nature commonly occurs in the free state. Also, a metal or alloy whose corrosion products are formed with a low negative or positive free energy change.

**Oxygen concentration cell.** A galvanic cell caused primarily from differences in oxygen concentration.

**pH.** The relative acidity of a solution as determined by the concentration of hydrogen ions. It is defined by the equation:  $pH = \log_{10} (1/a_{H^+})$ , where  $a_{H^+}$  = hydrogen ion activity = the molal concentration of hydrogen multiplied by the mean ion activity coefficient.

**Protective potential.** A term used in cathodic protection to describe the potential as measured against an appropriate half-cell at which all anodic corrosion reactions can be assumed to be eliminated and protection provided for the materials.

**Spalling.** Spontaneous separation of a surface layer from a metal.

**Stray current corrosion.** Corrosion caused by corrosion through paths other than the normal circuit or by extraneous current in the earth.

**Stress corrosion cracking.** Spontaneous cracking produced by the combined action of corrosion and static stress (residual or applied).

**Tuberculation.** The formation of localized corrosion products which are scattered over the surface in the form of knoblike mounds.

**Underfilm corrosion.** Corrosion that occurs under films in the form of randomly distributed hairlines (also known as filiform corrosion). ■ ■

This glossary is based on definitions arrived at by the Intersociety (NACE, ASTM, ECS) Subcommittee on Standard Definitions and Terminology, as well as on definitions published in the *Glossary of Corrosion Terms*, International Nickel Co., Inc., and *The Corrosion Handbook*, John Wiley & Sons, Inc., New York, 1948.

This is the second issue which M/DE has devoted to a single, vital subject. The other was "The Challenge of the Materials Age" (Sept '60)—a comprehensive review of the expanding materials technology and its effects on engineering organization, education, societies, etc. To order either reprint, use the coupon on p 158.