CHAPTER 44
CORROSION

Milton G. Wille, Ph.D., P.E.
Professor of Mechanical Engineering
Brigham Young University
Provo, Utah

44.1 INTRODUCTION

Corrosion removal deals with the taking away of mass from the surface of materials by their environment and other forms of environmental attack that weaken or otherwise degrade material properties. The complex nature of corrosion suggests that the designer who is seriously concerned about corrosion review a good readable text such as *Corrosion Engineering* by Fontana and Greene [44.1].

Included in this chapter are many corrosion data for selected environments and materials. It is always hazardous to select one material in preference to another based only on published data because of inconsistencies in measuring corrosion, lack of completeness in documenting environments, variations in test methods, and possible publishing errors. These data do not generally indicate how small variations in temperature or corrosive concentrations might drastically increase or decrease corrosion rates. Furthermore, they do not account for the influence of other associated materials or how combinations of attack mechanisms may drastically alter a given material's behavior. Stray electric currents should be considered along with the various attack mechanisms included in this chapter. Brevity has required simplification and the exclusion of some phenomena and data which may be important in some applications.

The data included in this chapter are but a fraction of those available. *Corrosion Guide* by Rabald [44.2] can be a valuable resource because of its extensive coverage of environments and materials.

Again, all corrosion data included in this chapter or published elsewhere should be used only as a guide for weeding out unsuitable materials or selecting potentially acceptable candidates. Verification of suitability should be based on actual experience or laboratory experimentation. The inclusion or exclusion of data in this chapter should not be interpreted as an endorsement or rejection of any material.

44.2 CORROSION RATES

The vast majority of metal corrosion data in the United States are expressed in terms of surface regression rate *mpy* (mils, or thousands of an inch, per year). Multiply *mpy* by 0.0254 to obtain millimeters per year (mm/yr). To convert to mass-loss rate, multiply the surface regression rate by surface area and material density, using consistent units.

Polymer attack typically involves volume changes, usually increases, caused by liquid absorption; reductions in mechanical properties such as yield strength, tensile strength, flexure strength, and tensile modulus; discoloration; and/or changes in surface texture. Certain plastics are degraded by ultraviolet light, which limits their usefulness in sunlight unless they are pigmented with an opaque substance such as lamp-black carbon.

44.3 METAL ATTACK MECHANISMS

The attack on metals involves oxidation of neutral metal atoms to form positively charged ions which either enter into solution or become part of an oxide layer. This process generates electrons, which must be consumed by other atoms, reducing them, or making them more negatively charged. Conservation of electrons requires that the rate of metal oxidation (corrosion) equal the rate of reduction (absorption of electrons by other atoms).

44.3.1 General Attack

In general attack, oxidation and reduction occur on the same metal surface, with a fairly uniform distribution. Most of the corrosion data in this chapter are for selected materials subject to uniform attack in a given environment.

Once a suitable material is selected, further control of uniform attack can be achieved by coatings, sacrificial anodes (see Galvanic Corrosion), anodic protection (see Passivation), and inhibitors. Coatings are many times multilayered, involving both metallic and polymer layers. Inhibitors are additions to liquid environments that remove corrosives from solution, coat metal surfaces to decrease surface reaction rates, or otherwise alter the aggressiveness of the environment.

Chemically protective metallic coatings for steels are usually zinc (galvanized) or aluminum (aluminized). Aluminized steel is best for elevated temperatures up to 675°C and for severe industrial atmospheres. Both may be deposited by hot dipping, electrochemistry, or arc spraying. Common barrier-type metallic platings are those of chromium and nickel. The Environmental Protection Agency has severely limited or prohibited the use of lead-bearing and cadmium platings and cyanide plating solutions.

Polymer coatings (such as paints) shield metal surfaces from electron-receiving elements, such as oxygen, reducing corrosion attack rates. Under mild conditions, even "decorative paints" can be effective. Under more severe conditions, thicker and tougher films are used which resist the effects of moisture, heat, chlorides, and/or other undesirable chemicals. Acrylics, alkyds, silicones, and silicone-modified alkyds are the most commonly used finishes for industrial equipment, including farm equipment. The silicones have higher heat resistance, making them useful for heaters, engines, boilers, dryers, furnaces, etc.

44.3.2 Galvanic Corrosion and Protection

When two dissimilar metals are electrically connected and both are exposed to the same environment, the more active metal will be attacked at a faster rate than if there had been no electrical connection between the two. Similarly, the less active metal will be protected or suffer less attack because the surface areas of both metals can be used to dissipate the electrons generated by oxidation of the more active metal. The net flow of electrons from the more active to the less active metal increases the attack rate of the more active metal and decreases that of the less active metal.

An *adverse area ratio* is characterized by having a larger surface area of less active metal than that of the more active metal. Cracks in a barrier protective coating (i.e., polymers) applied to the more active metal in a galvanic-couple situation can create an extremely adverse area ratio, resulting in rapid localized attack in the cracks. The standard electromotive force (emf) series of metals (Table 44.1) lists

TABLE 44.1 Standard EMF Series of Metals

Metal–metal ion equilibrium (unit activity)	Electrode potential vs. normal hydrogen electrode at 25°C, V
$Au\text{-}Au^{3+}$	+1.498
$Pt\text{-}Pt^{2+}$	+1.2
$Pd\text{-}Pd^{2+}$	+0.987
$Ag\text{-}Ag^{+}$	+0.799
$Hg\text{-}Hg_2^{2+}$	+0.788
$Cu\text{-}Cu^{2+}$	+0.337
$H_2\text{-}H^{+}$	0.000
$Pb\text{-}Pb^{2+}$	−0.126
$Sn\text{-}Sn^{2+}$	−0.136
$Ni\text{-}Ni^{2+}$	−0.250
$Co\text{-}Co^{2+}$	−0.277
$Cd\text{-}Cd^{2+}$	−0.403
$Fe\text{-}Fe^{2+}$	−0.440
$Cr\text{-}Cr^{3+}$	−0.744
$Zn\text{-}Zn^{2+}$	−0.763
$Al\text{-}Al^{3+}$	−1.662
$Mg\text{-}Mg^{2+}$	−2.363

metals in order of increasing activity, starting with gold (Au), which is the least active. If two of the metals listed were joined in a galvanic couple, the more active one would be attacked and plating or deposition of the less active one would occur. This is based on the fact that solutions contain only unit activity (concentration) of ions of each of the two metals.

The standard EMF series is valid only for pure metals at 25°C and in equilibrium with a solution containing unit activity (concentration) of its own ions. If ion concentrations are greater than unit activity, the potentials are more positive; if less, the opposite is true.

TABLE 44.2 Galvanic Series of Some Commercial Metals and Alloys in Seawater

↑	Platinum
	Gold
Noble or cathodic	Graphite
	Titanium
	Silver
	[Chlorimet 3 (62 Ni, 18 Cr, 18 Mo)
	Hastelloy C (62 Ni, 17 Cr, 15 Mo)]
	[18-8 Mo stainless steel (passive)
	18-8 stainless steel (passive)
	Chromium stainless steel 11-30% Cr (passive)]
	[Inconel (passive) (80 Ni, 13 Cr, 7 Fe)
	Nickel (passive)]
	Silver solder
	[Monel (70 Ni, 30 Cu)
	Cupronickels (60-90 Cu, 40-10 Ni)
	Bronzes (Cu-Sn)
	Copper
	Brasses (Cu-Zn)]
	[Chlorimet 2 (66 Ni, 32 Mo, 1 Fe)
	Hastelloy B (60 Ni, 30 Mo, 6 Fe, 1 Mn)]
	[Inconel (active)
	Nickel (active)]
	Tin
	Lead
	Lead-tin solders
	[18-8 Mo stainless steel (active)
	18-8 stainless steel (active)]
	Ni-Resist (high Ni cast iron)
	Chromium stainless steel, 13% Cr (active)
	[Cast iron
	Steel or iron]
	2024 aluminum (4.5 Cu,. 1.5 Mg, 0.6 Mn)
Active or anodic	Cadmium
	Commercially pure aluminum (1100)
	Zinc
↓	Magnesium and magnesium alloys

SOURCE: M. G. Fontana and N. D. Greene, *Corrosion Engineering*, 2d ed., McGraw-Hill, New York, 1978. Used by permission.

The galvanic series (Table 44.2) shows a similar relationship, except that impure metals such as alloys are also included and the medium is seawater. Other media, other concentrations, and other temperatures can further alter the order of the list. Therefore, care should be exercised in applying these data to a given galvanic corrosion situation except as a general, loose guide.

44.3.3 Passivation

Certain common engineering materials, such as iron, nickel, chromium, titanium, and silicon as well as their alloys (i.e., stainless steels), exhibit a characteristic of being able to behave both as a more active and as a less active (passive) material.

Note in the galvanic series (Table 44.2) that several stainless steels are listed twice, once as passive and once as active. Some common metals other than those mentioned also exhibit passivity, but to a lesser extent.

A graphical representation of passivity is shown in Fig. 44.1. The three regions—active, passive, and transpassive—help to explain seemingly inconsistent behavior of active-passive materials under various degrees of attack severity.

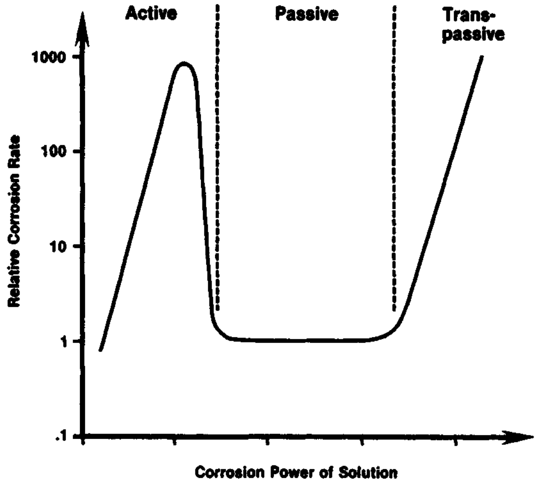

FIGURE 44.1 Corrosion characteristics of an active-passive metal.

There are both advantages and disadvantages to be gained or suffered because of active-passive behavior. In very aggressive environments, a method called anodic protection can be used whereby a *potentiostat* is utilized to electrochemically maintain a passive condition and hence a low rate of corrosion. However, accelerated corrosion test results may be useless because increasing the corrosion power of the medium may cause a shift from a high active corrosion rate to a low passive condition, producing the invalid conclusion that corrosion is not a problem. Another example involves inhibitors which function by maintaining a passive condition. If the concentration of these inhibitors were allowed to decrease, high corrosion could result by passing from a passive to an active condition.

Active-passive materials have a unique advantage in the area of corrosion testing and corrosion rate prediction. *Potentiodynamic polarization* curves can be generated in a matter of hours, which can provide good quantitative insights into corrosion behavior and prediction of corrosion rates in a particular environment. Most other corrosion testing involves months or years of testing to obtain useful results.

44.3.4 Crevice Corrosion and Pitting

Crevice corrosion is related to active-passive materials which are configured such that crevices exist. Mated screw threads, gaskets, packings, and bolted or lapped joints are common examples of crevices. Inside the crevice, oxygen or other corrosives required for passivation have restricted entrance, resulting in reduced concentration as they are consumed by corrosion in the crevice. When the concentration of these corrosives is low enough to fail to maintain passivity, the metal in the crevice becomes active. The large electrically connected, passivated surface outside the crevice completes a galvanic couple with a large adverse-area ratio, providing high attack rates within the crevice. Welding or forming can be used to avoid crevices. However, intergranular corrosion may occur in welded stainless steels (see Sec. 44.3.9).

Pitting is a very localized attack that results in holes, or voids, on a metal surface. Although not restricted to active-passive metals, pitting is commonly related to these. With active-passive metals, pieces of dirt, scale, or other solid particles may rest on the bottom of a pipe or tank where velocities are not sufficient to move them. These particles form crevices, resulting in a localized attack similar to crevice corrosion.

44.3.5 Sacrificial Anodes

Magnesium rods are placed in steel glass-lined hot-water tanks, and zinc is used to coat sheet steel (galvanized steel) to provide protection to the steel against corrosion. As the more active magnesium rod is attacked, the electrons generated are conveyed to the electrically connected steel tank, which needs protection only for regions where cracks or flaws exist in the glass lining. Similarly, for galvanized steel, protection is required only for regions of scratches or where steel edges are exposed.

44.3.6 Stress Corrosion Cracking

In stress corrosion cracking (SCC), most of a metal's surface may show little attack, while fine intergranular or transgranular cracks may penetrate deeply into the surface. There may be a single continuous crack or a multibranched crack, or the entire surface may be covered with a lacy network of cracks. Usually dye penetrants and sectioning are needed to reveal the extent and depth of cracking.

Certain classes of alloys and environments are susceptible to this phenomenon, and usually tensile stresses are involved, with crack penetration rates increasing with increasing tensile stress. The higher the strength condition of a given alloy, the greater seems to be the tendency to suffer SCC. Table 44.3 lists some materials and environments that have been known to produce SCC.

Frequently, a difference in color or texture is noticeable between a stress corrosion crack and an adjacent region of overstress when the fracture is completed by mechanical means. Scanning electron micrographs are frequently useful in identifying SCC.

44.3.7 Selective Leaching

Selective leaching refers to the chemical removal of one metal from an alloy, resulting in a weak, porous structure. Brass sink traps suffer this type of attack by zinc being leached out of the yellow brass, leaving behind a porous structure of reddish copper. Aluminum and silicon bronzes and other alloys are also subjected to selective leaching.

TABLE 44.3 Environments That May Cause Stress Corrosion of Metals and Alloys

Material	Environment	Material	Environment
Aluminum	$NaCl$-H_2O_2 solutions	Ordinary	$NaOH$ solutions
alloys	$NaCl$ solutions	steels	$NaOH$-Na_2SiO_2 solutions
	Seawater		Calcium, ammonium, and
	Air, water vapor		sodium nitrate solutions
	Ammonia vapors and		Mixed acids (H_2SO_4-HNO_3)
Copper alloys	solutions		HCN solutions
	Amines		Acidic H_2S solutions
	Water, water vapor		Seawater
Gold alloys	$FeCl_3$ solutions		Molten Na-Pb alloys
	Acetic acid-salt	Stainless	Acid chloride solutions
	solutions	steels	such as $MgCl_2$ and $BaCl_2$
Inconel	Caustic soda solutions		$NaCl$-H_2O_2 solutions
Lead	Lead acetate solutions		Seawater
Magnesium	$NaCl$-K_2CrO_4 solutions		H_2S
alloys	Rural and coastal		$HaOH$-H_2S solutions
	atmospheres		Condensing steam from
	Distilled water		chloride waters
Monel	Fused caustic soda	Titanium	Red fuming nitric acid,
	Hydrofluoric acid	alloys	seawater, N_2O_4,
	Hydrofluosilicic acid		methanol-HCl
Nickel	Fused caustic soda		

SOURCE: M. G. Fontana and N. D. Greene, *Corrosion Engineering*, 2d ed., McGraw-Hill, New York, 1978. Used by permission.

44.3.8 Hydrogen Embrittlement

In any electrochemical process where hydrogen ions are reduced, monatomic hydrogen atoms are created prior to their joining in pairs to form diatomic hydrogen gas (H_2). Monatomic hydrogen, being small, can diffuse into metals, causing embrittlement. Corrosion of metals by acids, including cleaning by pickling, can produce hydrogen embrittlement. Heating can drive out monatomic hydrogen, reversing the process. If monatomic hydrogen diffuses into voids in a metal, high-pressure pockets of H_2 gas are formed which are not eliminated by heating, but rather may form hydrogen blisters.

44.3.9 Intergranular Corrosion

In some alloys, frequently related to prior heating, grain boundaries can experience localized variations in composition that can result in corrosion attack along or immediately adjacent to grain boundaries. The 18-8 stainless steels (such as type 304), when heated in the approximate range of 500 to 790°C, experience the precipitation of chromium carbides in grain boundaries, removing chromium from the regions adjacent to grain boundaries. This process is called *sensitization.* It is theorized that intergranular attack proceeds in the chromium-depleted regions of the grain boundaries, since these lack the protection provided by chromium alloying. When this class of stainless steels is welded, regions a bit removed from the weld axis are heated sufficiently to become sensitized and hence become subject to subsequent intergranular

(continued on page 44.28)

TABLE 44.4 Corrosion Data by Environment and Material†

Acetone

Nonmetallics. **ABS** — satis. **Acetal copolymer**—after 6 mos at 120 F: yld str −19%, tens mod −48%, length +2.1%, weight +4.5%, appearance no change. **Acetal homopolymer**—1 yr at 120 F: tens mod −40%, tens str −7%, length +1.1%, weight +2.6%. **Acrylic**—unsatis in 90% at 100 F. **Butyl rubber**—70 hrs at r.t.: +2% vol change. **Chlorinated polyether**—res at 80 F. **Chlorosulfonated polyethylene rubber**—minor to moderate effect at r.t. **Ethylene-propylene rubbers**—at r.t. after 70 hrs retain 81-83% ten str, vol changes −17 to +4%. **Fluorocarbon**—res to boiling. **Fluorocarbon (PVF_2)**—fair at 70 F, NR at 120 F. **Fluoroelastomer**—severe effect at r.t. **Glass (borosilicate)**—satis at 150 F. **Graphite (impervious)**—res 100% boiling. **Hydrocarbon rubber**—little or no effect at r.t. **Natural rubber**—satis. **Neoprene**—minor to moderate effect at r.t. **Nylon**—satis at 120 F. Polyacrylate rubber—after 70 hrs at r.t.: +201% vol change. **Polycarbonate**—not resistant after 6 mos at r.t. **Polyester (glass reinf)**—NR. **Polyethylene (hi-D)**—unsatis after 1 yr at 70 F. **Polyimide (glass reinf)**—after 7 days exp retains 100% of flex mod and 98% of r.t. flex str. **Polystyrene**—not res. **PVC**—plast and unplast unsatis at 68 F. **PVC-acrylic alloy**—attacked at 73 F. **SBR rubber**—after 70 hrs at r.t.: +18% vol change. **Silicone rubber**—after 7 days at 75 F: ten str −85%, volume +180%. **Styrene-acrylonitrile**—not resistant at 73 F. **Urethane rubber**—severe effect at r.t. **Vinyl ester (glass reinf)**—NR in 100%.

Ammonia

Metals. **Aluminum**—res. to dry gas even at elevated temp. If moist, attack low for all con. up to 120 F. **Copper and alloys**—generally res. if dry, rapidly attacked if moist. **Iron and steels**—good res. to aqueous and anhydrous sol. **Lead**—res. to dry gas. After 2 days in 1.7% sol. at r.t.: 1.9 mpy under quiet conditions, 1.1 mpy under aerated cond. **Magnesium**—res. to dry gas at r.t.; presence of water vapor may cause attack. **Nickel and alloys**—nickel res. to anhydrous, and to aqueous up to about 1% sol. Nickel alloys generally res., except Ni-Cu. Ni-Cu res. anhydrous ammonia, but readily attacked by aqueous ammonia and ammonium hydroxide. **Stainless steels**—high res. under certain conditions, severely attacked in others, depending on con., temp and pressure. After 2 mos in 99% NH_3 vapor at 932 F, 7 to 54 mpy for type 310, more severe attack on 304, 309, 316 and 446 grades. **Tin**—res. to gaseous ammonia, even if heated, but ammonia may become decomposed. Res. liquid ammonia, but readily attacked if sodium in sol.

Nonmetallics. **ABS**—satis in gas. **Chlorinated polyether**—res to gas at 220 F. **Acrylic**—satis in gas at 100 F. **Chlorosulfonated polyethylene rubber**—minor to moderate effect by anhydrous at r.t. **Fluorocarbon (PVF_2)**—exc to 275 F. **Fluorocarbon (TFE, FEP)**—res liquid at 78 F. **Fluoroelastomer**—severe effect by anhydrous at r.t. **Hydrocarbon rubber**—no data, likely to be compatible at r.t. **Neoprene**—little or no effect by anhydrous at r.t. **Nylon**—satis in gas at r.t. **Polyethylene (Hi-D)**—satis after 180 days at 122 F. **PVC**—dry: unplast satis at 140 F; liquid: unplast shows some att or absorp at 68 F and unsatis at 140 F, plast unsatis at 68 F. **Silicone rubber**—no change in vol after 7 days at 75 F. **Urethane rubber**—no data, likely to be compatible with anhydrous.

†A footnote on the last page of the table supplies spelled-out forms for the abbreviations used.

Ammonium hydroxide

Metals. Aluminum—low rate of attack in all con. up to 120 F. **Cobalt**—good res. in dilute sol. at r.t.; 0.8 mpy in 5% con. at 77 F under static conditions. **Copper and alloys**—rapidly attacked if more than a few ppm ammonia present, cupronickels being the most resistant. **Irons and steels**—good res.; moderately attacked in hot con. **Lead**—"satisfactory" with liquid or gas at most con. and temps. **Nickel and alloys**—nickel has high res. in very dilute sol., but rapidly attacked in increasing con.; < 1 mpy in 1% sol., over 500 mpy in 13% sol. after 20 hrs at r.t. Aeration may increase res. in low con., but increases attack in high con. Except for Ni-Cu alloys, which are readily attacked, nickel alloys have high res. in all con. to boil. pt. **Stainless steels**—good res. in all con. up to boil. pt; rapid attack likely above atmospheric boil. pt. **Tin**—0.1 to 0.3 mpy in IN sol. at 68 F after 24 hrs. **Titanium**—good res.; 0.2 mpy in 5% sol., 0.1 mpy in 28% sol. at r.t. **Tungsten**—good res., only slightly attacked. **Zinc**—12 mpy in quiet (28 mpy for air agitated) 3.4% sol. after 2 days. **Zirconium**—res. in 28% solution, r.t. to 212 F.

Nonmetallics. ABS—satis. **Acetal copolymer**—after 6 mos at 180 F in 10%: yld str −0.3%, tens mod −12%, length · +0.4%, weight +0.74%, discoloration. **Acetal homopolymer**—90 days at 73 F at 10%: unsatis. **Acrylic**—satis in 30% at 100 F. **Acrylic-PVC alloy**—no change in 10% after 7 days at 73 F. **Alumina (porous)**—res 28% at r.t. **Chlorosulfonated rubber**—little or no effect at 200 F. **Fluorocarbon (PVF_2)**—exc to 275 F. **Fluoroelastomer**—little or no effect at r.t. **Graphite (impervious)**—res in all conc at boiling. **Hydrocarbon rubber**—little or no effect at r.t. **Natural rubber**—satis. **Neopene**—little or no effect at 158 F. **Nitrile rubber**—rec in 28%. **Nylon**—satisfactory at r.t. **Phenolic**—varies with grade, some show little weight change in 10% and exc appearance after 1 yr. **Polyester (glass reinf)**—rec in 5% to 160 F. **Polyethylene (hi-D)**—satis in 28% after 90 days at 70 F. **Polyimide (glass reinf)**— 7 days in 10%: retains 81% of flex mod and 77% of r.t. flex str. **Modified polyphenylene oxide**—no effect in 10% after 3 days at 185 F. **Polypropylene**—satis for 30 days at r.t. **Polystyrene**—res conc; heat reduces res. **Silicone rubber**—after 7 days at 75 F in sat'd: ten str −45%, volume +5%. **Styrene-acrylonitrile**—resistant in 30% at 122 F. **Thermoplastic rubber**—satis in 3% after 2 weeks at r.t. **Urethane rubber**—little or no effect at r.t. **Vinyl ester (glass reinf)**—rec in 20% at 150 F, 29% at 100 F.

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Atmosphere — General outdoors except marine

Metals. Aluminum and alloys—high res.; weathering rate is self-limiting, decreasing with time. Alloys tend to acquire light gray patina. In clean atmos away from seacoast, transformation is slow, surface may retain some sheen even after many years. Depth of attack ranges from virtually nil in dry rural atmos (Phoenix) to 5 mils max. after 20 yrs in severe industrial atmos (New Kensington, Pa.). **Beryllium**—information limited, but commercially pure grade develops tough, stable, oxide coating which inhibits attack under normal conditions. **Cadmium**—fair to good res.; 0.4 mpy after 1 yr for 0.8 in thk plate in urban indus atmos (N.Y.C.); 0.2 mpy for 3 mos, 0.6 mpy for 9 mos in London. 60 to 90% rusting in severe indus atmos (Altoona, Pa). 4 to 12% in rural (State College, Pa.) after 1 yr. **Carbon steels**—rust rapidly, but rust may be more or less protective depending on steel composition and contaminants in atmos. Rust most protective if surface washed by rain and dries periodically. Plain carbon steel (0.02Cu) attacked to depth of 4 mils after 2 yrs, 13 mils after 10 yrs in severe indus atmos (Pittsburgh). **Cast irons**—fair to good res. depending on type. Austenitic grades generally best; not rust-free, but superior to gray iron and far superior to plain carbon steel. **Chromium**—high res. **Cobalt and alloys**—high res. **Columbium**—high res.; expected to acquire only slight tarnish after 15 yrs in indus atmos. **Copper and alloys**—high res.; copper tarnishes to a brown color which gradually turns black and, after a few yrs, the characteristic green patina starts to form and lasts indefinitely. Some alloys react similarly; but high-zinc brasses and nickel silvers are more resistant to tarnishing than copper. Rate of attack for copper is 0.01 to 0.02 mpy in rural atmos (State College and Phoenix), 0.05 mpy in severe indus atmos (Altoona) after 20 yrs. High-copper alloys (over 70% Cu) have similar res. in above rural areas, somewhat less (0.06 to 0.12 mpy) in Altoona. **Lead**—high res.; 0.01 mpy in rural atmos (State College and Phoenix), 0.01 to 0.02 mpy in urban indus (N.Y.C.) after 20 yrs.; 0.02 to 0.03 mpy in severe indus atmos (Altoona) after 10 yrs. **Low alloy steels**—rust rapidly, but rust may be more or less protective depending on steel composition and contaminants in atmos. Copper structural steel (0.24 Cu) about twice as resistant as plain carbon steel (0.04 Cu) for 0 to 12 yrs in indus atmos (Kearney, N.J.). "High strength low alloy" steels, which include "weathering" grades, at least twice as resistant as copper steel. For 0.2 Cu-0.2 Ni steel, 1.8 mpy after 1 yr and 0.8 mpy after 3 yrs in indus atmos (Bayonne, N.J.). For 5 Ni steel, 1.3 and 0.6 mpy, resp, at same site. **Magnesium**—Good res, may be superior to aluminum in certain atmos. Highly protective oxide film forms upon exposure to atmos. **Molybdenum**—High res; tarnishes quickly in indus atmos (Bayonne, N.J.) but attacked very slowly (0.03 mpy after 2.2 yrs). **Nickel and alloys**—good to excellent res. Nickel stays bright in clean, dry atmos, tarnishes if relative humidity exceeds about 70%. Tarnishes to faint gray in rural atmos; green corrosion products may form if sheltered from rain. Rate of attack very low in rural areas (State College and Phoenix). Pollutants in severe industrial (Altoona) and urban industrial (N.Y.C.) increase attack markedly. Nickel alloys have high resistance to almost all atmos, 67Ni-33Cu roofing in N.Y.C. shows no measurable loss in thickness after 44 yrs; however, slight pitting (2 to 4 mils) and tarnishing may occur over 20 yrs in Altoona and N.Y.C. **Precious metals**—high res, although some may tarnish under certain conditions. **Stainless steels**—high res for most grades; "300" grades best and will retain brightness for many yrs in most urban and rural atmos; but slight staining occurs in sulfur-bearing industrial atmos. **Tantalum**—should have high res. **Tin**—high res; corrosion rates (mpy) for 20 yrs: 0.02 in rural atmos (State College and Phoenix); 0.07 in severe indus (Altoona); **Titanium and alloys**—high res; 0.0008 mpy in an indus atmos. **Tungsten**—high res. **Zinc and alloys**—good res; rate of attack after 10 to 20 yrs < 0.01 mpy in dry rural atmos (Phoenix), 0.20 to 0.23 mpy in urban-indus (N.Y.C.) and 0.19 to 0.31 mpy in severe indus (Altoona). Rate of attack is roughly similar whether in form of galvanized steel, die castings or rolled sheet. **Zirconium and alloys**—high res.

Nonmetallics. Acetal copolymer and homopolymer—special UV stabilized and black pigmented grades prevent little loss in prop. **Acrylic**—satis up to 20 yrs. **Epoxy (glass reinf)**—after 1 yr retains 98+% flex str. **Fluorocarbon (PVF_2)**—exc after 8 yrs. **Polyethylene**—not normally res but can be made to produce satis service for 5-20 yrs.

Metals. Aluminum and alloys—1000, 3000, 5000 and 6000 series alloys have high res. with 5000 grades genrally the most suitable. In severe atmos; initial attack may be as high as 4 mpy, but usually tapers off to as low as 0.1 mpy after first yr. After 5 yrs 80 ft and 800 ft from tide at Kure Beach, attack ranged from 0.007 to 0.025 mpy. Most widely used are 5083, 5086, 5154, 5052 and 6061. Many alloys apt to pit but tapers off in time. Above alloys also have good res. in splash zone, where pitting tendency may be less, but attack rate high if pits develop. Corrosion rate higher in mean-tide than splash zone, but less than if fully immersed. **Beryllium**—information very limited, but believed apt to pit. **Cadmium**—very good res. based on tests at Kure Beach. **Carbon steels**—rapidly attacked in splash zone, rates ranging to 50 mpy, which may be 10 times higher than for same steel submerged. Attack decreases with distance from tide: 47 mpy 80 ft from mean tide, 1.3 to 1.6 mpy 800 ft from tide, at Kure Beach. 2.3 to 2.8 mpy 300 ft from tide at Cristobal, Canal Zone. **Cast irons**—Austenitic cast irons have good res. and plain cast iron is about twice as res. as 0.2% copper steel, based on 7½ yrs exposure at Kure Beach. **Cobalt and alloys**—very good res. 0.1 mpy 80 ft from tide and 0.2 mpy 800 ft from tide after 3 yrs at Kure Beach for cobalt. At same site, 67Co-30Cr-2W, a wear-resistant alloy, lost none of its reflectivity after 1½ yrs. **Columbium**—should be res. to attack. **Copper and alloys**—good to high res.; 0.01 to 0.17 mpy for copper, various brasses, and cupronickels exposed for up to 20 yrs at Cristobal, Kure Beach, Key West, La Jolla, Calif. and Sandy Hook, N.J. Rate of attack somewhat higher in tropical zones than in temperate climates. Alloying with aluminum, nickel, zinc tend to increase, silicon and tin decrease, res. over pure copper, but differences slight. In general, alloy with 15% or more zinc susceptible to dezincification, but can be controlled by small additions of arsenic, antimony or phosphorus. Performance in splash zone more similar to that in atmos than in immersion. Generally, alloys having good res. in severe atmos (Cristobal) also good in splash zone. At mean tide, attack about 20 to 60% that for fully immersed. **Lead**—very good res. 0.02 mpy for chemical and antimonial lead after 20 yrs at La Jolla and Sandy Hook; 0.08 mpy after 8 yrs at Cristobal. Even better res. if atmos polluted. **Low alloy steels**—substantially greater res. than plain carbon steels: 0.7 to 0.9 mpy for low alloy steels, 1.8 mpy for copper steel, at Cristobal; in general, total alloy content of 2% seems to provide maximum return in performance. At Kure Beach, 800 ft from tide, 0.350 mpy for nickel-copper-molybdenum steel having alloy content of 2%, 0.582 mpy for 1.1%. **Magnesium and alloys**—fair; 1 mpy fairly typical. For AZ31 alloy: 0.94 mpy after 16 yrs at Cristobal; about 0.9 mpy after 32 mos. at Daytona Beach; 0.57 mpy 80 ft from tide after 4 yrs at Kure Beach. Oxide film which form upon exposure to normal atmos tends to break down in salt-laden atmos, especially salt spray. **Molybdenum and alloys**—high res. in atmos; 0.1 mpy (max pit 2.4 mils) after 7 yrs, 80 ft and 800 ft from tide at Kure Beach. Alloys TZM and Mo30W should behave similarly. **Nickel and alloys**—generally high res.; 0.01 mpy or less for nickel (0.0095 mpy after 7 yrs 80 ft from tide at Kure Beach, 0.0075 mpy and negligible pitting after 16 yrs at Cristobal). Ni-Cu, "Monel 400," will tarnish, but attack rate low (0.014 mpy after 7 yrs at Kure Beach and 16 yrs at Cristobal; other tests show lower rates). Ni-Cr, "Inconel 600": 0.0016 mpy (1.3 mils max pit depth) after 7 yrs 80 ft from tide at Kure Beach. Ni-Cr-Fe, "Incoloy 800" and "825": 0.006 mpy (0.9 and 0.7 mil max pit depths, resp.) after 7 yrs at Kure Beach. Ni-15/22Cr-3/7Mo alloys such as "Hastelloys F" and "G", "Inconel 700" and "718", "Illium R" and "Elgiloy" are even more res. Most res. of all (only titanium alloys have comparable res.) are Ni-16/22Cr-9/18Mo alloys like "Hastelloy C", "C-276" and "X", "Inconel 625", "MP35N" (based on preliminary tests), "Chlorimet 3" and "Rene 41". Res. in splash zone is virtually as good as in atmos, but may be somewhat reduced in tide zone. **Precious metals**—except for silver, which tarnishes, especially if sulfur compounds present, major noble metals, e.g. platinum, palladium and gold, virtually immune to attack, platinum being the most resistant. **Stainless steel**—good to high res.; austenitic grades generally preferred because of greater res. to staining. Type 304: $<$ 0.1 mpy 800 ft from tide at Kure Beach (somewhat more staining but also negligible attack 80 ft from tide). Type 316 even more resistant. Types 301, 316 and 321 free from pitting and weight loss after 8 yrs at Cristobal. Martensitic grades, typified by 410, may resist after few months, pit on long term (up to 5 mils deep after 8 yrs at Cristobal, but negligible weight loss, e.g., 0.007 mpy). Ferritic 430 subject to partial rusting after about 1 yr at Christobal, but weight loss negligible. Resistance in splash zone also good (austenitic grades again superior). However, subject to some attack in tide zone, e.g., 0.02 mpy for 316 stainless, 0.11 mpy for 304 after 8 yrs in Pacific off Canal Zone. **Tantalum**—should be res. **Tin**—good res.; 0.07 mpy at Sandy Hook, 0.11 mpy at La Jolla, after 20 yrs 0.09 mpy after 10 yrs at Key West. **Titanium and alloys**—excellent res.; immune to crevice attack, pitting and general corrosion at ambient temperatures. Corrosion rate nil for commercially pure titanium after 5 yrs 80 ft and 800 ft from tide at Kure Beach. Also virtually immune to corrosion in splash and tide zones. **Tungsten**—

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Atmosphere — Marine (Continued)

should be res. **Wrought iron**—somewhat similar res. to carbon steel. 1.2 mpy at Halifax, Nova Scotia; 2.2 mpy, Aukland, New Zealand; 4.7 mpy, Plymouth, England; 11 mpy, Colombo, Ceylon; 2.1 to 3.5 mpy, 300 ft from tide at Cristobal. **Zinc and alloys**—good res.; 0.02 to 0.03 mpy at Key West; 0.06 to 0.07 mpy, Sandy Hook; 0.05 to 0.08 mpy, La Jolla, Calif; for various grades of rolled zinc after 10 to 20 yrs. At Kure Beach, rolled zinc contaminated with traces of iron: 0.4 to 0.5 mpy 80 ft from tide (0.3 mpy at 800 ft) after 6 mos.; 0.3 to 0.4 mpy, 80 ft (0.2 at 800 ft) after 1 yr.

Ref. Fink, F. W.; Boyd, W. K.; "The Corrosion of Metals in Marine Environments," DMIC Report 245, Battelle (Columbus), May '70. Published by: Bayer & Co., Col., Ohio.

Carbon tetrachloride

Nonmetallics. ABS—unsatis. **Acetal copolymer**—after 6 mos at 120 F: yld str −11%, ten mod −32%, length +1.2%, weight +5.2%, appearance no change. **Acetal homopolymer**—365 days at 120 F: ten mod −44%, ten str −7%, length −0.3%, weight +5.7%. **Butyl rubber**—70 hrs at r.t.: +214% vol change. **Chlorinated polyether**—res at 80 F. **Chlorosulfonated polyethylene rubber**—severe effect at r.t. **Fluorocarbon (PVF_2)**—exc to 275 F. **Fluoroelastomer**—little or no effect at 158 F. **Fluorosilicone rubber**—after 7 days at 75 F: ten str. −45%, volume +20%. **Graphite (impervious)**—res 100% boiling. **Hydrocarbon rubber**—severe effect at r.t. **Neoprene**—severe effect at r.t. **Nitrile rubber**—rec. **Nylon**—little or no att. **Phenolic**—varies with grade, some show little weight change and exc appearance after 1 yr. **Polycarbonate**—not res after 6 mos at r.t. **Polyester (glass reinf)**—NR. **Polyethylene (hi-D)**—marginal after 7 days at 70 F. **Polyimide (glass reinf)**—after 7 days exp retains 92% of flex mod and 76% of flex str. **Polypropylene**—unsatis after 100 days at 140 F. **Polystyrene**—soluble. **Polysulfone**—7 days at 72 F: weight +0.2%. **PVC-acrylic: alloy**—very slightly whitened after 7 days at 73 F. **Silicone rubber**—after 5 days at 120 F: t.s. −45%, volume +20%. **Styrene-acrylonitrile**—moderately resistant at 73 F. **SBR rubber**—after 70 hrs at r.t.: +207% vol change. **Urethane rubber**—severe effect at 122 F. **Vinyl ester (glass reinf)**—rec at 80 F.

Chlorine

Metals. Aluminum—res. to normal amounts (10 ppm or less) used to treat water. **Carbon steels**—res. to dry, liquid or gaseous at r.t. **Columbium**—little or no attack in wet at 205 F. **Lead**—res. to dry; attacked, but suitable for use if moist up to 230 F; res. to amounts used to treat water. **Magnesium**—res. to dry at r.t., attacked if moist. **Molybdenum**—attacked by wet at r.t. and by dry above 480 F (but little weight loss up to 1470 F). **Nickel and alloys**—res. to dry, liquid or gaseous at r.t., and at elevated temps. under certain conditions. **Precious metals**—gold and palladium rapidly attacked; platinum, rhodium and ruthenium slightly attacked, iridium unaffected by dry or moist at moderate temp. Silver has good res. at r.t. **Stainless steels**—austenitic grades have good res. to dry gas at r.t., severely attacked at high temps. or by wet gas. Rate of attack in dry gas about 10 mpy at 400 F, 60 mpy at 600 F, 400 mpy at 800 F. **Tantalum**—no appreciable attack in wet or dry below 300 F. **Tin**—severely attacked. **Titanium**—exc. res. in moist; < 0.1 mpy at r.t. if more than 0.1% water present; rapid attack if dry (< 0.1% water). **Tungsten**—attacked by dry at about 480 F. **Zinc**—res. to dry gas. **Zirconium**—res. to dry gas, attacked if moist.

Nonmetallics. Chlorinated polyether—res to wet or dry at 80 F. **Chlorosulfonated polyethylene rubber**—dry and wet at r.t.: severe effect. **Fluorocarbon (PVF_2)**—exc in dry and wet to 212 F. **Fluorcarbon (TFE, FEP)**—res at 200 F. **Fluoroelastomer**—dry at 212 F and wet at r.t.: little or no effect. **Graphite (impervious)**—res 100% dry at r.t. **Hydrocarbon rubber**—dry at r.t.: no data, not likely to be compatible; wet at r.t.: severe effect. **Neoprene**—dry at r.t.: minor to moderate effect; wet at r.t.: severe effect. **Nylon**—unsatis in gas at r.t. **Polyethylene (Hi-D)**—unsatis at 70 F. **Polypropylene**—unsatis in gas and marginal in liquid at 68 F. **PVC**—100% dry: unplast satis at 68 F, some att or absorp at 140 F. **Silicon carbide**—at 390 F: dry −0.1 mpy, wet +0.1 mpy. **Urethane rubber**—dry and wet at r.t.: no data, not likely to be compatible. **Vinyl ester (glass reinf)**—rec in wet and dry at 210 F.

Citric acid

Metals. Aluminum—generally res. **Beryllium**—initially attacked, but res. in time. **Cast irons**—rapidly attacked. Even austenitic grades have poor res., 90 mpy in 5% solution at 60 F. **Chromium**—good res. in dilute sol. at r.t.; no attack in 10% sol. at 54 F, 7 mpy at 136 F. **Copper**—moderate res.; 2.2 mpy in 0.2% sol. at 70 F after 5 days. **Nickel**—good res. in dilute sol. at r.t., 0.8 mpy after 5 days in 2% sol. Moderately attacked in higher con. and temps; 5 mpy in 5% sol. at r.t. after 7 days, 20 mpy at 140 F after 7 days. Aeration increases attack. **Silver**—good res. **Stainless steels**—high to moderate res., some pitting may occur. In 10% sol. at 210 to 215 F after 4 hrs: 0.5 mpy for 316, 0.8 mpy for 430, 8 mpy for 302 and 304, 10 mpy for 410. In 60 to 78% sol. at 125 F after 5 wks: 0.1 mpy for 304 and 316. **Tin**—good res. in dilute, air-free sol.; 0.12 mpy in 0.75% sol. after 9 days. Poor res. in hot, con. or aerated sol. **Titanium**—high res.; 0.5 mpy in all con. at 212 F. **Zinc**—attacked. **Zirconium**—high res.; 0.5 mpy and 0.2 mpy max at 140 and 212 F resp. for all con.

Nonmetallics. Acetal copolymer—after 12 mos at 73 F at 10%: yld str +3%, tens and mod −10%, length +0.2%, weight +1.9%, appearance NC. **Acrylic**—limited service in 80% at 220 F. **Chlorinated polyether**—res at 250 F. **Chlorosulfonated polyethylene rubber**—little or no effect at r.t. **Fluorocarbon (PVF_2)**—exc to 250 F. **Fluoroelastomer**—little or no effect at r.t. **Graphite (impervious**—res to all conc at boiling. **Hydrocarbon rubber**—little or no effect at r.t. **Neoprene**—little or no effect at r.t. **Nylon**—little or no att to some att in 10% at r.t. **Polyethylene (hi-D)**—satis after 180 days at 122 F. **Polyester (glass reinf)**—rec in all conc to 200 F. **Polypropylene**—satis after 30 days at 140 F. **Polystyrene**—res to 10%, heat reduces res; slight att in 20%; heat reduces res. **Polysulfone**—7 days at 72 F at 40%: weight +0.4%. **PVC**—unplasticized satis at 140 F, plast at 68 F. **PVC-acrylic alloy**—no change in 10% after 7 days at 73 F. **Styrene-acrylonitrile**—res in 10% at 122 F. **Urethane rubber**—little or no effect at r.t. **Vinyl ester (glass reinf)**—rec at 210 F.

Detergents

Nonmetallics. ABS—satis. **Acetal copolymer**—after 6 mos at 180 F: yld str +3%, tens mod −15%, length +0.3%, weight +1%, slight discoloration. **Acetal homopolymer**—1 yr at 73 F in Lestoil: ten str −4%, weight +0.2%. **Ethylene-propylene rubber**—at r.t. after 70 hrs ten str is 100-105% of original, vol changes −1 to −2%. **Fluorocarbon (TFE, FEP)**—res to boiling. **Nylon**—no att. **Phenolic**—varies with grade, some show little weight change and exc appearance after 1 yr. **Polyester (glass reinf)**—rec in sulfonated to 140 F. **Polyethylene (hi-D)**—satis at 70 F. **Polypropylene**—satis after 30 days at 140 F. **Polysulfone**—7 days in Lestoil: weight +0.3%. **Styrene-acrylonitrile**—resistant at 73 F.

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Ethyl alcohol

Nonmetallics. ABS—satis in 50%. **Chlorosulfonated polyethylene rubber**—little or no effect at 200 F. **Fluorocarbon (TFE, (F.EP)**—res at 400 F. **Fluoroelastomer**—little or no effect at r.t. **Fluorosilicone rubber**—after 7 days at 75 F: t.s. −30%, volume +5%. **Graphite (impervious)**—res 100% boiling. **Hydrocarbon rubber**—little or no effect at r.t. **Neoprene**— little or no effect at 158 F. **Nitrile rubber**—rec. **Polycarbonate**—res in 96% after 6 mos at r.t. **Polyester (glass reinf)**—rec. **Polypropylene**—satis after 100 days at 140 F. **Polystyrene**—slight att; heat reduces res. **Polysulfide rubber**—exc (0-20% vol swell) for 30 days at 80 F. **PVC**—unplast satis at 68 F, some att or absorp at 140 F, plast satis at 68 F. **PVC-acrylic alloy**—no change in 95% after 7 days at 73 F. **Silicone rubber**—after 7 days at 75 F: t.s. −30%, volume +5%. **Urethane rubber**—severe effect at r.t.

Ethylene glycol

Metals. Aluminum—res.; attack may occur if less than 0.01% water present, and at elevated temps. **Cast irons**—gray irons have good res.; austenitic and high-silicon irons even more res. **Copper and alloys**—res. **Magnesium**—res. at r.t. **Nickel and alloys**—res. **Stainless steel**—exc. res.; < 0.1 mpy for 302 and 316 at 70 to 160 F.

Nonmetallics. ABS—satis. **Acetal copolymer**—after 6 mos at 180 F at 50%: yld str 0% change, ten mod −18%, length +0.4%, weight +1.3%, slight discoloration. **Acrylic**—satis at 100 F. **Butyl rubber**—70 hrs at 212 F: −1% vol change. **Chlorinated polyether**—res at 220 F. **Chlorosulfonated polyethylene rubber**—little or no effect at 200 F. **Epoxy (glass reinf)**—after 30 days little weight change, retains 100% flex str. **Ethylene-propylene rubber**—at r.t. after 70 hrs t.s. is 87-102% of original, vol change negligible. **Fluorocarbon (PVF_2)**—exc to 275 F. **Fluoroelastomer**—little or no effect at 250 F. **Fluorosilicone rubber**—after 7 days at 180 F: t.s. −5%, volume no change. **Graphite (impervious)**—res all conc at 338 F. **Hydrocarbon rubber**—little or no effect at r.t. **Natural rubber**—satis. **Neoprene**—little or no effect at 158 F. **Nitrile rubber**—rec. **Polyacrylate rubber**—after 70 hrs at 212 F: +37% vol change. **Nylon**—satis at 90% at r.t. **Polyester (glass reinf)**—rec to 200 F. **Polyethylene (Hi-D)**—satis after 180 days at 122 F. **Polypropylene**—satis after 1 yr at 73 F. **Polysulfide rubber**—exc (0-20% vol swell) for 30 days at 80 F. **PVC**—unplast satis at 140 F, plast satis at 68 F. **SBR rubber**—after 70 hrs at 212 F: +4% vol change. **Silicone rubber**—after 7 days at 180 F: t.s. −5%, vol no change. **Styrene-acrylonitrile**—resistant at 73 F. **Urethane rubber**—minor to moderate effect.

Ferric chloride

Metals. Aluminum—attacked. **Cobalt**—negligible attack after 1 day in 2% sol. for 50Co-20Cr-15W-10Ni alloy; 0.2 to 10 mpy for various Co-Cr-W alloys. **Columbium**—high res. No attack in 10% sol. after 1 mo. **Chromium**—high res. in dilute sol. at r.t.; no attack in 10% sol. at 54 F; 16 mpy at 136 F. **Copper and alloys**—moderate to severe attack. **Lead**—rapidly attacked. **Magnesium**—rapidly attacked. **Nickel and alloys**—nickel rapidly attacked except in very dilute sol. Most nickel alloys also readily attacked; however, high-molybdenum and chromium alloys, e.g., 54Ni-16Mo-16Cr, may be exception. **Precious metals**—platinum has high res.; 0.01 mpy to 10% sol. at r.t. Hot sol. attacks gold, palladium, platinum and the rhodium-and-iridium-platinum alloys. Iridium, rhodium and ruthenium resist hot sol. **Stainless steels**—most grades apt to pit, some very severely. Molybdenum-bearing grades, e.g., 316, 329, generally most res. **Tantalum**—high res. **Tin**—rapidly attacked. **Titanium**—exc. res.; < 0.5 mpy in 1 to 30% con. at 212 F, 0.7 mpy in 50% con. at 235 F. **Zinc**—attacked. **Zirconium**—exc. res. in very dilute sol. at r.t. and moderately elevated temps. Moderate to severe attack with increasing con. and temps. Based on 6-day tests: 0.1 mpy at 95 F, 0.2 mpy (140 F), 0.4 mpy (212 F) in 1% sol., 1 mpy (95 F), 0.7 mpy (140 F), 31 mpy (212 F) in 5% sol., 3.9 mpy (95 F), 5.4 mpy (140 F), 145 mpy (212 F) in 10% sol.

Nonmetallics. Acetal homopolymer—1 yr at 73 F at 5%: ten str −4%, weight −0.9%. **Chlorinated polyether**—res at 250 F. **Chlorosulfonated polyethylene rubber**—little or no effect at 200 F. **Fluorocarbon (PVF₂)**—exc in 50% to 275 F. **Fluoroelastomer**—little or no effect at r.t. **Graphite (impervious)**—res all conc at boiling. **Hydrocarbon rubber**—little or no effect at r.t. **Natural rubber**—ebonite is satis; soft is limited. **Neoprene**—little or no effect at r.t. **Nylon**—unsatis at r.t. **Polyester (glass reinf)**—rec to 200 F. **Polyethylene (hi-D)**—satis at 70 F. **Polypropylene**—satis at 73 F **Polystyrene**—res; heat reduces res. **PVC**—satis at 140 F. **Silicone rubber**—unaffected in 60% after 7 days at 212 F. **Styrene-acrylonitrile**—resistant at 122 F. **Urethane rubber**—little or no effect at r.t. **Vinyl ester (glass reinf)**—rec at 210 F.

Freon

Metals. Aluminum—res. to most types, slight attack in others. **Carbon steel**—should be satisfactory. **Copper and alloys**—res. **Magnesium**—res. if dry at r.t.; attacked if moist and at elevated temps.

Nonmetallics. ABS—varies with type: satis in 12, unsatis in 11. **Chlorinated polyether**—res at 150 F. **Chlorosulfonated polyethylene rubber**—little or no effect by 11, 12, 22, 113, 114 at r.t. **Fluoroelastomer**—no to moderate effect by 11, 12 at r.t.; severe effect by 22 at r.t.; little or no effect by 113, 114 at r.t. **Graphite (impervious)**—res 11, 12 at r.t. **Hydrocarbon rubber**—severe effect by 11, 22, 113, 114 at r.t.; minor to moderate effect by 12 at r.t. **Neoprene**—little or no effect by 12, 22, 113, 114 at r.t. **Nitrile rubber**—rec in 11, 12, 13, 32, 113. **Polyethylene (hi-D)**—satis at 70 F. **Polypropylene**—satis at 73 F. **Polysulfide rubber**—exc (0-20% vol swell) in 11, 12, 13, 32, 112, 114, 115, 218; fair (40-80% vol swell) in 22 and 31; unsatis in 21; all values 30 days, 80 F. **Silicone rubber**—varies with type: in Freon 12 vol changes +45 to +150% after 3 days at 75 F. **Styrene-acrylonitrile**—at r.t. not resistant to 11, res. to 12. **Urethane rubber**—minor-moderate effect by 11 at r.t.; little or no effect by 12, 113 at r.t.; severe effect by 22 at r.t.

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Gasoline
Metals. Aluminum—high res. to refined and anhydrous, attacked in sour. **Copper and alloys**—high res. to refined, fair to poor res. in sour. **Nickel alloy**—"Monel" has high res. to refined, poor res. to sour. **Stainless steels**—high res. for most grades to refined; in sour, 302, 304, 316 have high res.; 410, 416, 430 fair res. **Tin**—high res. if moisture- and sulfur-free. **Nonmetallics. ABS**—unsatis. **Acetal copolymer**—after 6 mos at 120 F: yld str −12%, ten mod −12%, length +0.7%, weight +1.5%, appearance no change. **Acetal homopolymer**—820 days at 73 F in Texaco: ten mod −17%, ten str −7%, length +0.7%, weight +1.6%. **Acrylic**—unsatis at 100 F. **Chlorinated polyether**—res at 220 F. **Chlorosulfonated polyethylene rubber**—minor to moderate effect at r.t. **Fluorocarbon (TFE, FEP)**—res at 200 F. **Fluoroelastomer**—little or no effect at r.t. **Graphite (impervious)**—res boiling. **Hydrocarbon rubber**—minor-severe effect at r.t. **Neoprene**—minor-moderate effect at r.t. **Nitrile rubber**—rec. **Nylon**—no att. **Polyester (glass reinf)**—rec at ambient. **Polyethylene (hi-D)**—marginal after 365 days at 68 F. **Polypropylene**—satis after 100 days at 140 F, marginal after 1 yr at 73 F. **Polystyrene**—not res. **Polysulfide rubber**—exc (0-20% vol swell) for 30 days at 80 F. **Polysulfone**—7 days at 72 F: weight +0.1%. **PVC-acrylic alloy**—no change after 30 days at 73 F except very sl staining. **PVC**—unplast satis at 140 F. **Silicone rubber**—after 7 days at 75 F, volume +165%. **Styrene-acrylonitrile**—resistant at 122 F. **Urethane rubber**—minor-moderate effect at r.t. **Vinyl ester (glass reinf)**—rec at 100 F.
Grease
Nonmetallics. Acetal copolymer—after 6 mos at 180 F: yld str +4%, tens mod +3%, length +0.2%, weight −0.03%, appearance NC. **Acetal homopolymer**—240 days at 200 F in chassis lubricant: ten str 0% change, weight −0.3%. **Polypropylene**—satis at 68 F. **Silicone rubber**—after 3 days at 300 F: no change in ten str, volume +20%. **Styrene-acrylonitrile**—moderately resistant at 73 F.

Hydraulic fluid

Nonmetallics. ABS—unsatis in Skydrol-500, 700. **Acetal copolymer**—after 6 mos at 180 F in Lockheed 21: yld str −11%, ten mod −41%, length +1.4%, weight +3.6%, appearance no change. **Acetal homopolymer**—after 310 days at 160 F in Lockheed 21: ten str −23%, length +0.3%, weight +0.9%. **Butyl rubber**—70 hrs at 212 F: +3% vol change. **Chlorosulfonated polyethylene rubber**—severe effect by Skydrol-500 at r.t. **Epoxy (glass reinf)**—after 30 days little weight change, retains 100% flex str. **Ethylene-propylene rubbers**—after 70 hrs at 212 F in Skydrol-500A retain 87-99% of ten str, vol changes −24 to +11%. **Fluoroelastomer**—severe effect by Skydrol-500 at r.t. **Fluorosilicone rubber**—after 7 days at 120 F in Skydrol-500A; ten str −35%, volume +10%. **Hydrocarbon rubber**—little or no effect by Skydrol-500 at 250 F. **Neoprene**—severe effect by Skydrol-500 at r.t. **Nitrile rubber**—rec. **Polyacrylate rubber**—after 70 hrs at 212 F: +116% vol change. **Polyimide (glass reinf)**—after 60 days in Skydrol-500 flex mod is 95% of r.t. value. **Polysulfide rubber**—good (20-40% vol swell) in Skydrol for 30 days at 80 F. **Polysulfone**—3 days at 250 F in Skydrol 500A: dissolves. **Silicone rubber**—after 7 days in Skydrol-500A at 160 F: ten str −10 to −80%, volume +10 to +30%. **Styrene-acrylonitrile**—moderately resistant at 73 F. **SBR rubber**—after 70 hrs at 212 F: +10% vol change. **Urethane rubber**—severe effect by Skydrol-500 at 122 F.

Hydrochloric acid

Metals. Aluminum—rapidly attacked. **Beryllium**—rapidly attacked at r.t. **Carbon steels**—rapidly attacked. **Cast irons**—unalloyed and low alloy grades rapidly attacked. High-silicon irons, especially those containing molybdenum, have good res. (up to 5 mpy) under most conditions. **Chromium**—rapidly attacked. **Cobalt alloys**—certain Co-Cr-W and Co-Cr-W-Ni alloys attacked at 9 to 52 mpy in 5% con. at r.t. after 24 hrs; may be more rapidly attacked in 10% to con. sol. at moderately elevated temps. **Columbium**—virtually immune to attack (0 to 0.1 mpy) in 18.37% con. at r.t.; 4 mpy in 37% solution at 230 F. **Copper and alloys**—rapidly attacked in con. sol. and moderately elevated temps. For copper, attack at r.t. may range from 4 mpy in 0.03% sol. to over 160 mpy in 37% con. For more res. alloys, rates may vary from 4 to 32 mpy at r.t. to 256 mpy for con. sol. at higher temps. Aeration accelerates corrosion. **Lead**—attacked at about 10 to 13 mpy in con. < 1%, 20 mpy in 5 to 20% sol. at r.t. Antimonial lead fairly resistant in con. below 18% up to 212 F. **Low alloy steels**—generally similar to carbon steels. **Magnesium**—rapidly attacked. **Molybdenum**—high res. to hot or cold sol.; 1.1 mpy for 1 to 20% con. at 160 F after 2 days, appreciably higher attack for longer periods; 0.3 mpy in con. sol. at 230 F. Presence of oxidizing agents accelerates attack. **Nickel and alloys**—nickel is only moderately attacked (1-10 mpy) in air-free, dilute (up to 10%) sol. at r.t. Rate of attack increases with increasing con.; 70 mpy for 30% air-free sol. at r.t. Substantially greater attack (50 to 90 mpy) in air saturated solutions up to 30% con. at r.t. Certain alloys have better res. (62Ni-

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Hydrochloric acid (Continued)

28Mo considered best, 54Ni-16Mo-16Cr second best). Rates for 62Ni-28Mo: 0.3 to 2 mpy for 2 to 37% con. at r.t.; 6 to 9 mpy for 2 to 15% con. at 150 F; 3 mpy for boil. (214 F) 2% sol. **Precious metals**—generally exc res. in absence of oxidizing agents. No appreciable attack for gold, iridium, osmium, palladium, platinum, rhodium and ruthenium in 36% con. at r.t. after 1 week. At 212 F, iridium, ruthenium and rhodium unattacked; gold and platinum slightly attacked; palladium and osmium attacked at 2 and 6.1 mpy resp. Silver is res. under certain conditions, but subject to attack with increasing con. and temps. **Stainless steels**—rapidly attacked. Higher nickel alloys are less susceptible to attack, but are res. only in very dilute sol. **Tantalum**—high res.; < 1 mpy in 18% solution at 75 F, no attack in 37% solution at 230 F. **Tin**—moderate res., 2 to 14 mpy, in dilute (up to 6%); air-free sol r.t. Poor res. in high con. or aerated sol. **Titanium**—rapidly attacked; addition of 0.15 Pd to Ti or nitriding improves res. in dilute sol. **Tungsten**—generally res.; no attack in dilute (10%) sol. at r.t., moderate attack (18 mpy) at elevated temps. **Zinc**—rapidly attacked. **Zirconium**—high res.; < 1 mpy in boiling 20% sol. and 37% sol. at 212 F.

Nonmetallics. ABS—in 50% satis after 30 days at r.t., unsatis in 140 F. **Acetal copolymer**—not rec in 10%. **Acetal homopolymer**—90 days at 73 F at 10%: unsatis. **Acrylic**—satis in 40% at 150 F, limited service in 30% at 212 F. **Acrylic-PVC alloy**—no change in 10% after 7 days at 73 F. **Alumina (porous)**—res 35% at 212 F. **Butyl rubber**—70 hrs at r.t. in conc: no change. **Chlorinated polyether**—res to 35% at 250 F. **Chlorosulfonated polyethylene rubber**—varies from little or no effects to 37% at 122 F to minor-moderate effect at 200 F. **Epoxy (glass reinf)**—after 30 days in 10% little weight change, retains 60% flex str. **Ethylene-propylene rubber**—after 70 hrs in 30% at r.t. retains 94-99% of ten str, vol change −1 to +4 %. **Fluoroelastomer**—varies from little or no effect to 37% at 158 F, to minor-moderate effect at 230 F. **Fluorocarbon (TFE, FEP)**—res to 0-100% at boiling. **Fluorocarbon (PVF_2)**—exc in conc to 275 F. **Glass-ceramic**—exc in 37% at 194 F. **Graphite (impervious)**—res to all conc at boiling. **Hydrocarbon rubber**—no effect to moderate effect at r.t. **Natural rubber**—satis. **Nitrile rubber**—variable in 20, 30%; not res in 37%. **Nylon**—unsatis in 10% at r.t. **Phenolic**—varies with grade, some show little weight change and exc appearance in 10% after 1 week. **Polyacrylate rubber**—after 70 hrs at r.t. in conc: 4% vol change. **Polyester (glass reinf)**—rec in 37% to 140 F, 20% to 160 F, 10% to 200 F. **Polyethylene (hi-D)**—satis in 37% after 90 days at 70 F. **Modified polyphenylene oxide**—no effect in conc after 3 days at 185 F. **Neoprene**—varies from little or no effect to 37% at r.t. to severe effect at 200 F. **Polysulfide rubber**—varies from exc (0-20% vol swell) in 10%, to good (20-40% vol swell) in 50%, to unsatis in 100%; all values for 30 days, 80 F. **Polysulfone**—7 days at 72 F at 20%: weight +0.4%. **Polypropylene**—satis in 35% after 180 days at r.t., marginal after 100 days at 140 F. **Polystyrene**—res 10%, heat reduces res.; slight att in 38%, heat reduces res. **PVC**—plasticized and unplast satis in 22% at 140 F; in conc HCl plast and unplast satis at 68 F, plast satis at 140 F, unplast some att at 140 F. **Silicon carbide**—minus 0.1 mpy in 25% at boiling temp. **Silicone rubber**—after 3 days at 150 F: t.s. −35%, volume +10%. **Styrene-acrylonitrile**—at 122 F res in 25%, moderately res in 37%. **SBR rubber**—after 70 hrs at r.t. in conc: +3% vol change. **Urethane rubber**—severe effect at r.t. **Vinyl ester (glass reinf)**—rec in 37% at 210 F.

Motor oil

Nonmetallics. ABS—satis. **Acetal copolymer**—after 6 mos at 180 F: yld str +5%, ten mod 0% change, length −0.1%, weight −0.1%, appearance no change. **Acetal homopolymer**—1 yr at 160 F: ten mod +2%, ten str +3%, length −0.3%, weight −0.2%. **Chlorosulfonated polyethylene rubber**—severe effect at r.t. **Fluorelastomer**—little or no effect at r.t. **Hydrocarbon rubber**—severe effect at r.t. **Neoprene**—severe effect at r.t. **Polypropylene**—satis after 100 days at 140 F. **Polystyrene**—slight att; heat does not reduce res. **Polysulfide rubber**—exc (0-20% vol swell) for 30 days at 80 F. **Polysulfonate**—7 days at 72 F: weight unchanged. **Silicone rubber**—after 3 days at 300 F: t.s. −5%, vol no change. **Urethane rubber**—little or no effect at 158 F.

Nitric acid

Metals. Aluminum—good res. at con. above 82% at r.t. and slightly elevated temps. **Beryllium**—good res. to con. sol. if cold (violent reaction upon heating). Slow attack in dilute sol. **Carbon steels**—attacked by dilute and intermediate sol. **Cast irons**—high-silicon and high-chromium grades generally res.; others rapidly attacked. **Chromium**—attacked; 12 mpy after 1 day in 32% sol. at 60 F. **Cobalt alloys**—certain Co-Cr-W and Co-Cr-W-Ni alloys have good res. based on 24 hr tests (0.5 to 6 mpy in boil. 10% sol, 0.5 to 32 mpy in 40% con. at 150 F). **Columbium**—high res.; no attack in 70% con. at 75 F and 212 F. **Copper and alloys**—rapidly attacked except by very dilute (0.1% max) sol. **Lead**—moderately attacked in high con. (48 mpy in 95% sol at r.t.). Severely attacked in con. below 80%. **Low alloy steels**—generally similar to carbon steels. **Magnesium**—rapidly attacked. **Molybdenum**—res. attack in con. sol. at r.t; rapidly attacked by boil. con. sol. and dilute (about 25%) sol. at r.t. **Nickel and alloys**—nickel rapidly attacked except possibly in very dilute (less than 0.5%) cold sol. Of the alloys, 47Ni-22Cr-17Fe-6Mo and 42Ni-30Fe-22Cr-3Mo are most res. For 42Ni alloy: 0.5 mpy after 1 mo. in white fuming acid at r.t. (43 mpy after 1 wk at 160 F). For 47Ni alloy: 0.1 mpy in 10 to 70% con. at r.t.; 0.1 to 1 mpy at 150 F and 0.4 to 16 mpy at boil., under same conditions. **Precious metals**—exc. res in 60% and 95% con at r.t. for iridium, platinum, rhodium and ruthenium. These metals also highly res. to 95% concentrations at 212 F. Poor res. for osmium and palladium under these conditions. Gold highly res. to 70% con. at r.t., but subject to some attack in 95% sol. Silver rapidly attacked. **Stainless steels**—austenitic grades generally have high res.; < 0.1 mpy for 304, 321 and 347 in all con. at r.t., and up to 200 F in dilute sol. These grades have high to moderate res (0.1 to 50 mpy) in 10 to 95% sol from r.t. to boil. pt. (210 to 240 F); rate of attack increasing with con. and temp. Type 430 also has good res.; < 0.1 to 0.4 mpy in con. up to 80% at 0 to about 125 F. In general, all grades are attacked (45 to 400 mpy) by fuming nitric. **Tantalum**—only slightly attacked by con. sol. at r.t. and mod-

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Nitric acid (Continued)

rately elevated temps.; $<$ 1 mpy in '0% sol at 75 and 185 F. Negligible ittack in red fuming acid at 250 to 00 F. **Tin**—poor res.; 150 mpy in erated or air-free 3% sol. at r.t. **itanium**—exc res. to all con. includ- ng fuming at r.t. and at least up to '0% con. at 95 F. However, under ertain conditions (e.g. less than .34% H_2O or more than 6% NO_2) 1 fuming nitric, pyrophoric reactions nay occur. Moderate res., 0.2 to 8 npy in 5 to 65% sol. at 212 F; $<$ 0 mpy in all con. up to 345 F. **Tung- ten**—generally res. in dilute (10%) ol. at r.t. **Zinc**—attacked. **Zirconium** —high res. in con. up to 69.5% at oil. pt.; $<$ 1 mpy at 95 F. in White uming, $<$ 1 mpy at 160 F. in red uming, $<$ 5 mpy at 60 F.

Nonmetallics. ABS—unsatis in conc; n 20% satis after 30 days at r.t., insatis at 140 F. **Acetal copolymer**— not rec in 10%. **Acetal homopolymer** —275 days at 75 F at 10%: unsatis. **Acrylic**—lim service at r.t. **Acrylic-PVC alloy**—no change in 70% after 7 days at 73 F. **Alumina (porous)**—res 70% at 212 F. **Butyl rubber**—70 hrs at r.t.; excessive softening in conc. **Chlorinated polyether**—res to 10% at 180 F, 70% at 80 F, 100% not rec. **Chlorosulfonated polyethylene rubber**—little or no effect by 10% at r.t., severe effect by 30% at 158 F, minor-moderate effect by 60-70% at r.t. **Ethylene-propylene rubbers**—after 70 hrs at r.t. in 10% t.s. is 87-109% of original, vol changes −3 to +10%. **Epoxy (glass reinf)**—after 30 days in 10% little weight change, retains 50% flex str. **Fluorocarbon (TFE, FEP)**—res to 0-100% at b.p. **Fluorocarbon (PVF_2)**—exc in conc to 120F. **Fluoroelastomer**—little or no effect by 10-70% at r.t. **Fluorosilicone rubber**—after 7 days at 75 F in 70%: t.s. −40%, volume +5%. **Glass (borosilicate)**—satis at 150 F. **Glass-ceramic**—exc in 70% at 194 F, 98% at 77 F. **Graphite (impervious)**—res 0-10% at 185 F, 10-20% at 140 F, NR over 20%. **Hydrocarbon rubber**—minor-moderate effect by 10-30% at r.t., severe effect by 30% at 158 F and 60-70% at r.t. **Natural rubber**—not generally rec in 20%. **Neoprene**—minor to moderate effect by 10% at r.t., severe effect by 30%. **Nitrile rubber**—varies in 20, 30%; not rec in 40%. **Nylon**—unsatis in 10% at r.t. **Phenolic**—Varies with grade, some show little weight change and exc appearance in 10% after 1 week. **Polyacrylate rubber**—after 70 days at r.t.: +52% vol change in conc. **Polyester (glass reinf)**—rec in 5% to 140 F. **Polyethylene (hi-D)**—satis in 25% at 70 F, marginal in 50% at 70 F. **Polyimide (glass reinf)**—7 days in 10%: retains 94% of flex mod and 80% of r.t. flex str. **Modified polyphenylene oxide**—no effect in 10% after 3 days at 185 F. **Polypropylene**—satis in 75% after 180 days at 68 F, unsatis after 100 days at 100 F. **Polystyrene**—not res to 20%. **Polysulfide rubber**—unsatis in 10% for 30 days at 80 F. **Polysulfone**—7 days at 72 F at 71%: weight +3.8%, surface attacked, discolored. **PVC**—varies from satis at 5% at 140 F to unsatis in 95% at 68 F. **Silicon carbide**—at boiling temp, 0.0 mpy in 50%, −0.2 mpy in 70%. **Silicone rubber**—little change in 10% at 75 F; after 3 days at 150 F in 50% ten str −80%, volume +5%; after 7 days at 75 F in 70% t.s. −40%, volume +5%. **Styrene-acrylonitrile**—at 122 F resistant in 10%, not res in 25%. **SBR rubber**—after 70 hrs in conc at r.t. disintegrates. **Thermoplastic rubber**—after 2 weeks at r.t. 4-5% wt gain, 90+% decrease in ten str. **Urethane rubber**—severe effect by 10-70% at r.t. **Vinyl ester (glass reinf)**—rec in 20% at 150 F.

Metals. Aluminum alloys—tend to pit, rate of penetration generally decreasing with increasing oxygen content. Pitting rate highest first yr, tapering off to much lower rate in time. In well-aerated waters pitting not a serious problem for certain alloys; "2000" and "7000" series alloys most susceptible; "5000" alloys relatively immune. Depth of pitting generally increases with increasing ocean depths; even 5000 alloys may show severe pitting at great depths. Alloys most susceptible to pitting also generally most susceptible to crevice attack, and vice versa. Crevice attack also more severe at greater ocean depths than in surface waters. **Beryllium**—will pit, rate of pitting being most intense during first 2 mos. **Carbon steels**—chloride ion (sea salt is about 55% chloride) very corrosive to caroon steels, rate of attack increasing with increasing velocity, available oxygen, temperature and pollutants. Certain biofouling, mineral deposits and film formations tend to reduce attack. Rate of attack tends to be less at greater ocean depths than in surface waters. Average penetration rates generally 2 to 5 mpy. **Cast iron**—res. about half that of carbon steel. **Chromium**—should be res. in sheet form and local attack apt to be less than for stainless steel. **Cobalt and alloys**—electrolytic cobalt moderately attacked: 0.7 mpy after 2 yrs; may tend to pit in quite sea water. Co-Cr-Mo alloys have high res. **Columbium**—should be resistant; no measurable attack after 6 mos. **Copper and alloys**—for copper: 0.5 to 2 mpy typical in shallow and deep ocean; lower rates reported, e.g., 0.38 mpy after 16 yrs in shallow depths of Pacific off Panama Canal. **Single phase brasses, silicon and phosphor bronzes are generally similar. Beryllium-copper** slightly more res. Res. of iron-modified alloy 194 seems to be considerably greater than for copper. Brasses vary res.; high zinc grades tend to fail by dezincafication, especially those of two or more phases. Alloys with 15% Zn or less not as apt to fail in this manner. Red brass, Alloy 230, similar to copper (0.5 to 2 mpy) in deep and shallow waters. Arsenic inhibited admiralty brass also resistant (0.6 mpy after 3 yrs in both shallow and deep waters). Aluminum brass (Alloy 687) has very high res.; 0.7 mpy after 5 mos., 0.2 mpy after 3 yrs at 6000 ft. Silicon bronze similar to copper in rate of attack. 5% aluminum bronze has high res. ($<$ 1 mpy after several mos., 0.3 mpy after 3 yrs). 7% aluminum bronze prone to dealuminumization. Cupronickels have high res.; 0.1 to 1.3 mpy after several mos., about 0.8 mpy after 3 yrs. **Lead**—0.4 to 1.2 mpy at shallow depths (6 mos. to 4 yrs); 0.3 to 1.1 mpy (after 6 mos.) at 2000 to 6000 ft. **Low alloy steels—generally similar to carbon steels. Magnesium and alloys**—poor res.; highly purified distilled grade attacked at rate of 10 mpy; commercial grade often corrodes at 100 times this rate, largely because of impurity content. **Molybdenum**—slight attack; 0.3 mpy, in synthetic ocean water at r.t. Attack increases at moderately elevated temps.; 2.1 mpy (140 F), 3.5 mpy (212 F). **Nickel and alloys**—relatively poor res. for nickel; 5 mpy in rapidly flowing water, greater attack with severe pitting in quiet waters. Ni-Cu "Monel 400" and "K500", have high res. in high velocity waters, but tend to pit in quiet waters. Cupronickels are more resistant than "400." Molybdenum imparts virtual immunity to nickel alloys as evidenced by exc res. of "Hastelloy B" (Ni-28Mo-5Fe) and Ni-Cr-Mo alloys like "Hastelloy C", "Inconel 625", others. "Inconel 600" and "X750" resist well-aerated sea water, but apt to pit. "Inconel 718" (3% Mo) much more res. Overall, "Hastelloy C" and "Inconel 625" are best (based on extensive data); among common metals, their res. to sea water is said to be equalled only by titanium. **Precious metals**—platinum and gold have exc. res. Palladium also res., but less so than platinum. **Stainless steels**—In general, all grades susceptible to local attack, highly alloyed grades being most res. Although 304 and 316 will pit, satisfactory service is possible in moderate to high velocity waters. Alloy 20Cb superior to 304 and 316, especially in high velocity waters, but will also pit under low velocity conditions. Ferritic and martensitic grades generally not recommended. 17-4PH can be used effectively under high velocity conditions. **Tantalum**—tantalum and 90Ta-10W alloy virtually immune at ambient conditions. **Tin**—tends to pit, severely at times. **Titanium alloys**— virtually immune to attack at all depths and velocities, including polluted, diluted and hot waters as well as waters containing chlorine, ammonia, hydrogen sulfide gases or excess carbon dioxide. **Tungsten**—subject only to slight attack at ambient and moderately elevated temps., e.g., 0.3 mpy after 6 months in sea water; 0.2 mpy (95 F), 0.3 mpy (140 F), 0.7 mpy (212 F) in synthetic sea water.

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Sea water (Continued)
Wrought iron—somewhat more res. than carbon steel. **Zinc**—generally attacked at rates of 1 to 2 mpy; higher rates have been reported. **Zirconium**—normally high res.; however, presence of free chlorine will cause attack. **Ref.** Fink, F. W.; Boyd, W. K.; "The Corrosion of Metals in Marine Environments", DMIC Report 245, Battelle (Columbus), May '70. Published by: Bayer & Co., Columbus, Ohio. **Nonmetallics. Chlorosulfonated polyethylene rubber**—little or no effect at r.t. **Fluorocarbon (PVF)**—exc to 275 F. **Fluoroelastomers**—little or no effect at r.t. **Glass (borosilicate)**—satis at 150 F. **Hydrocarbon rubber**—little or no effect at r.t. **Neoprene**—little or no effect at r.t. **Polyethylene (hi-D)**—satis at 70 F. **Polypropylene**—satis at 212 F. **PVC**—satis at 140 F. **Urethane rubber**—little or no effect at r.t.
Sodium chloride
Metals. Aluminum—attacked. **Copper**—moderate res., aeration accelerates attack. After 2 days in 1N sol. at r.t., 2.6 mpy (unagitated), 4.6 mpy (air-agitated). Up to 12 mpy reported after 3 days under strong aeration and agitation in 3% sol. **Chromium**—high res. in dilute sol.; no attack in 10% sol. at 54 F and 136 F. **Lead**—good to moderate res. in dilute sol.; 0.2 to 1.2 mpy in 0.25 to 5.7% con. at 46 F after 200 days. 4 to 5 mpy in 5.5% sol. after 2 days. **Magnesium**—rapidly attacked. **Nickel and alloys**—generally good res. **Tantalum**—res. **Tin**—good res. in very dilute sol.; 0.3 mpy after 1 wk, 0.6 after 1 mo., in 1.3% sol. at 68 F. **Titanium**—exc. res., 0.01 mpy in 3% boil. sol., 0.1 mpy in 29% sol. at 230 F, 0.05 mpy in boil. saturated con. under unaerated conditions. **Zinc**—moderate res. in very dilute sol.; 5 to 10 mpy after 1 mo. in 3.5% sol. at r.t. **Zirconium**—high res. in 3% sol. at r.t.   **Nonmetallics. ABS**—satis after 30 days at 140 F. **Acetal copolymer**—after 6 mos at 180 F at 10%: yld str +4%, tens mod −10%, length +0.2%, weight +0.49%, slight discoloration. **Acrylic**—satis in 30% at 200 F. **Acrylic-PVC alloy**—no change in 10% after 7 days at 73 F. **Butyl rubber**—70 hrs at 212 F: no change in sol'n. **Chlorinated polyether**—res at 250 F. **Chlorosulfonated polyethylene rubber**—little or no effect at r.t. **Epoxy (glass reinf)**—after 30 days in 10%, little weight change, retains 90+% flex str. **Fluorocarbon (PVF_2)**—exc to 275 F. **Fluoroelastomer**—little or no effect at r.t. **Glass (borosilicate)**—satis at 150 F. **Graphite (impervious)**—res all conc at boiling. **Hydrocarbon rubber**—little or no effect at r.t. **Modified polyphenylene oxide**—no effect after 3 days at 185 F. **Neoprene**—little or no effect at r.t. **Nitrile rubber**—rec **Nylon**—satis at r.t. **Phenolic**—varies with grade, some show little weight change and exc appearance in 10% after 1 yr. **Polyacrylate rubber**—after 70 days at 212 F: 2% vol change in sol'n. **Polyester (glass reinf)**—rec to 200 F. **Polypropylene**—satis in 10% after 30 days at 140 F. **Polystyrene**—slight att in 20%; heat does not reduce res. **Polysulfide rubber**—exc (0-20% vol swell) in 10% for 30 days ae 80 F. **PVC**—satis at 140 F. **SBR rubber**—after 70 hrs in sol'n at 212 F: no change. **Silicone rubber**—no vol change in 2% after 7 days at 75 F. **Styrene-acrylonitrile**—resistant at 122 F. **Thermoplastic rubber**—satis in 10% after 2 weeks at r.t. **Urethane rubber**—little or no effect at r.t. **Vinyl ester (glass reinf)**—rec at 210 F.

Sodium hydroxide

Metals. Aluminum—rapidly attacked. **Beryllium**—attack not as severe as on many other materials, but use is not recommended for extended periods over 1000F. **Carbon steels**—res. in dilute sol., attacked in hot con. sol. **Cast irons**—moderately res.; $\leqq$ 5 mpy for gray cast iron up to 70% con. and up to about 180 F. Austenitic cast irons attacked at rate of $<$ 5 mpy at temps. up to boil. pt. in con. up to 70%. Rate of attack increases rapidly above 70% con. at temps. near boil. **Cobalt**—certain Co-Cr-W and Co-Cr-W-Ni alloys have high res.; negligible attack to 0.6 mpy in 50% con. at 150 F after 1 day. **Columbium**—embrittled by boil. sol. of even low con. **Copper and alloys**—both copper and alloys are moderately attacked in dilute sol. For copper, 14 mpy in 3.9% sol. at 86 F after 2 days under static conditions (20 mpy under air-agitated cond.); lower rates have been reported. Of alloys, cupronickels most resistant. **Iron and carbon steels**—moderate to good res. in very dilute sol.; 1 mpy for mild steel in 50% sol. at 100 F after 7 mos.; rapid attacks in 73% sol. after 4 mos. **Lead**—moderate res. in very dilute unaerated sol.; 9.4 mpy in quiet (47 mpy air-agitated) 3.8% sol. after 2 days at r.t. Poor res. in hot or con. sol. **Molybdenum**—severely attacked in fused at 1000 F. **Nickel and alloys**—exc. res.; 0.01 mpy for nickel, 67Ni-33Cu and 76Ni-16Cr-7Fe in 50% con. at 100 F after 7 mos.; 0.1 mpy for 67Ni-33Cu, 1 mpy for nickel and 76Ni-16Cr-7Fe alloy, in 73% con. at 265 F after 7 mos. In fused 100% con., 0.9 to 2.5 mpy for nickel at 750 to 1075 F. **Precious metals**—silver has high res., even at elevated temps. Gold and platinum metals also have good res. **Stainless steels**—exc. res. for both chromium and chromium-nickel grades in dilute sol. up to moderately elevated temps. High to moderate res. in high con. at moderately elevated temps. Cracking may occur near boil. pt. After 3 to 4 mos.: in 20% con. at 120 to 140 F, $<$ 0.1 mpy for 302, 304, 309, 310; 0.1 mpy for 410, 430. In 72% con. at 245 to 255 F, under moderate aeration, 0.1 mpy for 21Cr-34Ni-0.5Cu alloy, 0.3 mpy for 329, 3.1 mpy for 316, 3.7 mpy for 304, 6 mpy for 410, 32 mpy for 430. In 73% nonaerated sol. at 212 to 248 F, 38 mpy for 302, 45 mpy for 304. **Tantalum**—res. to 5% boil. sol., but attacked in fused at 605 F, severely attacked at 1000 F. **Tin**—severely attacked. **Titanium**—high to moderate res.; 0.8 mpy in 10% boil. sol.; 0.1 mpy in 28% sol. at r.t.; 5 mpy in 40% sol. at 176 F. In molten, attacked at 1000 F. **Tungsten**—slight attack in hot alkaline sol.: severely attacked at 1000 F. **Zinc**—attacked; after 2 days in 3.9% sol. at r.t. 18 mpy under quiet conditions, 35 mpy under air-agitated con. **Zirconium**—res.

Nonmetallics. ABS—satis in 25%. **Acetal copolymer**—after 6 mos at 180 F at 60%: yld str -3%, ten mod -6%, length -0.1%, weight -0.18%, slight discoloration. **Acrylic**—limited service in 10% at 120 F. **Acrylic-PVC alloy**—no change in 10% after 7 days at 73 F. **Alumina (porous)**—edges rounded in 10% at 212 F. **Chlorinated polyether**—res to 70% at 250 F. **Chlorosulfonated polyethylene rubber**—little or no effect by 73% at 280 F. **Ethylene-propylene rubbers**—after 70 hrs at r.t. in 50% t.s. is 99-118% of original, vol changes 0 to -1%. **Fluorocarbon (PVF$_2$)**—exc in 50% to 275 F. **Fluorocarbon (TFE, FEP)**—res to 0-100% at boiling. **Fluoroelastomer**—little or no effect by 47% at r.t., severe effect by 50% at r.t. **Fluorosilicone rubber**—after 7 days at 75 F in 50%: ten str -10%, volume no change. **Glass (borosilicate)**—satis at 150 F. **Glass-ceramic**—good (less than 20 mpy) in 1% at 194 F, satis (20-25 mpy) in 7% at 194 F. **Graphite (impervious)**—res 6-67% at boiling, 67-80% at 275 F. **Hydrocarbon rubber**—little or no effect by 20-73%. **Modified polyphenylene oxide**—no effect in conc after 3 days at 185 F. **Neoprene**—little or no effect by 20, 73% at r.t. and 47% at 158 F. **Nitrile rubber**—rec in 50%. **Nylon**—satis at r.t. **Phenolic**—generally poor res in 10% after 1 week. **Polyester (glass reinf)**—rec in 10 and 25% to 130 F, 5% to 160 F, NR in 50%. **Polyethylene (hi-D)**—satis at 70 F. **Polyimide (glass reinf)**—7 days in 10%: retains 93% of flex mod and 82% of r.t. flex str. **Polypropylene**—satis in 60% after 30 days at 140 F. **Polystyrene**—slight att in 1-50%; heat does not reduce res. **Polysulfide rubber**—exc (0-20% vol swell) in 20% for 30 days at 80 F. **Polysulfone**—110 days at 72 F at 5%: weight -0.03%. **PVC**—unplasticized satis at 140 F, plast some att or absorp at 140 F. **Silicon carbide**—$+73$ mpy in 25% at boiling temp. **Silicone rubber**—after 7 days at 75 F: t.s. -10%, vol no change. **Styrene-acrylonitrile**—resistant in sat at 122 F. **Urethane rubber**—at r.t. little or no effect by 20%, severe effect by 50%. **Vinyl ester (glass reinf)**—rec in 50% at 210 F.

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Sulfuric acid

Metals. Aluminum—res. attack in very dilute (1% or less) or very high con. (98 to 100%) at r.t. Rapidly attacked at other con. and higher temps. **Beryllium**—rapidly attacked at r.t. **Carbon steels**—moderately res. at con. above 70% (5 to 20 mpy at 75 F, 20 to 50 mpy at 125 F, 50 to 200 mpy at 175 F in static tests; higher rates likely in service); more res. at 100% con. Rapidly attacked by con. below 70%. **Cast irons**—good res. in certain con. and temps. High-silicon irons generally best, followed by austenitic grades. For gray iron < 5 mpy in con. above 65% at r.t., but rapid attack at lower con. **Chromium**—attacked; 28 mpy after 1 day in 17% sol. at 60 F. **Cobalt and alloys**—cobalt has moderate res.; 9 mpy in 5% con. at r.t. under static conditions. Certain Co-Cr-W and Co-Cr-W-Ni alloys suffer negligible attack in high con. (77 to 96%) at r.t., but may be attacked by 25% sol. at moderately elevated temps. (150 F). **Columbium**—virtually immune to attack in 20% con. at 200 F and 40% and 95% con. at 75 F. Slight attack (0.1 mpy) in 98% con. at 75 F. Slight attack (0.1 mpy) in 98% con. at r.t. At high con. (95%) rate of attack increases with temp.; 0.8 mpy at 120 F, 19 mpy at 212 F, 180 mpy at 290 F. **Copper and alloys**—copper has high res.; up to 2 mpy in 10 to 80% con. at r.t.; decreasing temps. increase attack (6 to 15 mpy at 140 F). In 60 to 70% sol., attack moderate (3 to 12 mpy) up to 176 F. Rates roughly similar for Si-Mn bronze and 70Cu-30Ni cupronickel. Aeration increases attack. **Lead**—good res.; < 5 mpy in 5 to 50% con. Attack markedly increased in con. below 5%. Attack up to 50 mpy at 50 to 97% con. up to boil. temp. Antimonial lead superior to chemical lead at high con. **Low alloy steels**—generally similar to carbon steels. **Magnesium**—rapidly attacked. **Molybdenum**—high res.; 0.15 mpy to cold sol. up to about 96% con. Good res. to boil. sol. up to 50% con. Increasing con. and temps. increase attack severely. **Nickel and alloys**—Nickel has moderate res.; 2 to 9 mpy in unaerated, dilute (1 to 20%) sol. at r.t. Aeration increases attack appreciably (50 to 60 mpy for 1% and 5% sol.) Con. sol. more aggressive: 30 and 70 mpy for 70% and 95% con. Attack 10 to 30 mpy for 5 to 48% sol. at 140 to 180 F. Among nickel alloys, Ni-Mo, Ni-Mo-Cr and Ni-Si grades are best overall (< 5 mpy for virtually all con. to about 200 F to 250 F). 67Ni-33Cu also has moderate res. (< 5 mpy) in con. up to 80%. **Precious metals**—gold, iridium, osmium, palladium, platinum, rhodium and ruthenium have exc. res. in 98% con. at r.t. and all but rhodium (moderately attacked) and palladium (excessively attacked) have high res. at 212 F. Iridium and ruthenium also have high res. at 570 F for 7 hrs. in 98% sol.; gold only slightly attacked (0.7 mpy). Silver res. dilute sol. at r.t. and is only slightly attacked (0.7 mpy) in boil. 10% and 20% sol. **Stainless steels**—several austenitic grades have high res. in aerated sol. at low and moderately elevated temps. In general, increasing con. and temps. and absence of air-accelerate attack. In nitrogen-saturated 5% sol. at 86 F, < 0.1 mpy for 317, 0.6 mpy (316), 1.2 mpy (310 and 321), 9 mpy (301), 12 mpy (347) and 57 mpy (304); 201, 302, 430 rapidly attacked. In aerated dilute sol. (up to about 10%), 304, 310, 316 and 317 have high res.; < 0.1 mpy at temps. of 0 to 160 F. These grades about equally res. at all con. in aerated sol. at temps up to 70 to 125 F.

Types 310 and 317 also have high res. in intermediate (20 to 60%) aerated sol. at 125 to 150 F, 310 being somewhat superior. **Tantalum**—high res.; 0 to 0.1 mpy in 20 to 95% con. at 75 to 350 F. Some attack in 95% sol. at higher temp.; 1.5 mpy at 390 F, 29 mpy at 480 F. In fuming acid: 0.3 mpy at 75 F, 9 mpy at 160 F. **Tin**—moderate res., 2 to 10 mpy in dilute (up to 10%), air-free sol. at r.t. Poor res. in high con.; 70 mpy in air-free 20% sol. at r.t. **Titanium**—high res. in very dilute sol. at r.t.; 0.1 mpy in 1% sol. Moderate to poor res. with increasing con. (75 to 80% sol. being most corrosive) and temps.; 4 mpy in 1% sol. at 100 F, 9 mpy in 5% sol. at r.t. and 30 mpy at 100 F, 60 mpy in 40% sol. at r.t., 250 mpy in 50% sol. at 100 F. Addition of 0.15 Pd increases res. in dilute sol., anodizing improves res. in 40% sol. **Zinc**—attacked. **Zirconium**—high res. < 1 mpy in con. up to 70% up to boil. pt. Severe attack in con. above 80%, especially with increasing temp.

Nonmetallics. ABS—in 50% after 30 days satis at r.t., unsatis at 140 F. **Acetal copolymer**—NR in 30%. **Acetal homopolymer**—316 days at 95 F at 10%: unsatis. **Acrylic**—limited service in 10% at 180 F, 50% at 100 F, unsatis in 50% at 150 F. **Acrylic-PVC alloy**—no change in 30% after 7 days at 73 F. **Alumina (porous)**—res 96% at 212 F. **Butyl rubber**—70 hrs at r.t.: +1% vol change in 50%. **Chlorinated poly-**

ether—res to 80% at 250 F, 90% at 180 F, 96% at 80 F, NR in 98%. **Chlorosulfonated polyethylene rubber**—little or no effect by up to 50% at 250 F, 50-80% at 158 F, 95% at r.t. **Diallyl phthalate**—retains 80% of flex str in 3% after 1 yr. **Epoxy (glass reinf)**—in 3% after 30 days little weight change, retains 75% flex str. **Ethylene-propylene rubber**—after 70 hrs in 98% at r.t. retains 23-80% of ten str, vol change +5 to +8%; in 10% at 212 F t.s. is 96-111% of original, vol change 0 to −2.5%. **Fluorocarbon (TFE, FEP)**—in 0-100% TFE res to 500 F, FEP to 400 F. **Fluoroelastromer**—little or no effect up to 80% at r.t., 60% at 250 F, 90% at 158 F. **Fluorocarbon (PVF_2)**—exc in 60% to 230 F, 85% to 150 F. **Glass-ceramic**—exc in 98% at 194 F. **Graphite (impervious)**—res 0-70% at boiling, 70-85% at 338 F, 85-90% at 300 F, 90-93% at 160 F, 93-96% at r.t., NR over 96%. **Hydrocarbon rubber**—at r.t. little or no effect to 50%, severe effect 60-95%. **Natural rubber**—satis in 50%. **Neoprene**—little or no effect up to 50% at 158 F, generally severe effect over 50% at r.t. **Nitrile rubber**—rec in 17, 30%; varies in 42, 56%; not rec in 70%. **Nylon**—unsatis at r.t.. **Phenolic**—varies with grade, some show little weight change and exc appearance in 30% after 1 yr. **Polyacrylate rubber**—after 70 days at r.t.: disintegrates in conc, +3% vol change in 50%. **Polyester (glass reinf)**—rec in 70% to 140 F, 50% to 200 F. **Polyethylene (hi-D)**—at 70 F satis in 70%, marginal in 95%. **Polymide (glass reinf)**—7 days in 10%: retains 88% of flex mod and 88% of r.t. flex str. **Modified polyphenylene oxide**—no effect in 90% after 3 days. **Polypropylene**—satis in 97% after 30 days at 140 F. **Polystyrene**—slight att in 10-50%; heat reduces res, NR in conc. **Polysulfide rubber**—varies from exc (0-20% vol swell)in 10%, to fair (40-80% vol swell) in 20%, to unsatis in 50% and 100%; all values 30 days, 80 F. **Polysulfone**—69 days at 72 F at 95%: dissolves. **PVC**—unplast satis to 80% at 140 F, plast satis to 45% at 140 F; check perf at higher conc. **Silicone carbide**—+0.1 mpy in 80% at boiling temp. **Silicone rubber**—after 3 days at 150 F in 50% ten str −35%, volume no change; decomposes in 95% after 7 days at 75 F. **SBR rubber**—after 70 hrs at r.t.: disintegrates in conc, +3% vol change in 50%. **Styrene-acrylonitrile**—at 122 F resistant in 25%, not res in conc. **Thermoplastic rubber**—satis in 10% after 2 weeks at r.t. **Urethane rubber**—severe effect at r.t. **Vinyl ester (glass reinf)**—rec in 70% at 210 F.

TABLE 44.4 Corrosion Data by Environment and Material (*Continued*)

Waters other than sea water

Metals. Aluminum and alloys—high res. in high purity (distilled or deionized) or water vapor up to about 400 F. In general, good res. to most neutral or nearly neutral waters providing waters do not contain compounds other than salts of alkaline earth metals. Acid waters containing chlorides can cause severe pitting; sulfate waters of low pH also aggressive. Compounds of Cu, Pb, Sn, Ni and Co in waters promote pitting of alloys ("alclad" aluminum coatings help reduce attack). **Beryllium**—high res. at ambient temps. in neutral waters, even under static conditions. Under aeration and flowing cond., good res. at moderately elevated temps. Protection required above 500 F. Presence of chloride ions in water markedly increases attack. Sulfate, cupric or ferric ions also increase attack. **Carbon steels**—fresh waters: normally pit in neutral solutions since protection afforded by rust is usually irregular; supply of dissolved oxygen and deposited protective films being most critical factors governing attack. 2 to 5 mpy avg rate of attack in quiet waters free of salts and containing dissolved air. Agitation or aeration usually increase attack; deposition of compounds usually supresses attack. Presence of various salts or other substances may either increase or decrease attack. Boiler water: supply of dissolved oxygen again critical factor; deaeration common corrosion preventative. Mine waters: can cause severe attack. **Cast irons**—res. generally similar to carbon steels for plain cast irons. **Cobalt**—good res. in distilled water, 0.2 mpy at 77 F under static conditions. Wear resistant alloys undergo little attack in mine and boiler waters at ordinary temps. **Columbium**—good resistance to 500 F in oxygenated water. Res. seems good under both static and dynamic conditions. **Copper and alloys**—copper has good res. to all fresh waters, attack ranging from 0.2 to 1 mpy, sometimes less. Hard waters seldom corrosive, but soft waters, especially with substantial amounts of free carbon dioxide, may be sufficiently corrosive to cause green stains on plumbing fixtures by reacting with soap. Distilled water not very corrosive, but will pick up trace of copper on long standing. Carbonated water much more corrosive, after 20 hrs at r.t. in water saturated with air and carbon dioxide: 2 to 10 mpy in city water, 2 to 6 mpy in distilled water. Some copper alloys, e.g., red brass, better than pure copper for fresh water plumbing. Silicon and phosphor bronzes, cupronickels, cast bronzes and nickel silvers also have high res. Tin-bearing copper alloys, e.g., 88Cu-10Zn-2Sn, most res. to river waters containing acid-mine drainage. **Lead**—not attacked by pure distilled water free of dissolved gases, but aerated distilled water free of carbon dioxide can be corrosive. Also resists non-potable water, except possibly acid mine waters. Soft waters attack lead sufficiently to have discontinued its use for potable soft water systems (toxicity problem). Fresh waters may also be corrosive if containing carbon dioxide or small amounts of organic acids. Small amounts of nitrates in ground water also increase corrosivity. **Low alloy steels**—more or less similar to carbon steels for fresh waters, with variations in attack more likely under short-term submergence, e.g., over long-term no significant difference in attack of copper structural steels and plain carbon steels. In partly stagnant waters corrosion rate of low alloy steel similar to carbon steel, i.e., about $\frac{1}{2}$ rate in aerated waters. Nickel additions may be marginally beneficial, e.g., in Pittsburgh water at 140 to 145 F: 14.6 mpy for mild steel, 13.2 mpy for 1.65Ni steel, 12.2 mpy for 3.61Ni steel, 12.6 mpy for 5.20Ni steel. In simulated reactor boiling water, essentially no difference between carbon steels and steels of up to 5% alloy content. **Magnesium and alloys**—good res. in stagnant distilled water at r.t. Pitting may occur if small amounts of chlorides, heavy metal salts or carbon dioxide present. Agitation or constant replenishment of water may lead to attack, e.g., little attack on AZ31 alloy after 35 days in stagnant distilled water at 125 F; when water continuously replenished to maintain 6.8pH, rate of attack 7 mpy. Corrosion rates in water at different temperatures: MIA—13.2 mpy (95 F), 6.0 mpy (150 F), 13.2 mpy (180 F), 72 mpy (212 F); AZ92A—0.8 mpy (95 F), 16.3 mpy (212 F); AM100A—0.8 mpy (95 F), 26.9 mpy (212 F). **Molybdenum**—tranished but not attacked by fresh waters up to moderately elevated temps. Poor res. to oxygenated water at 600 F and to water vapor at 1200 F. **Nickel**—high res. to most natural, fresh, distilled, deionized and high purity waters; attack usually < 0.1 mpy. Attack usually < 0.02 mpy in domestic hot water up to 200 F. Res. to carbonated fresh water also good, 0.2 mpy after 10 days at r.t. and 200 psig. Nickel may be attacked in polluted (acid drainage) rivers, e.g., 3.8 mpy in Monongahela River at 5pH (0.3 mpy, 6.5pH), and severely attacked by acid mine waters. **Stainless steels**—high res. to distilled, tap and other fresh waters, including relatively polluted lake and river waters, cold or hot; e.g., after 490 days in Monongahela containing coal mine drainage and spent pickling acid, attack rate < 0.1 mpy for 304, 316, 410 and 430 steels; 2 mpy for 502. In general negligible attack from boiler, high purity and mine waters under most conditions. **Tantalum**—tarnishes in oxygenated water at 500 F. **Tin**—will tarnish, but virtually immune to distilled water and only slightly attacked by carbonated waters. Attacked by drinking waters purified by addition

Waters other than sea water (Continued)

of strong oxidizing agents which produce nascent oxygen. **Titanium and alloys**—high res. even to brackish river waters, and distilled, degassed-distilled or oxygenated-distilled waters at 500 F. **Tungsten**—no attack from cold or hot water. **Wrought iron**—more or less similar to carbon steels, but may be more res. to pitting under certain conditions. **Zinc**—good res., but only in narrow pH range around neutral point. Can provide good galvanic protection to steel in fresh waters. Moderate attack in aerated distilled water up to about 120 F, severe attack from 120 to 200 F. Aeration increases attack in distilled water, especially if trace amounts of carbon dioxide present. Some rates: 2.0 mpy for plain water at 54 F after 2 months; 4.8 mpy in quiet distilled water. **Zirconium and alloys**—good res. to high temperature waters and steam to 900 F. **Nonmetallics. ABS**—satis. **Acetal copolymer**—rec for continuous use at 180 F, retains nearly original tens str in boiling after 22 weeks. **Acetal homopolymer**—not rec for long-term service over 150 F. **Acrylic**—satis after 5 yrs. **Butyl rubber**—disintegrated after 70 hrs at 212 F. **Chlorinated polyether**—res at 250 F. **Chlorosulfonated polyethylene rubber**—little or no effect at 212 F. **Epoxy (glass reinf)**—after 5 yrs immersion minor weight change. **Ethylene-propylene rubber**—after 70 hrs at 212 F t.s. is 76-110% of original, vol change +2%. **Fluorocarbon (PVF)**—in brine exc to 275 F. **Fluoroelastomer**—little or no effect at 212 F. **Fluorosilicone rubber**—in steam after 1 day at 100 psi: t.s. −20%, volume no change. **Graphite (impervious)**—res boiling. **Hydrocarbon rubber**—little or no effect at 212 F. **Neoprene**—little or no effect at 212 F. **Nitrile rubber**—rec in distilled. **Nylon**—no att in cold, little or no att in hot. **PVC-acrylic alloy**—no change after 7 days at 140 F except slight staining (none at 73 F). **Phenolic**—varies in distilled with grade, some show little weight change and exc appearance after 1 yr. **Polyacrylate rubber**—after 70 days at 212 F: +23% vol change. **Polyester (glass reinf)**—rec to 200 F. **Polyethylene (hi-D)**—satis after 1 yr at 70 F. **Polyimide (glass reinf)**—in boiling after 7 days flex mod is +3% and flex str is +12% over r.t. values. **Polypropylene**—satis in distilled after 160 days at 140 F. **Polystyrene**—in distilled—res; heat reduces res. **Polysulfide rubber**—exc (0-20% vol swell) after 30 days at 80 F. **Polysulfone**—7 days at 72 F: weight +0.6%. 7 days at 210 F: weight +0.9%. **SBR rubber**—after 70 hrs at 212 F: +10% vol change. **Silicone rubber**—no change after 3 days at 212 F. **Styrene-acrylonitrile**—in distilled res at 122 F. **Thermoplastic rubber**—in distilled satis after 2 weeks at r.t. **Urethane rubber**—little or no effect at 212 F.

†Abbreviations used in this table: ABS = acrylonitrile-butadiene-styrene; att = attack; atmos = atmosphere; boil pt = boiling point; con, connc = concentrated; exc = excellent; flex mod = flexural modulus; flex str = flexural strength; indus = industrial; max = maximum; mos = months; mpy = mils per year; plast = plasticized; ppm = parts per million; PVC = polyvinyl chloride; res = resistance; resp = respectively; r.t. = room temperature; satis = satisfactory; SBR = styrene butadiene; sol = soluble; ten mod = tensile modulus; tens str = tensile stress; unsatis = unsatisfactory; unplast = unplasticized; vol = volume; yld str = yield stress or strength; yrs = years.

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corrosion (weld decay). Heating to higher temperatures, 1060 to 1120°C, followed by water quenching will redissolve the precipitated carbides and keep them in solution. Appropriate alloying changes can reduce carbide precipitation.

44.3.10 Mechanical Contributions

Fluid flow or mechanical rubbing can cause removal of or damage to a protective oxide, increasing the proximity of the bare metal and the attacking medium. This can result in increased attack rates because a stable oxide layer is frequently a corrosion rate limiter. An example is *erosion corrosion* caused by high flow rates of domestic hot water in copper pipes, especially around fittings, which can generate turbulence. Another example involves the press fit of gears, wheels, pulleys, etc., onto shafts that experience elastic torsion, or bending. Small relative motions occur at the contacting surfaces which mechanically break up protective oxide layers. This type of corrosion is known as *fretting corrosion.*

44.4 CORROSION DATA FOR MATERIALS SELECTION†

Subject to the limitations mentioned at the beginning of this chapter, the corrosion data in Table 44.4 can be used as a guide in selecting materials for the environments listed. The organization is first by environments and then by materials, metals followed by nonmetals. The abbreviation NR means not recommended.

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