40 Aluminum and Aluminum Alloys

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A. ALUMINUM PROPERTIES AND ALLOYS

Aluminum is second only to iron as the most important metal of commerce. Aluminum is also the third most abundant metal in the crust of the earth, almost twice as plentiful as iron, the fourth most abundant metal. Pure aluminum has a relatively low strength. The density of all alloys (99.65–99.99%) is of the order of 2.7 g/mL, one-third that of steel. In addition to recycling and new smelting processes, aluminum has a relatively low cost, and its alloys provide a high ratio of strength to weight. Salts of aluminum do not damage the environment or ecosystems and are nontoxic. Aluminum and its alloys are nonmagnetic and have high electrical conductivity, high thermal conductivity, high reflectivity, and noncatalytic action [1].

1. Wrought Alloys

Wrought alloys are of two types: non-heat treatable, of the 1XXX, 3XXX, 4XXX, and 5XXX series, and heat treatable, of the 2XXX, 6XXX, and 7XXX series. Strengthening is produced by strain hardening, which can be increased by solid solution and dispersion hardening for the non-heat-treatable alloys. In the heat-treatable type, strengthening is produced by (1) a solution heat treatment at 460 to 565°C (860 to 1050°F) to dissolve soluble alloying elements; (2) quenching to retain them in solid solution; and (3) a precipitation or aging treatment, either naturally at ambient temperature, or more commonly, artificially at 115 to 195°C (240 to 380°F), to precipitate these elements in an optimum size and distribution; (4) solution heat treatment and natural aging; (5) air quenched and aged; (6) solution heat treatment and annealed; (7) like entry 6, but overaged; (8) like entry 3, but with accelerated aging; (9) like entry 6 and followed by strain hardening (cold working).

Strengthened tempers of non-heat-treatable alloys are designated by an "H" following the alloy designation, and of heat-treatable alloys, by a "T"; suffix digits designate the specific treatment (e.g., 1100-H14 and 7075-T651). In both cases, the annealed temper, a condition of maximum softness, is designated by an "O" [1]. The temper designation system is used for all forms of wrought and cast aluminum and aluminum alloys except ingot cast materials. Basic temper designations consist of letters; subdivisions of the basic tempers, where required, are indicated by one or more digits following the letter [2]. The nominal chemical compositions of representative wrought aluminum alloys are given in Table 1. Typical tensile properties of these alloys in tempers representative of their most common usage are given in Tables 2 and 3.

Uhlig's Corrosion Handbook, Second Edition, Edited by R. Winston Revie.
ISBN 0-471-15777-5 © 2000 John Wiley & Sons, Inc.

TABLE 1. Nominal Chemical Compositions of Representative Aluminum Wrought Alloys[a]

	Percent of Alloying Elements								
Alloy	Si	Cu	Mn	Mg	Cr	Zn	Ti	V	Zr
				Non-heat-Treatable Alloys					
1060	99.60%	min Al							
1100	99.00%	min Al							
1350	99.50%	min Al							
3003		0.12	1.20						
3004			1.20	1.0					
5052				2.5	0.25				
5454			0.80	2.7	0.12				
5456			0.80	5.1	0.12				
5083			0.70	4.4	0.15				
5086			0.45	4.0	0.15				
7072[b]						1.0			
				Heat-Treatable Alloys					
2014	0.8	4.400	0.80	0.5					
2219		6.30	0.30				0.06	0.10	0.18
2024		4.40	0.60	1.5					
6061	0.6	0.28		1.0	0.20				
6063	0.4			0.7					
7005			0.45	1.4	0.13	4.5	0.04		0.14
7050		2.30		2.2		6.2			
7075		1.60		2.5	0.23	5.6			

[a] Reprinted from Ref. [1], pp. 111–145 by courtesy of Marcel Dekker, Inc.
[b] Cladding for Alclad products.

All non-heat-treatable alloys have a high resistance to general corrosion. Aluminum alloys of the 1XXX series representing unalloyed aluminum have a relatively low strength. Alloys of the 3XXX series (Al–Mn, Al–Mn–Mg) have the same desirable characteristics as those of the 1XXX series, but somewhat higher strength. Almost all the manganese in these alloys is precipitated as finely divided phases (intermetallic compounds), but corrosion resistance is not impaired because the negligible difference in electrode potential between the phases and the aluminum matrix in most environments does not create a galvanic cell. Magnesium, added to some alloys in this series, provides additional strength through solid solution hardening, but the amount is low enough that the alloys behave more like those with manganese alone than like the stronger Al–Mg alloys of the 5XXX series. Alloys of the 4XXX series (Al–Si) are low-strength alloys used for brazing and welding products and for cladding in architectural products. These alloys develop a gray appearance upon anodizing. The silicon, most of that is present in elemental form as a second-phase constituent, has little effect on corrosion.

Alloys of the 5XXX series (Al–Mg) are the strongest non-heat-treatable aluminum alloys, and in most products, they are more economical than alloys of the 1XXX and 3XXX series in terms of strength per unit cost. Magnesium is one of the most soluble elements in aluminum, and when dissolved at an elevated temperature, it is largely retained in solution at lower temperatures, even though its equilibrium solubility is greatly exceeded. It produces considerable solid solution hardening, and additional strength is produced by strain hardening. Alloys of the 5XXX series have not only the same high resistance to general corrosion as other non-heat-treatable alloys in most environments, but in slightly alkaline ones, a better resistance than any other aluminum alloy. They are widely used because of their high as-welded strength when welded with a compatible 5XXX series filler wire, reflecting the retention of magnesium in solid solution.

TABLE 2. Typical Tensile Properties of Representative Non-Heat-Treatable Aluminum Wrought Alloys in Various Tempers[a,b]

	Strength (MPa)		Percent Elongation	
Alloy and Temper	Ultimate	Yield	In 50 mm[c]	In 5D[d]
1060 -O	70	30	43	
-H12	85	75	16	
-H14	100	90	12	
-H16	115	105	8	
-H18	130	125	6	
1100 -O	90	35	35	42
-H14	125	125	9	18
-H18	165	150	5	13
3003 -O	110	40	30	37
-H14	150	145	8	14
-H18	200	185	4	9
3004 -O	180	70	20	22
-H34	240	200	9	10
-H38	285	250	5	5
5052 -O	195	90	25	27
-H34	260	215	10	12
-H38	290	255	7	7
5454 -O	250	115	22	
-H32	275	205	10	
-H34	305	240	10	
-H111	260	180	14	
-H112	250	125	18	
5456 -O	310	160		22
-H111	325	230		16
-H112	310	165		20
-H116, H321	350	255		14
5083 -O	290	145		20
-H116, H321	315	230		14
5086 -O	260	115	22	
-H116, H32	290	205	12	
-H34	325	255	10	
-H112	270	130	14	

[a] Averages for various sizes, product forms, and methods of manufacture; not to be specified as engineering requirements or used for design purposes.

[b] Reprinted from Ref. [1]. pp. 111–145 by courtesy of Marcel Dekker, Inc.

[c] A 1.60-mm-thick specimen.

[d] A 12.5-mm-diameter specimen.

Among heat-treatable alloys, those of the 6XXX series, which are moderate-strength alloys based on the quasibinary Al–Mg_2Si (magnesium silicide) system, provide a high resistance to general corrosion equal to or approaching that of non-heat-treatable alloys. Heat-treatable alloys of the 7XXX series (Al–Zn–Mg) that do not contain copper as an alloying addition also provide a high resistance to general corrosion.

All other heat-treatable wrought alloys have a significantly lower resistance to general corrosion. These include all alloys of the 2XXX series (Al–Cu, Al–Cu–Mg, Al–Cu–Si–Mg) and those of the 7XXX series (Al–Zn–Mg–Cu) that contain copper as a major alloying element. As described later, the lower resistance is caused by the presence of copper in these alloys, which are designed primarily for aeronautical applications, where strength is required and where protective measures, are justified [1].

TABLE 3. Typical Tensile Properties of Representative Heat-Treatable Aluminum Wrought Alloys in Various Tempers[a,b]

	Strength (MPa)		Percent Elongation	
Alloy and Temper	Ultimate	Yield	In 50 mm[c]	In 5D[d]
2014 -O	185	95		16
-T4, T451	425	290		19
-T6, T651	485	415		11
2219 -O	170	75	18	
-T37	395	315	11	
-T87	475	395	10	
2024 -O	185	75	20	20
-T4, T351	470	325	20	17
-T851	480	450	6	
-T86	515	490	6	7
6061 -O	125	55	25	27
-T4, T451	240	145	22	22
-T6, T651	310	275	12	15
6063 -O	195	90	25	27
-H34	260	215	10	12
-H38	290	255	7	7
7005 -O	195	85		20
-T63, T6351	370	315		10
7050 -T76, T7651	540	485		10
-T736, T73651	510	455		10
7075 -O	230	105	17	14
-T6, T651	570	505	11	9
-T76, T7651	535	470		10
-T736, T7351	500	435		11

[a] Averages for various sizes, product forms, and methods of manufacture; not to be specified as engineering requirements or used for design purposes.

[b] Reprinted from Ref. [1], pp. 111–145 by courtesy of Marcel Dekker, Inc.

[c] A 1.60-mm-thick specimen.

[d] A 12.5-mm-diameter specimen.

2. Cast Alloys

Cast alloys are also of two types: non-heat-treatable, designated by an "F" for which strengthening is produced primarily by intermetallic compounds; and heat treatable, designated by a "T," corresponding to the same type of wrought alloys where strengthening is produced by dissolution of soluble alloying elements and their subsequent precipitation. Alloys of the heat-treatable type are usually thermally treated subsequent to casting, but in a few cases, where a significant amount of alloying elements are retained in solution during casting, they may not be given a solution heat treatment after casting; thus they may be used in both the F and fully strengthened T tempers (Tables 4 and 5).

Aluminum casting alloys are produced by all casting processes of which die, permanent mold, and sand casting account for the greatest proportion. Unlike wrought alloys, their selection involves consideration of casting characteristics as well as of properties.

As with wrought alloys, copper is the alloying element most deleterious to general corrosion. Alloys such as 356.0, A356.0, B443.0, 513.0, and 514.0 that do not contain copper as an alloying element have a high resistance to general corrosion comparable to that of non-heat-treatable wrought alloys. In other alloys, corrosion resistance becomes progressively less the greater the copper

TABLE 4. Nominal Chemical Compositions of Representative Aluminum Casting Alloys[a]

	Percent of Alloying Elements				
Alloy	Si	Cu	Mg	Ni	Zn
			Alloys Not Normally Heat Treated		
360.0	9.5		0.5		
380.0	8.5	3.5			
443.0	5.3				
514.0			4.0		
710.0		0.5	0.7		6.5
			Alloys Normally Heat Treated		
295.0	0.8	4.5			
336.0	12.0	1.0	1.0	2.5	
355.0	5.0	1.3	0.5		
356.0	7.0		0.3		
357.0	7.0		0.5		

[a] Reprinted from Ref. [1]. pp. 111–145 by courtesy of Marcel Dekker, Inc.

content. More so than with wrought alloys, a lower resistance is compensated by the use of thicker sections usually necessitated by requirements of the casting process [1].

Other Al-based materials, such as laminates, composites, and ultrafine structures, prepared by conventional or novel techniques are becoming available and their applications will depend in part on their corrosion performance.

Alclad alloys are duplex wrought products, supplied in the form of sheet, tubing, and wire, which have a core of one aluminum alloy and a coating on one or both sides, of aluminum or another

TABLE 5. Typical Tensile Properties of Representative Aluminum Casting Alloys in Various Tempers[a]

		Strength (MPa)		Percent Elongation
Alloy and Temper	Type Casting	Ultimate	Yield	In 50 mm[c]
295.0 -T6	Sand	250	165	5
336.0 -T5	Permanent mold	250	195	1
355.0 -T6	Sand	240	170	3
-T6	Permanent mold	375	240	4
-T61	Sand	280	250	3
-T62	Permanent mold	400	360	1.5
356.0 -T6	Sand	230	165	3.5
-T6	Permanent mold	255	185	5
-T7	Sand	235	205	2
-T7	Permanent mold	220	165	6
357.0 -T6	Sand	345	295	2
-T6	Permanent mold	360	295	5
-T7	Sand	275	235	3
-T7	Permanent mold	260	205	5
360.0 -F	Pressure die	325	170	3
380.0 -F	Pressure die	330	165	3
443.0 -F	Pressure mold	160	60	10
514.0 -F	Sand	170	85	9
710.0 -F	Sand	240	170	5

[a] Reprinted from Ref. [1], pp. 111–145 by courtesy of Marcel Dekker, Inc.

[b] Averages for separate cast test bars; not to be specified as engineering requirements or used for design purposes.

[c] A 1.60-mm-thick specimen.

aluminum alloy. Generally, the core comprises 90% of the total thickness with a coating comprising about 5% of the thickness on each side. The coating is metallurgically bonded to the core over the entire area of contact. In the most widely used Alclad materials, the coating alloys are selected so that they will be anodic to the core alloys in most natural environments. Thus, the coating will galvanically protect the core where it is exposed at cut edges, rivet holes, or scratches. Such Alclad alloys are usually more resistant to penetration by neutral solutions than are any of the other aluminum-base alloys [3].

The recent worldwide interest shown in the metal matrix composite "MMC" materials has been fueled by the fact that mechanical properties of light alloys can be enhanced by incorporating reinforcing fibers (usually ceramic). Several manufacturers are marketing a range of particulate reinforced MMC products with different compositions (e.g., 12% alumina, 9% carbon fiber, reinforced Al–12% SiC, particulate SiC/Al ingots). The major reinforcements used in aluminum-based MMCs are boron, graphite, silicon carbide, and alumina.

B. CORROSION BEHAVIOR OF ALUMINUM AND ITS ALLOYS

1. Description

Alloy 1100 (2S), sometimes known as commercially pure aluminum, contains ~99.0–99.3% aluminum. The rest of the alloy is made up mainly of iron and silicon with minor amounts of copper. Purer aluminum, containing up to ~99.95% aluminum is also available; in addition, electrolytic refining has produced a small amount of very pure metal, >99.99% aluminum. The resistance of pure aluminum to attack by most acids and many neutral solutions is higher than that of aluminum of lower purity or of most of the aluminum-base alloys.

Aluminum is an active metal, and its resistance to corrosion depends on the passivity produced by a protective oxide film. In aqueous solutions, the potential–pH diagram according to Pourbaix [4] in Figure 1 expresses the thermodynamic conditions under which the film develops. As this diagram shows, aluminum is passive only in the pH range of ~4 to 9. The limits of passivity depend on the temperature, the form of oxide present and the low dissolution of aluminum that must be assumed for inertness. The various forms of aluminum oxide all exhibit minimum solubility at about pH 5.

The protective oxide film formed in water and atmospheres at ambient temperature is only a few nanometers thick and amorphous. At higher temperatures, thicker films are formed; these may consist of a thin amorphous barrier layer next to the aluminum and a thicker crystalline layer next to the barrier layer. Relatively thick, highly protective films of boehmite, aluminum oxide hydroxide AlOOH, are formed in water near its boiling point, especially if it is made slightly alkaline, and thicker, more protective films are formed in water or steam at still higher temperatures.

Since the form of aluminum oxide produced depends on corrosion conditions, its identification is sometimes useful in establishing the cause of corrosion. At lower temperatures, the predominant forms produced by corrosion are bayerite, aluminum trihydroxide $Al(OH)_3$, while, at higher temperatures, it is boehmite $Al_2O_3.H_2O$. During aging of aluminum hydroxide, which is first formed during corrosion in an amorphous form, still another aluminum trihydroxide, gibbsite or hydrargilite ($Al_2O_3.3H_2O$) may also be formed, especially if ions of alkali metals are present.

Above a temperature of ~230°C (445°F), a protective film no longer develops in water or steam, and the reaction progresses rapidly until eventually all the aluminum exposed in these media is converted into oxide. Special alloys containing iron and nickel have been developed to retard this reaction, and these alloys may be used up to a temperature of ~360°C (680°F) without excessive attack [5].

2. Effect of O_2 and Some Gases

Oxygen does influence the corrosion of aluminum. The corrosion of aluminum is very slow in deaerated solutions. In the presence of O_2, corrosion is accelerated. In general, high concentrations

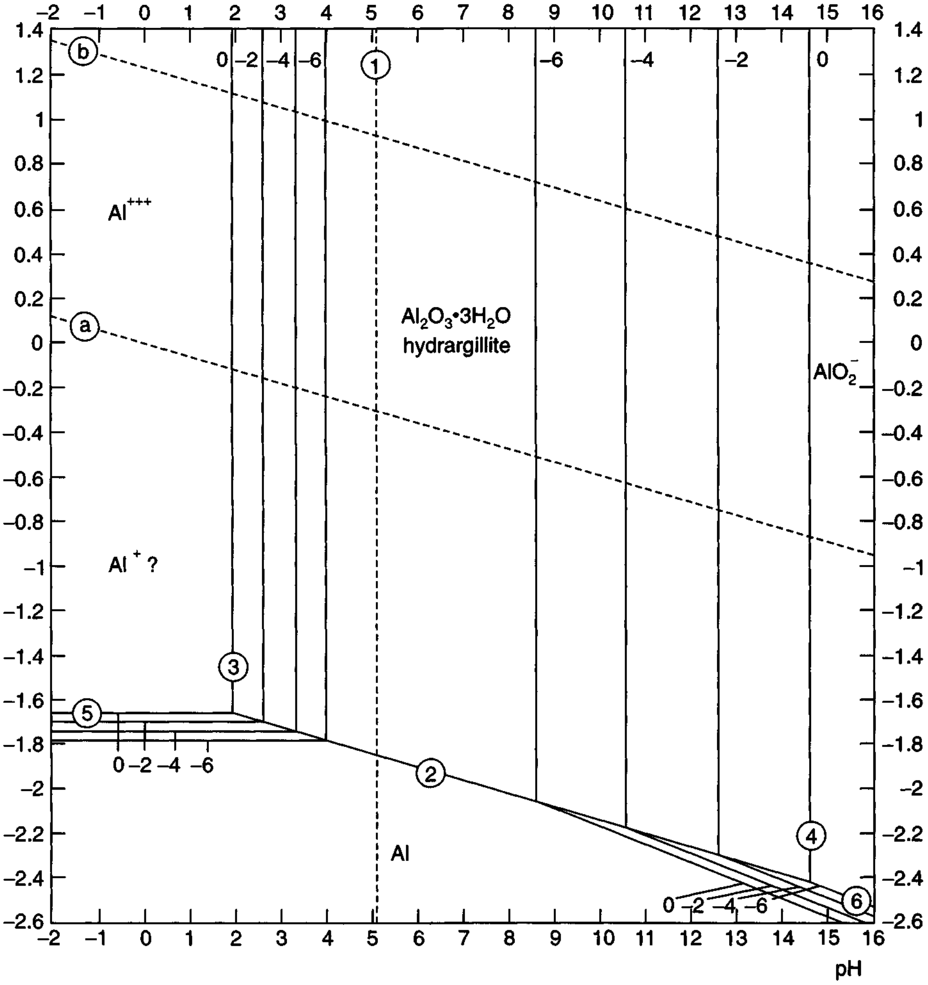

FIGURE 1. Potential versus pH diagram for Al/H_2O system at 25°C [4]. (Reprinted with permission from [4], NACE International and CEBELCOR.)

of dissolved oxygen tend to stimulate attack, especially in acid solutions, although this effect is less pronounced than for most of the other common metals. Hydrogen and nitrogen have no effect, except as they influence the oxygen content [3].

Carbon dioxide and hydrogen sulfide, even in high concentrations, appear to have a slight inhibiting action on the effect of aqueous solutions on aluminum alloys. Aqueous solutions containing sulfur dioxide etch aluminum, but less than copper or steel. Aqueous solutions of hydrogen chloride are strongly corrosive to aluminum.

3. Temperature

At low temperatures (4°C [40°F] or below), the action of most aqueous solutions is much slower than at room temperature. However, in many solutions, increasing temperatures above ~80°C (180°F) results in a decrease in the rate of attack. Thus a temperature of 70 to 80°C (160 to 180°F) is likely to result in more severe corrosion than temperatures of 20°C (70°F) or 100°C (212°F).

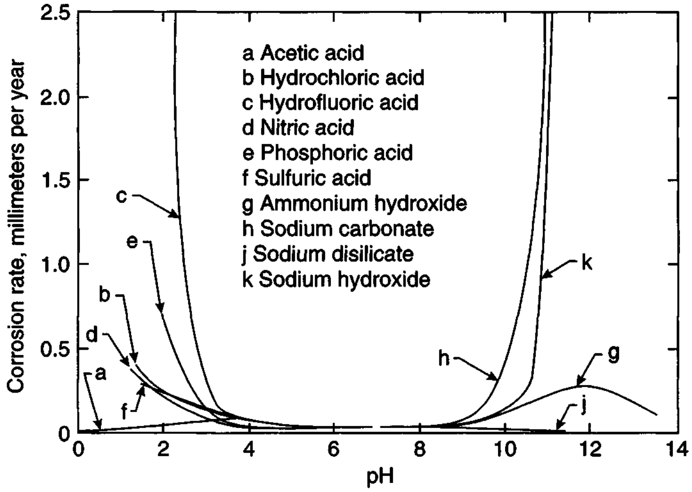

FIGURE 2. Relation to pH of the corrosivities toward 1100–H14 alloy sheet of various chemical solutions. (Reprinted from Ref. [1]. pp. 111–145 by courtesy of Marcel Dekker, Inc.)

4. pH

Corrosion of aluminum and its alloys is passive between pH of ~ 5 and 8.5. Reflecting its amphoteric nature, and as illustrated in Figure 1 [4], aluminum corrodes under both acidic and alkaline conditions, in the first case to yield Al^{3+} ions, and in the second case to yield AlO_2^- (aluminate) ions. There are a few exceptions, either where the oxide film is not soluble in specific acidic or alkaline solution, or where it is maintained by the oxidizing nature of the solution. Two exceptions, acetic acid and sodium disilicate, are included in Figure 2 (Alcoa Laboratories). Ammonium hydroxide $>30\%$ concentration by weight, nitric acid $>80\%$ concentration by weight, and sulfuric acid of 98 to 100% concentration are also exceptions [1].

There is no general relationship between pH and rate of attack because the specific ions present largely influence the behavior. Thus most aluminum alloys are inert to strong nitric or acetic acid solutions, but are readily attacked in dilute nitric, sulfuric, or hydrochloric acid solutions. Similarly, solutions with a pH as high as 11.7 may not attack aluminum alloys, provided silicate inhibitors are present but, in the absence of silicates, attack may be appreciable at a pH as low as 9.0. In chloride-containing solutions, generally less corrosion occurs in the near-neutral pH range, say 5.5 to 8.5, than in either distinctly acid or distinctly alkaline solutions. However, the results obtained vary somewhat, depending on the specific aluminum alloy under consideration.

5. Fresh Waters

Aluminum-base alloys are not appreciably corroded by distilled water even at elevated temperatures (up to 180°C [350°F] at least). Furthermore, distilled water is not contaminated by contact with most aluminum-base alloys. For this reason, there is a fairly extensive and satisfactory use of aluminum alloy storage tanks, piping valves, and fittings for handling distilled water.

Because natural fresh waters differ so widely in their composition and behavior, it is extremely difficult to make generalizations regarding the resistance of aluminum-base alloys to their action. Most commercial aluminum-base alloys show little or no general attack when exposed to most natural waters at temperatures up to 180°C (350°F) at least. However, certain waters may cause severe localized attack or pitting. Pitting is of most importance where the metal section thickness is small, since the rate of attack at the pits generally falls off with increasing time of exposure. In general, the time necessary to perforate an aluminum alloy sheet 0.10 cm thick or greater is prolonged, as attested to by the wide and successful use of aluminum tea kettles.

The Alclad products are much more resistant to perforation by pitting than are the other aluminum alloys. Therefore, wherever the characteristics of specific water are not known in advance, it is safer to employ aluminum alloys such as Alclad 3003. Water staining, a type of crevice corrosion of aluminum can occur.

6. Seawater

Of the aluminum alloys in common use, those that do not contain copper as a major alloying constituent are resistant to unpolluted seawater. Among wrought alloys, those of the 5XXX series have the highest resistance to seawater, and considering their other desirable characteristics, they are the most widely used for marine applications. Among casting alloys, those of the 356.0 and 514.0 types are used extensively for marine applications [1]. As in other natural waters, any attack that does develop in seawater is likely to be extremely localized (i.e., pitting corrosion). Therefore, rate of attack calculated from weight change data has little value. Measurement of change in tensile strength is the most widely used criterion.

Corrosion of aluminum alloys in seawater is mainly of the pitting type, as would be expected from its salinity and enough dissolved oxygen as a cathodic reactant to polarize the alloys to their pitting potentials. Rates of pitting usually range from 3 to 6 μm/year during the first year and from 0.8 to 1.5 μm/year averaged over a 10-year period; the lower rate for the longer period reflects the tendency for older pits to become inactive. The corrosion behavior of aluminum alloys in deep seawater, judging from tests at 1.6 km, is generally the same as at the surface except that the effect of crevices is greater [6].

7. Atmospheric Corrosion

7.1. Outdoor Exposures The aluminum-base alloys as a class is highly resistant to normal outdoor exposure conditions. The alloys containing copper as a major alloying constituent (over ~1%) are somewhat less resistant than the other aluminum-base alloys, whereas the Alclad alloys are generally the most resistant. Results of typical outdoor exposure tests are based on exposure of machined tensile specimens 103.1 mm (4.06) in thick. Loss in tensile strength is generally of the order of 1 to 2% for the first year depending on the alloy and the atmosphere. An alloy such as 2017T can lose up to 17% in tensile strength during the first year [3].

If the specimens had been thinner, obviously the losses would have been relatively greater; whereas if they had been thicker, the losses would have been smaller. This effect of thickness is especially pronounced in the case of aluminum-base alloys, since the rate of attack greatly decreases with increasing time of exposure.

Specimens were freely exposed to the outdoor locations. If they had been partially sheltered, the rate of attack would have been somewhat greater; if they had been largely sheltered, very little attack would have occurred. Apparently, in the case of aluminum-base alloys, periodic exposure to rain is beneficial probably because the rain washes off corrosive products that settle from the air. Evidently, free exposure to rain is not harmful but, on the contrary, is beneficial.

The gases ordinarily found in industrial atmospheres have little effect in accelerating the corrosion of aluminum-base alloys. Carbon particles from the atmosphere may accelerate corrosion by galvanic action. Under outdoor atmospheric exposure conditions, this factor is of secondary importance even in intensely industrial regions. Sulfur compounds, such as H_2S have no specific effect in accelerating the tarnishing or corrosion of aluminum alloys. However, the highly acidic nature of water containing dissolved SO_2 or SO_3 causes it to become somewhat corrosive [3].

7.2. Indoor Exposures The effects of indoor exposure differ greatly, depending on the exposure conditions. Exposure indoors in homes or offices ordinarily causes, at most, only a mild surface dulling of aluminum-base alloys even after prolonged periods of exposure. In damp locations,

TABLE 6. Soil Burial Tests of 5 Years Duration with Aluminum Alloy Specimens[a,b]

	Well-Drained Soil			Marshy Soil		
Alloy	Max Depth of Attack[c] (in.)	% Change in Tensile Strength[d]	Remarks (in. = 25.4 mm)	Max Depth of Attack (in.)	% Change in Tensile Strength	Remarks
1100-½H	0.0017	−1	Mild general etching	0.0280	−7	Pitted
5052-½H	0.0007	+1	Mild general etching	0.0140	0	Pitted
6053-T	0.0007	0	Mild general etching	0.0150	0	Pitted
6053-T, Alrok No. 13 coated	0.0006	0	Mild general etching	0.0006	0	Mild general etching
6053-T, aluminite No. 204 coated	0.0003	0	Mild general etching	0.0002	+2	Mild general etching
2017-T	0.0380	−20	Severe pitting	0.0310	−41	Severely pitted
Alclad 2024-T	0.0013	0	Mild general etching	0.0028	−1	Generally etched
Steel	0.0640	−27	Completely perforated at 3 spots	0.0190	−17	Pitted

[a] Specimens in the form of panels 3 × 9 × 0.064 in. thick were buried to a depth of 61 cm in soil at the property of the Aluminum Research Laboratories in New Kensington, PA.

[b] See [7].

[c] Depth of attack determined by microscopic examination of cross-sections.

[d] Change in tensile strength determined by machining tensile specimens from the panels after exposure and comparing their strength with that of unexposed tensile specimens of the same materials.

especially where there is contact with moist insulating materials, such as wood, cloth, and paper insulation, attack may be more appreciable. In factories or chemical plants, fumes or vapors incident to the operations being conducted may cause a definite surface attack. However, in most indoor atmospheres where pools of contaminated water do not remain in prolonged contact with aluminum alloys, or where extended contact with moist, porous materials is avoided, no appreciable loss of mechanical properties through corrosion will occur. In particular, aluminum alloys are highly resistant to warm, humid conditions where there is appreciable moisture condensation so long as contact with porous materials is avoided. Bare aluminum alloy panels have been used in constructing humidity cabinets that operate just above the dew point at 50°C. After 5 years of use, there was no corrosion other than minor surface staining [3].

8. Soil Corrosion

The extent of attack that occurs on aluminum alloys buried underground varies greatly, depending on the soil composition and climatic conditions. In dry, sandy soil corrosion is negligible. In wet, acid or alkaline soils, attack may be severe. Results of soil corrosion tests in two locations are summarized in Table 6 [7]. In both these locations, panels of the various alloys were buried in clay soil of the Aluminum Research Laboratories' properties in New Kensington, PA. One location was in relatively well-drained soil and the other was in a marshy area < 100 ft away. In the well-drained soil, attack on all the aluminum-base alloys, except 2017, was mild after 5 years. The 2017-T was severely attacked although not as much as the steel.

In the marshy soil, maximum depths of attack on all the uncoated aluminum-base alloys, except Alclad 2024-T, were appreciable and of the same order of magnitude as on steel, although the relative loss in tensile strength was definitely less for most of the aluminum-base alloys than for steel. In the case of the Alclad 2024-T, the attack that occurred was all confined to the coating, as would be expected. Chemical dip and sulfuric acid anodic coatings were definitely protective to 6053-T and presumably to the other aluminum alloys.

9. Steam Condensate

Condensate from steam boilers, if free from carry-over of water from the boiler, is similarly inert to aluminum-base alloys. Thus, either wrought or cast aluminum alloys are used successfully for steam radiators or unit heaters. Where aluminum alloys are used, it is desirable to install suitable traps in the steam lines, since entrapped boiler water, especially if alkaline water-treating compounds are employed, may be corrosive.

10. Gases

Most gases, in the absence of water and at or near room temperature, have little or no action on aluminum-base alloys. In the presence of water, the acid gases, such as HCl and HF are corrosive, and wet SO_2 causes corrosion (Table 7). Hydrogen sulfide or ammonia, either in the presence or absence of water and at room temperature or slightly above, has negligible action on aluminum-base alloys. Halogenated hydrocarbons, such as dichlorodifluoromethane, dichlorotetrafluoromethane, and monochlorodifluoromethane, are almost completely inert to aluminum. However, methyl chloride and methyl bromide are corrosive and should not be used in contact with aluminum-base alloys.

11. Chemicals

11.1. Acids Acid mine waters are corrosive to aluminum-base alloys. The extent of attack depends on the specific composition of the water. Some use of aluminum pipe has been made in soft coal mines for handling acid mine waters. It has been found that pipe of aluminum alloy 3003

TABLE 7. Resistance of Aluminum to Aqueous Solutions of Several Gases[a]

	Carbon Dioxide[b] and Water		Sulfur Dioxide,[c] Air, and Water		Hydrogen Sulfide[d] and Water	
Metal	Av Wt Loss (g)	Av ipy[e]	Av Wt Loss (g)	Av ipy[e]	Av Wt Loss (g)	Av ipy[e]
Aluminum 1100	0.0003	0.00004	0.150	0.0498	0.002	0.00028
Copper			0.681	0.0701	0.237	0.01030
Steel	0.2153	0.00977	8.583[b]	1.02[b]	1.366	0.06800

[a] See [3].

[b] Metal specimens 1 × 4 × 1/16 in. (2.5 × 10.2 × 0.16 cm) were partially immersed (to depth of 51 mm).

[c] Metal specimens 2.5 × 10.2 × 0.16 cm. thick were partially immersed (to a depth of 2 in.) in distilled water through which air and sulfur dioxide were bubbled. The total period of exposure was 135 h at room temperature.

[d] Metal specimens 1 × 4 × 1/16 in. thick were partially immersed (to a depth of 51 mm) in distilled water through which hydrogen sulfide was bubbled. The total period of exposure was 320 h at room temperature.

[e] Inch/year; this calculation was based on the assumption that all corrosion was confined to the immersed areas of the specimens.

[f] Steel specimen corroded completely through at the water line.

greatly outlasts bare or galvanized steel pipe in this application. Many aluminum-base alloys are highly resistant to nitric acid in concentrations of ~80 to 99%. Alloys such as 1100, 3003, and 6061 have received the widest use for handling nitric acid of these concentrations. Nitric acid of lower concentrations is more corrosive.

Dilute sulfuric acid solutions, up to ~10% in concentration, causes some attack on aluminum-base alloys, but the action is not sufficiently rapid at room temperature to prevent their use in special applications. In the concentration range of ~40 to 95%, rather rapid attack occurs. In extremely concentrated or fuming acid, the rate of attack drops again to a very low value.

The action on aluminum (1100) of solutions containing sulfuric acid, nitric acid, and water is illustrated in Figure 3. It will be noted that aluminum is most resistant to solutions dilute in both acids, or high in nitric acid concentration, or in 100% sulfuric acid. Hydrofluoric, hydrochloric, and hydrobromic acid solutions, except at concentrations below ~0.1%, are definitely corrosive to aluminum alloys. The rate of attack is greatly influenced by temperature (Fig. 4).

Both perchloric acid and phosphoric acid solutions in intermediate concentrations definitely attack aluminum. Dilute (< 1%) phosphoric acid solutions have a relatively mild, uniform etching action that makes them useful for cleaning aluminum surfaces. Boric acid solutions in all concentrations up to saturation have negligible action on aluminum alloys. Chromic acid solutions in concentrations up to 10% have a mild, uniform etching action. Mixtures of chromic acid and phosphoric acid have practically no action on a wide variety of aluminum alloys, even at elevated temperatures. Such mixtures are used for quantitatively removing corrosion products or oxide coatings from aluminum alloys.

Most organic acids are well resisted by aluminum alloys at room temperature. In general, rates of attack are highest for solutions containing ~1 or 2% of the acid. Formic acid, oxalic acid, and some organic acids containing chlorine (such as trichloroacetic acid) are exceptions and are definitely corrosive. Equipment made of aluminum alloys, such as 1100 or 3003, are widely and successfully used for handling acetic, butyric, citric, gluconic, malic, propionic, and tartaric acid solutions.

11.2. Fruit Acids Aluminum alloys also have a high resistance to the action of uncontaminated natural fruit acids. Contamination of these substances by heavy metal compounds may cause them to become corrosive. In contrast, the addition of sugar to fruit acids causes them to become even less corrosive [3].

11.3. Organic Compounds Aqueous solutions of organic chemicals having a substantially neutral reaction are generally not corrosive to aluminum-base alloys, unless these solutions are

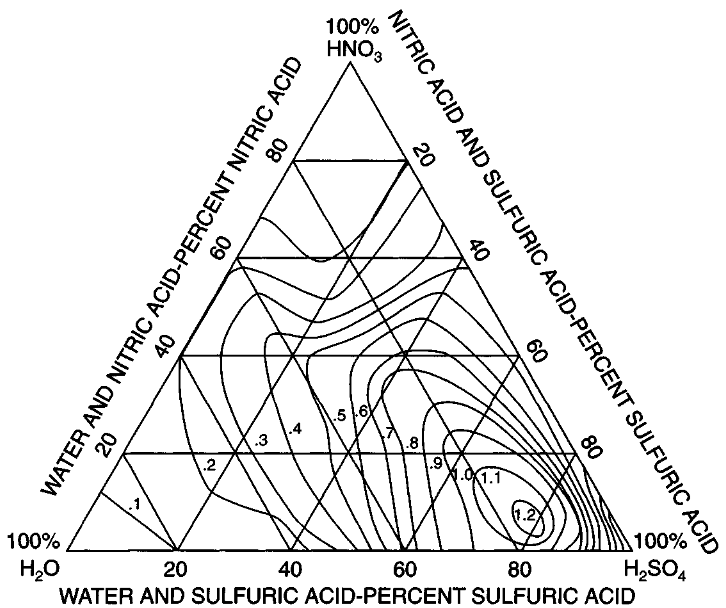

FIGURE 3. Action of mixtures of nitric and sulfuric Acids on 1100 aluminum 24-h tests room temperature; contours labeled in in./year (25.4 mm) [3].

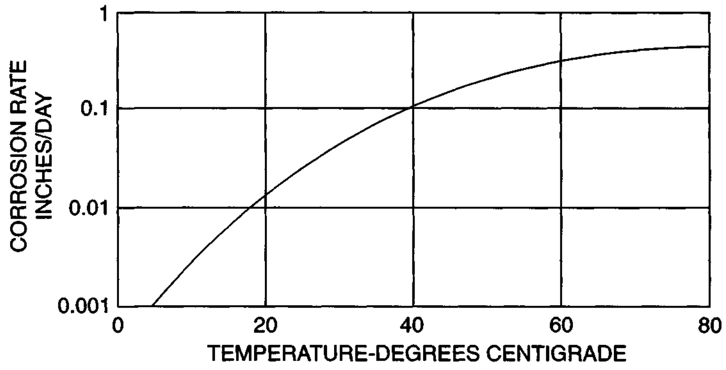

FIGURE 4. Effect of temperature on corrosion rate of (6053-T) aluminum in 10% HCl [3].

contaminated with other substances, particularly chlorides and heavy metal salts. At room temperature or slightly above, most organic compounds in the absence of water are completely inert to aluminum-base alloys. This is true for organic–sulfur compounds as well as for other organic compounds. At elevated temperatures, some organic compounds, such as methyl alcohol and phenol, definitely become corrosive, especially when they are completely anhydrous.

11.4. Alkalis Solutions of sodium hydroxide or potassium hydroxide in all but the lowest concentrations (<0.01%) rapidly attack aluminum and its alloys. Attack by the very dilute caustic solutions can be inhibited by corrosion inhibitors, such as silicates or chromates, but in more concentrated solutions none of the usual inhibitors are very effective. The alloys of aluminum containing more than ~4% magnesium are somewhat more resistant to attack by alkalis than are the other aluminum-base alloys. Lime or calcium hydroxide solutions are also corrosive, but the maximum rate of attack is limited by the low solubility of these materials.

The aluminum-base alloys are highly resistant to ammonia and ammonium hydroxide. The alloys that contain appreciable magnesium tend to be even less affected by ammonium hydroxide solutions than the other aluminum alloys. The amines generally have little or no action on aluminum alloys. However, a few of the most alkaline do cause definite attack.

11.5. Salt Solutions Neutral or nearly neutral (pH from ~5 to 8.5) solutions of most inorganic salts cause negligible or minor corrosion of aluminum-base alloys at room temperature. This is true for both oxidizing and nonoxidizing solutions. Any attack that does occur in such solutions is likely to be highly localized (pitting) with little or no general corrosion. Solutions containing chlorides are likely to be more active than other solutions. The simultaneous presence of salts of the heavy metals, especially copper, and chlorides may be very detrimental. Distinctly acid or distinctly alkaline salt solutions are generally somewhat corrosive. The rate of attack depends on the specific ions present. In acid solutions, chlorides, in general, greatly stimulate attack. In alkaline solutions, silicates and chromates greatly retard attack [3].

11.6. Dry Phenols Phenols and carbon tetrachloride nearly dry or near their boiling points are very corrosive to aluminum alloys. This behavior can be prevented by the presence of trace water [1].

11.7. Mercury The action of metallic mercury on aluminum is unique. It tends to amalgamate readily with aluminum at room temperature to produce an extraordinary corrosion rate in the presence of moisture with the production of voluminous columnar corrosion products. When that reaction is started, the rate of corrosion depends on relative humidity. When dry, metallic mercury reacts only with difficulty because of the oxide film on the aluminum surface. Traces of acidity or halides on the surface cause rapid attack. Solutions containing mercury ions tend to cause rapid pitting of aluminum alloys because mercury plate out in localized areas. In many cases, the amalgamation of stressed aluminum alloy with mercury results in cracking since the mercury penetrates selectively at grain boundaries, thus weakening the material. Mercury can be removed from aluminum surfaces by treatment with 70% nitric acid. Mercury can be distilled away from an aluminum surface by treatment with steam or hot air [8].

C. TYPES AND FORMS OF CORROSION

1. Uniform Corrosion

1.1. Potential of Aluminum and Its Alloys Table 8 is a galvanic series of aluminum alloys and other metals representative of their electrochemical behavior in seawater and in most natural waters and atmospheres. Figure 5 [9] shows the effect of alloying elements in determining the position of aluminum alloys in the series; these elements, primarily copper and zinc, affect electrode potential only when they are in solid solution.

As evident in Table 8, aluminum (and its alloys) becomes the anode in galvanic cells with most metals, protecting them by corroding sacrificially. Only magnesium and zinc are more anodic and corrode to protect aluminum. This type of corrosion can be found in strong acidic or strong basic solutions, as illustrated in Figure 6 [4,10]. The rate of corrosion can vary from several microns per year to several microns per hour.

In the range of pH between ~4 and 8, aluminum is protected by its oxides and hydroxides. The aluminum hydroxide gel is not stable, but crystallizes with time to give, first, the rhombohedral monohydrate ($Al_2O_3.H_2O$ or boehmite), then the monoclinic trihydrate ($Al_2O_3.3H_2O$ or bayerite), and finally another monoclinic trihydrate (hydrargilite). This development of aluminum hydroxide is known as "aging" [4].