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A Review of Aluminum Corrosion in Tap Waters

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General Survey

SINCE it has excellent corrosion resistance and good mechanical properties, aluminum is being used more and more as construction material in industrial and residential applications. Low cost, good formability, high thermal and electrical conductivity, and lack of toxicity, all make aluminum attractive. The relatively inert surface oxide film on aluminum has led to its use in many atmospheric and weathering applications. For over half a century, aluminum has successfully resisted rain and atmospheric precipitation on monumental and architectural surfaces. For a longer time, aluminum has been known to be suitable for seawater exposures. In recent years, high-purity waters for nuclear projects have been handled almost exclusively in aluminum pipes and equipment. Recent literature abounds with studies of the effects of high-temperature water (over 100°C) on aluminum.

This paper is concerned with a review of the usage of aluminum in fresh waters—waters obtained from natural sources as rivers, lakes, springs, and wells and processed for human consumption or industrial use. H. P. Godard[1] pointed out that water is a common and universal material. Ordinarily it is not used as pure H_2O. Water that is 99.7% pure has 3000 ppm of dissolved solids, which is usually unsuitable for industrial processes. Yet, this degree of purity is seldom found in other natural materials. Even rain is contaminated with sulfates, chlorides, silicates, dust, soot, carbonates, organic matter, oxides of sulfur and nitrogen, hydrogen sulfide, etc. Near a seacoast, rain may carry as much as 15 ppm of sea salt—the amount decreasing rapidly with distance from the sea.

Water hardness can be expressed in terms of calcium carbonate measured in ppm. Waters are classed further as soft or hard as shown in Table 1.

The good corrosion resistance of aluminum is a result of an oxide film. Cabrera and Hamon[2] have shown this film at room temperature to be between 20 and 100 Å thick. Hart[3] found it to be 40 Å in a humid oxide atmosphere. Pilling and Bedworth[4] measured 200 Å but believed that the observed film was nonuniform and only a few Å in some places. For air-formed oxides, the film probably is amorphous Al_2O_3. In water, Bayerite, $Al(OH)_3$, is the usual film at normal temperatures, but from 70° to 100°C, Boehmite, $AlO(OH)$, is formed. The rate of film formation depends on the alloying elements and impurities. Bryan[5] found that aluminum initially reacts with boiling distilled water with the evolution of hydrogen and the formation of a highly resistant protective surface film, and that a minimum quantity of free silicon in the aluminum will arrest its corrosion.

In 1920, Seligman and Williams[6] concluded that pitting is because of the simultaneous presence of chloride and bi-

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Received September 23, 1968; revision received March 7, 1969. This review has been aided immeasurably by the results of a number of British and Canadian investigations. These sources, and those from the United States, are referenced in the paper. Previously unpublished work done at Reynolds Metals Metallurgical Research Laboratories is indicated in Table 4. The sources of graphs or tables which have been included, are indicated in the paper.

Table 1 Water classification[1]

Classification	ppm $CaCO_3$
Very soft	1–30
Soft	31–60
Medium hard	61–120
Hard	121–180
Very hard	181

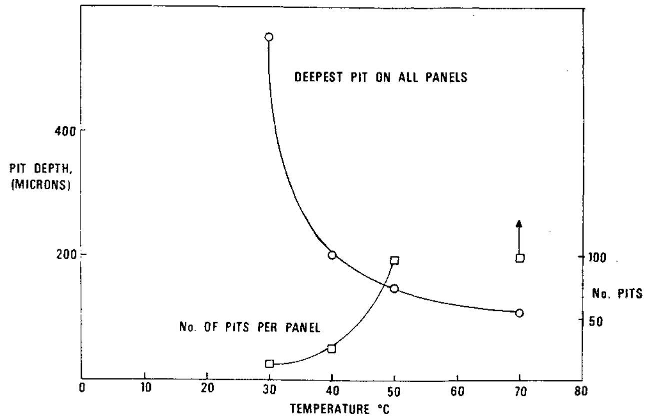

Fig. 1 Influence of temperature on pit depths (Ref. 10).

carbonate in the water, provided there was free access to oxygen. No record was given of the copper content in these solutions.

Sawyer and Brown[7] found that pitting occurred in aluminum within a week in the presence of heavy metals (copper, 0.09 ppm; cobalt, 0.08 ppm; nickel, 0.03 ppm); whereas without heavy metals the only effect was to darken the aluminum surface slightly. It is agreed that copper salts have the worst effect, but Akers and Mears[8] indicate that tin and nickel have a similar effect. Bromides appear to behave like chlorides.

Porter and Hadden[9] have made a comprehensive study on aluminum in supply waters. Most tap waters tested caused severe pitting of aluminum and its alloys. The depths of most pits increased with time at a diminishing rate. Changes in water composition caused greater differences than changes in alloys, and the order of attack on the alloys was the same in all waters, as shown in Table 2. Corrosive attack was most severe in the harder waters, this typically being nodular pitting, or deep pits covered by mounds of corrosion products consisting mainly of aluminum hydroxide. Such pitting develops when calcium bicarbonate, chlorides, copper salts, and dissolved oxygen are all present in the water. Under substantially stagnant conditions, a mound of insoluble aluminum hydroxide forms, as shown in Table 3, with acidic liquid trapped beneath, and pitting occurs.

Regular removal of corrosion products discourages or prevents pitting. Protection may be afforded by the calcium carbonate scale deposited from hard waters when hot. Protective films form more readily in hot waters than in cold, and the probability of pitting decreases markedly with temperature. Pitting can take place in waters containing dissolved copper (on the order of 1 ppm), even when hot. This type of pitting differs from nodular pitting. Of the alloys tested, $1\frac{1}{4}\%$ manganese alloy (3003 type) was most resistant to penetration, and $3\frac{1}{2}\%$ magnesium alloy (5154) type was almost as good. Magnesium silicide alloy (6061) was the least resistant. Super-purity metal (1199) was attacked as deeply as commercial-purity metal (1100) or $3\frac{1}{2}\%$ magnesium alloy. Clad metal, duralumin, was superior to all others; in no case was the basis metal pitted, and the maximum depth of attack was the thickness of the cladding (5% of the total thickness on each side). This material is similar to aluminum-copper alloy 2024 and has a cladding equivalent to commercial-purity aluminum.

Carbonate hardness, or a bicarbonate from which an insoluble carbonate can be derived, has been shown to be essential for nodular attack.[9] A continuous supply of oxygen is necessary to maintain attack after pitting has become well developed. Studies by Porter and Hadden indicated that, in general, all alloys show at least slight localized attack at all temperatures, but the incidence of pitting decreased with increasing temperatures beyond about 35°C. With rise of temperature, there was an increasing tendency for attack at edges.

Figure 1 shows temperature effects of water on aluminum as reported by Godard.[10] The rate of attack at higher temperatures for a pit, once established, was not materially greater than at room temperature. Increase in temperature is likely to reduce serious attack on aluminum alloys, but under unfavorable corrosive conditions (i.e., in waters of abnormally high copper content), rapid corrosion may ensue even in hot water. The manner of surface finishing (e.g., buffing, abrading, pickling, or electropolishing) made only slight differences in the form of attack and in loss of weight.

Davies tested 75 synthetic tap waters with commercial-purity aluminum.[11] In the presence of any two of the following constituents, sodium chloride, calcium carbonate, and dissolved copper, the loss of weight is very small, but nodular pitting is observed when all three are present as shown in Figs. 2 and 3. The effects of a tap water, with and without copper, are shown in Fig. 4. With constant concentrations of chloride (50 ppm) and calcium (80 ppm), the weight loss increased with copper content as given in Fig. 5. At constant copper concentration, the maximum weight loss occurred at 50 ppm calcium irrespective of chloride ion concentrations

Table 2 Order of merit of aluminum alloys in supply waters (by loss of weight and depth of attack): field tests[9]

British Isles site	By loss of weight				By depth of attack			
	Commercial purity Al	$1\frac{1}{4}\%$ Mn	$3\frac{1}{2}\%$ Mg	Mg_2Si type	Commercial purity Al	$1\frac{1}{4}\%$ Mn	$3\frac{1}{2}\%$ Mg	Mg_2Si type
Euston	4	1	2	3	3	2	1	4
Gerrards Cross	3	1	2	4	3	1	2	4
Milton	3	1	2	4	2	1	3	4
Burntisland	3	1	1	4	3	1	2	3
Leeds	4	1	2	3	2	1	2	4
Sheffield	2	1	3	4	3	2	1	4
Lochaber	4	1	2	3	3	1	2	4
Birmingham (Cu pipes)	4	1	2	3	3	1	2	4
Birmingham (Fe pipes)	2	1	3	4	No pitting attack			

Table 3 Composition of corrosion product: Euston (England) water[9]

Radical	% in corrosion product
Sulfate (as SO_4)	15–19.8
Chloride	n.d.[a]
Carbonate (as CO_3)	0.27
Nitrate (as N)	0.007
Silicon	0.7–0.82
Calcium	0.003–0.21
Iron	0.7–0.15
Copper	<0.01–0.03

[a] n.d.—not detected quantitatively; trace was found by qualitative test.

Davies showed that for anodizing to prevent nodular pitting, the film had to be subsequently sealed or very thick.

Corrosion tests[12] were carried out in a variety of public supply waters with aluminum-zinc cladding on aluminum ($1\frac{1}{4}\%$ manganese alloy) while varying the zinc content of the cladding between $\frac{3}{4}$ and $1\frac{1}{4}\%$ and the copper content of the base between 0.04 and 0.15%. The $1\frac{1}{4}\%$ zinc cladding gave satisfactory protection to the base metal in all waters, irrespective of its copper content. The $\frac{3}{4}\%$ zinc cladding generally failed to give protection even to the low copper base, especially when the cladding was machined away. 1% zinc cladding protected a 0.04% copper base in all but the most aggressive waters, but could not be relied upon when the base contained 0.1% or more of copper.

The effect on the corrosion of aluminum of mineral impurities in water was reported by Rowe and Walker.[13] They found no substantial increase in corrosion rate of aluminum when up to 300-ppm chlorides, sulfates, bicarbonates, or calcium were added to up to 2-ppm copper. Any two of these additions had little effect, but the combination of all three ions produced a significant increase in corrosion. In the absence of air, the rate dropped by $\frac{2}{3}$. Near-maximum effects were noted when ion concentrations were 300-ppm chloride, 300-ppm bicarbonate, and 2-ppm copper. Copper ion concentrations up to 0.5 ppm had the greatest effect with only slight additional effects up to 2 ppm and no additional effects up to 10 ppm. The effect of bicarbonate ion concentrations on the corrosion of aluminum at 71° C is shown in Fig. 6.

Bell[14] studied the effects of calcium carbonate on the corrosion of aluminum in waters with chlorides and copper present. After exposures of twelve weeks, corrosion was least in waters with approximately equal chloride and calcium carbonate contents. Corrosion was greatest in waters with a high proportion of calcium carbonate to chloride. The type of corrosion on the aluminum also depends on the sulfate content of the water and on pH.

Chlorine gas additions to water were investigated by Doyle and Godard.[15] Chlorine additions reduced the rate of pitting of immersed aluminum (in two Canadian tap waters). The chlorine also increased the amount of corrosion (both number of pits and weight loss). Chlorine of the order of 0.5–1.0 ppm had negligible effect. Up to 30 ppm, it increased the number of pits and general corrosion, but the authors reasoned this would not affect the life of an aluminum water pipeline.

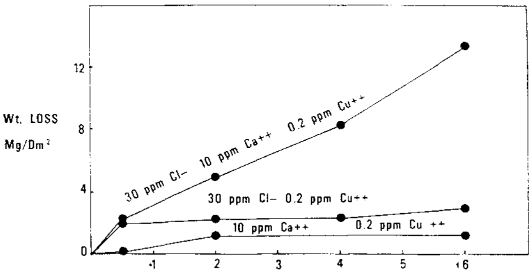

Fig. 2 Loss of weight of commercial aluminum in synthetic waters (Ref. 11).

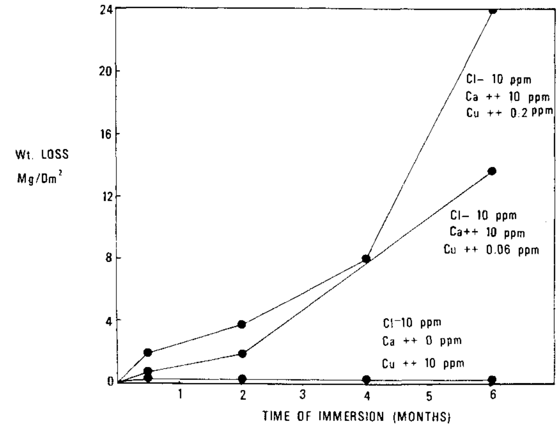

Fig. 3 Weight loss in synthetic water of low calcium content (Ref. 11).

In 1964, Murray[16] reported the results of studies of artificially created pits in aluminum. He noted that chemically or electrically stimulated pits could be used to predict pitting rates, and one week of such tests were comparable to three months of immersion tests in natural waters. His test requires only a small volume of water.

Bell and Campbell[17] in 1965 described results of over twelve years of research at the British Nonferrous Metal Research Association, which update the work by Porter and Hadden.[9] Results were summarized as follows:

1) An aluminum $1\frac{1}{4}\%$ zinc cladding protected an aluminum $1\frac{1}{4}\%$ manganese base in all waters, irrespective of the copper content. An aluminum 1% (or less) cladding was only effective for up to 0.04% copper in the basis metal in all but the most aggressive waters. The $1\frac{1}{4}\%$ zinc cladding was effective for over four years in even severe waters.

2) Sprayed coatings of aluminum 1% zinc on the 3003-type alloy gave good protection in nine different waters in tests lasting for 40 weeks. The sprayed coating did not flake off, and only small areas of bare metal were exposed.

3) Anodized films (0.15–0.5 mil) gave a high degree of protection in moderately severe waters even where the film was scratched. Pitting was not accelerated at the scratches.

4) Boehmite films, formed by immersing the aluminum for 30 min in boiling distilled water, gave some protection in less severe waters.

5) Chemical conversion coatings delayed the time to pit initiation, but the eventual pitting attack was similar to that on untreated metal. The area and depth of attack on cladding was reduced by a conversion coating, which may be desir-

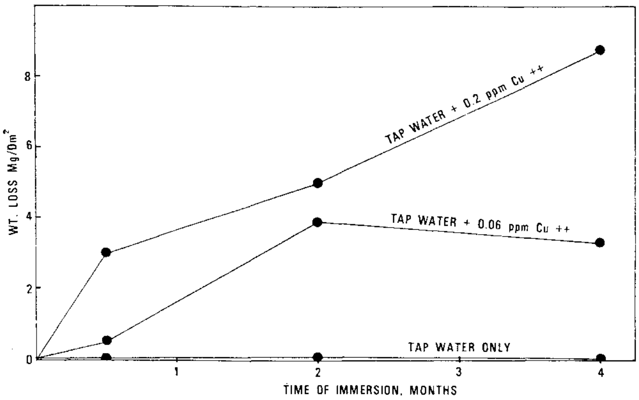

Fig. 4 Weight loss in Swansea tap water (Ref. 11).

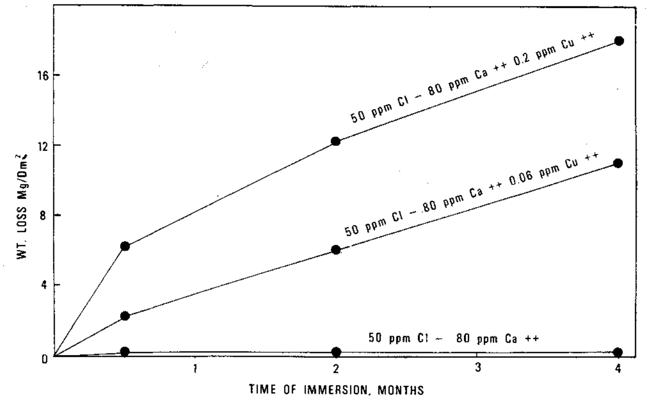

Fig. 5 Effect of dissolved copper on weight loss (Ref. 11).

able where reduction of corrosion product volume is important. Anodized cladding should not be used since the protection of the cladding is thereby reduced.

6) Nodular pitting can occur in waters of low-carbonate hardness when sulfates are present.

7) The effect of carbonate hardness and chloride content on the type of corrosion formed on aluminum is shown in Fig. 7.

8) Nodular pits were smaller and more numerous at the higher chloride concentrations. The areas of the pits and their number and depth increased with copper content.

9) The effect of calcium sulfate on the type of corrosion produced was equivalent to a large increase in temporary hardness. As little as 5 ppm could double the depth of pitting occurring in 48 weeks for solutions containing 20 ppm of carbonate hardness with copper present. Sulfate had no effect on weight loss.

10) At pH 9–9.5, film formation without pitting took place, the thickness increasing with decreasing chloride and increasing copper content. At pH 5–5.5, little general attack or film formation took place.

11) Pitting can occur in waters containing as little as 0.01-ppm copper. The effect of copper in one water is shown in Table 4.

12) Copper, silver, gold, platinum, mercury, and lead caused pitting of S1C aluminum (1100). Manganese and cobalt had little or no effect. Iron, nickel, chromium, tin, and zinc produced surface films with no pitting.

13) Oxygen must be present, along with carbonate hardness, chloride, sulfate, and copper, to cause corrosion in aluminum.

14) The addition of 1 ppm of sodium chromate to a corrosive water prevented pitting of 1100 aluminum (chromates must not be used in potable water systems). Additions of silicate were somewhat less effective.

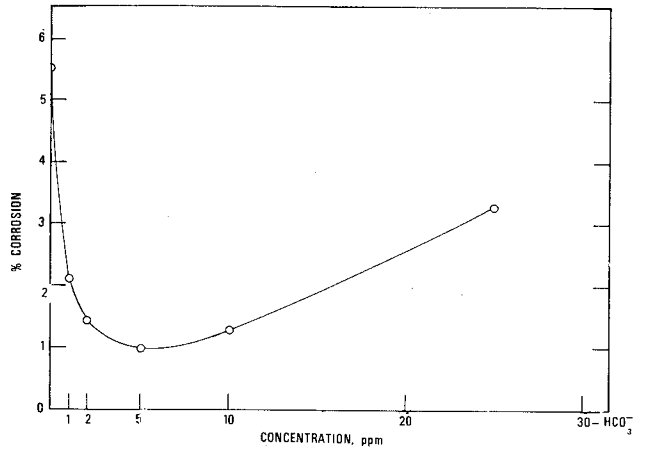

Fig. 6 Effect of the bicarbonate ion at low concentrations on the corrosion of aluminum at 71°C (a concentration of 300-ppm chloride and 2-ppm copper ion was used in all solutions) (Ref. 13).

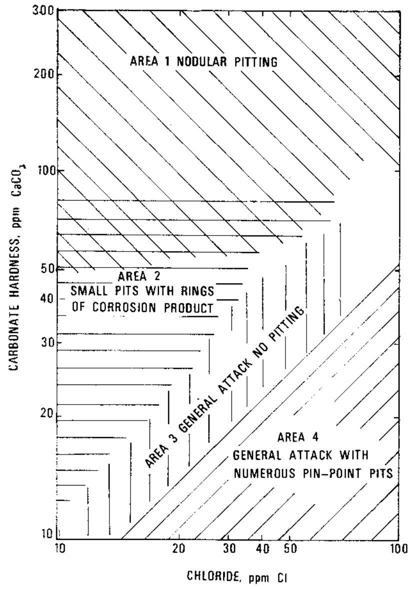

Fig. 7 Effect of carbonate hardness and chloride content on corrosion of aluminum in water (the influence of pH and sulphate content must be considered) (Ref. 17).

15) Higher temperatures of the water (up to 80°C) generally reduce corrosion.

16) Water velocities above 6 ft/min can sometimes prevent or diminish pitting corrosion, particularly in recirculating systems. This is because of a reduction in the dissolved oxygen and to film formation.

Booth et al.[18] have shown that failures of aluminum pipe from pitting attack are a result of perforation and not due to weakening of the wall. They note that addition of up to 0.5-ppm chlorine (for bactericidal purposes) is considered innocuous to aluminum. To extend the life of aluminum equipment, they recommend drainage of stagnant water, deaeration of water, use of inhibitors, cathodic protection, use of paints, and avoidance of galvanic contacts. 1% sodium silicate addition to water will prevent corrosion of aluminum in contact with copper or graphite. Zinc, magnesium, cadmium, and usually stainless steel may be safely coupled to aluminum. Copper, brass, bronze, and graphite are harmful.

Murray et al.[19] concluded that copper metal plates out in discrete particles in the vicinity of pitting sites from supply waters with 0.01- to 0.02-ppm copper. The authors found iron-rich constituents under the areas with metallic copper precipitates and deduced that the iron content had a marked influence on pitting susceptibility.

The rate of pitting penetration of aluminum in fresh waters has been shown to be proportional to the cube root of time,[1] viz., $d = kt^{1/3}$, where d is the maximum pit depth, k is a constant for alloy and water composition, and t is the time. Thus, doubling the wall thickness of an aluminum pipe will increase the time to penetration by a factor of eight. Using experimental data and regression analysis, Pathak and Godard[26]

Table 4 Corrosion of S1C aluminum (1100) after two years: Kinlochleven water (4-ppm carbonate hardness, 4-ppm chloride, 8-ppm sulfate, pH 5.9)[17]

Copper content (ppm)	Weight loss (mg/dm²)	Maximum pit depth (mm)
0	22	nil
0.02	305	0.61
0.05	419	0.75
0.5	660	0.95

Table 5 Five-month's immersion in high sulfide bearing water[7]

Alloy	Weight loss, g	Maximum depth of attack, in.	Penetration calculated, mils/yr	% change in tensile strength
3003-½ H	0.01	0.0121	0.02	−5
Alc 3003-½ H	0.04	0.0059	0.06	+8
5052-½ H	0.05	0.0023	0.07	−2
6061-T	0.08	0.0045	0.12	−4
Cold rolled steel	57.94	0.0125	15.5	−30

obtained the following, relating pitting rates to water analyses:

$$\log p = 2.5 - 0.28 \log (\mathrm{SO_4^{--}}) + 0.18 \log (\mathrm{Cl^-}) - 0.20 \log [(\mathrm{pH} - 7)^2 \times 100] - 0.42 \log (30{,}000/R) - 0.064 \log (\mathrm{Cu^{++}} \times 10^3)$$

where p is the pitting rate index (weeks required for a maximum pit depth of 40 mils), R is the resistivity in ohm-cm, and $\mathrm{SO_4^{--}}$, $\mathrm{Cl^-}$, and $\mathrm{Cu^{++}}$ represent concentrations of the respective ion in ppm. The equation is based on 67 waters and has a standard error of 0.391.

Experiences with Aluminum in Tap Waters

Sawyer and Brown[7] reported that after seven years' service with over 250,000 alclad 3003 tea kettles, only five known perforation failures occurred. Nearly neutral waters (pH 6–8) have little or no action upon aluminum-base alloys, as 1100, 3003, 3004, 5052, 5053, 6061, and alclad 3003. After seventeen years of hot water service, 3003 pipe was still in use at the Alcoa Research Laboratories. In 1934, alclad 3003 pipe replaced the 3003 hot water pipes, and after thirteen years' usage, no failures had occurred. An alclad 3003 hot water tank has been in continuous use for over twelve years at the Reynolds Metals Research Laboratories in Richmond, Va. Twelve months' hot water service in Royal Oak, Mich., (pH 7.4, 301-ppm chlorides) resulted in no deleterious effects on alclad 3003 pipe. Boiling water from Mountain Valley, Ark. (pH 7.8, 215-ppm bicarbonates) had little effect on welded 5053 cans after two months. An 1100 alloy aluminum pipe (⅛-in. wall) carried Westmoreland County, Pa., mine water (pH 2.9, 2460-ppm ferric ion) for nine years before failure. Altoona, Pa., water (pH 3.8–4.5, 4.4-ppm chlorides, 80–90 ppm total solids) was boiled in one 0.040-in. gauge alclad 3003 pan for 1552 hr without perforation, but another 3003 pan failed after 408 hr. Recirculated waters, because of metal pickup, salt concentration and air contaminants, generally become corrosive to aluminum. Table 5 shows the effects of immersing aluminum and steel in sulfide-containing water.

Bryan[5] found that the main cause of rapid pitting of aluminum porringers, used only for cooking oatmeal porridge containing salt, was contamination of the water supply with copper. Contamination of aluminum vessels by a metallic scourer containing copper can also give rise to severe pitting, but this was not severe in the absence of salt. Table 6 records the results of Bryan's work.

Godard[10] lists seven means for extending the life of aluminum, water-handling equipment:

1) Increase the wall thickness; doubling provides eight-times the life.

2) Use alclad aluminum. Cladding electrolytically protects the core and increases the time to penetration from five to ten times.

3) Increase water movement; i.e., avoid stagnant conditions.

4) Deaerate the water. Deaeration prevented initiation of pitting in Kingston, Ontario, tap water.

5) Use inhibitors. In a circulating system an inhibitor such as sodium dichromate* at 500 pm and pH 8 should completely prevent pitting. Polyphosphate and silicate inhibitors also may inhibit pitting.

6) Apply cathodic protection. In Kingston tap water initiation of pitting was prevented by the initial application of current density of about 2 mA/ft² at about 1.0 v negative to a copper-copper sulfate electrode. This is the same value necessary to prevent pitting of aluminum in seawater.

7) Avoid undesirable dissimilar metal couples. Aluminum in contact with metals other than zinc and cadmium tends to corrode galvanically, the severity depending on the conductivity of the water and on the metal. In fresh waters, the tendency is small; but in brines and seawater, it is large. The most aggressive metals are copper, brass, and bronze, followed by lead and then steel. Stainless steel can be safely used with aluminum in all but brines and seawater.

Godard further notes that both the occurrence and rate of pitting of aluminum in stationary water are dependent on pH, residue on evaporation, total hardness, chloride, oxygen, and copper. These factors are interrelated as indicated in Table 7.

Aluminum may undergo less corrosion at high water flow rates, because the more rapid renewal of dissolved oxygen at the metal surface leads to maintenance of the protective

Table 6 Effect of different cleaning methods on pitting[5]

Test metal	Cleaning method	Salt added[a]	Weight change, mg	Pitting
Commercial Al	Cotton wool	None	+3.6	None
Commercial Al	Cotton wool	Pure	+3.0	One visible pit
Commercial Al	Nylon sponge	None	+1.9	None
Commercial Al	Nylon sponge	Pure	+1.2	Microscopic size
Commercial Al	Nylon sponge	None	+1.5	None
Commercial Al	Nylon sponge	Pure	+2.0	Microscopic size
Al-Mn	Nylon sponge	None	+1.8	None
Al-Mn	Nylon sponge	Pure	+1.7	None
Commercial Al	Copper turnings	Pure	−50.2	Severe and extensive
Commercial Al	Copper turnings	Pure	−81.7	Severe and extensive
Al-Mn	Copper turnings	Pure	−62.9	One perforation, intense localized action

[a] In daily porridge cooking cycle.

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* It should be noted that chromates are not suitable for use with drinking water.

Table 7 Composition and pitting data for fresh waters tested (in increasing order of pitting corrosivity)[10]

Order	Time (weeks) to depth of 40 mils	Location	pH	Water composition Hardness	Copper
1	953	Shawinigan Falls	7.1	73	0.04
2	453	S. Shawinigan Falls, Que.	7.4	18	0.04
3	207	Crofton, B. C.	6.7	27	0.021
4	205	Hamilton Bay,	7.1	205	0.003
5		Kingston, Ont.	7.9	160	0.005
6	175	Credit Valley, Ont.	7.1	0	0.028
7	147	Columbia River, B.C.	7.5	72	0.017
8	83	Canyon Meadows, Alta.	7.9	169	0.005
9	46	Regal Golf Course, Calgary	8.1	331	0.007
10	25	N. Sask. River, Drayton Valley, Alta.	8.1	267	0.11
11	23	Peterboro, Ont.	7.5	86	0.012
12	17	R. G. May Golf Course, Calgary	7.9	218	0.002
13	8	Billingham Beck, England	8.7	443	0.011
14	6	Jasper, Alta.	8.2	196	0.007
15	6	Lethbridge, Alta.	7.9	228	0.017
16	4.4	S. Sask. River	7.6	206	0.04
17	2.6	Mossbank, Sask.	7.8	555	0.005

film.[20] Where corrosion takes place, it may be reduced by cathodic protection with zinc. An inhibitor such as sodium silicate or sodium chromate may also be useful.[21]

A 2000-ft line of 4-in.-diam water pipe at Arvida, Quebec, has been in service for over thirteen years, as shown in Fig. 8.[10] The maximum pit depth found was 53 mils, as shown in Table 8. A life of at least 23 years is predicted for the aluminum $3\frac{1}{2}\%$ magnesium alloy (5154 type).

At Shawinigan, Quebec, two large (50,000 gal), aluminum overhead, water storage tanks were built in 1948, one for an industrial plant and another for the municipality.[10] After nine years' service, the maximum pit in the first tank was 90 mils and in the other 184 mils. A maintenance-free life of at least 100 years is predicted for the industrial plant tank and 25 years for the city installation.

In Table 9, Godard compares water compositions which have aggressive and mild actions on aluminum.

An all-aluminum plant heat exchanger has given nine years service without maintenance at Ottawa, Canada, where galvanized steel failed in two years. A large all-aluminum plant heat exchanger in Canada has given over eight-years' service in air-conditioning service.

A field study[22] of circulating waters in cooling towers at New York, Philadelphia, and Washington has shown that six commercial aluminum alloys developed no appreciable corrosion when used with properly treated water.

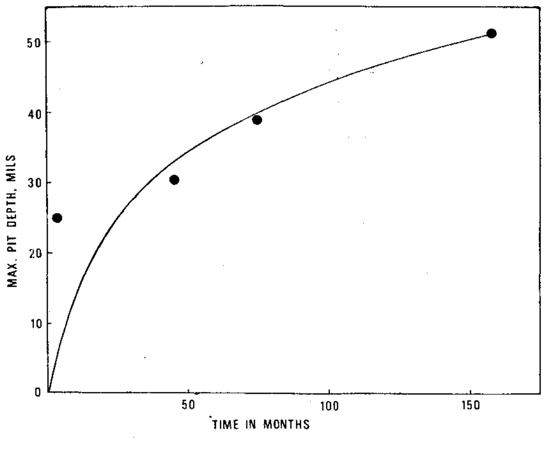

Fig. 8 Maximum pit depths on 4-in. 5052 alloy pipe in Arvida water line (Ref. 10).

At 26°C, Rowe and Walker[13] found that the combination of chloride, bicarbonate, and copper ions in the presence of air produced a significant increase in the corrosion rate of aluminum. In the absence of air, only $\frac{1}{3}$ the amount of corrosion occurred. Concentrations of 300-ppm chloride ion, 300-ppm bicarbonate, and 2-ppm copper gave a near-maximum effect. Increasing the copper concentrations as high as 10 ppm provided no additional effect on corrosion. A pitting type of corrosion was observed normally at this temperature (26°C). At 71°C, no pitting occurred, unless bicarbonate was absent. Pitting occurred only in solutions with chloride and copper ions. Addition of 5 ppm of bicarbonate stopped the pitting and inhibited corrosion. Large pits formed at 56°C and above in the absence of bicarbonate ion.

Table 8 Maximum pit depths in Arvida water line[10]

Period of service Months	Years	Maximum depth mils
5	0.42	25
40	3.3	31
72	6.0	40
156	13.0	53

Doyle and Godard[15,25] showed that chlorine additions of 0.5–1.0 ppm should have negligible influence on corrosive behavior of some river waters on 3003 and 6351 aluminum. The addition of chlorine at levels up to 30 ppm likely would increase the frequency of pitting and general corrosion, particularly for more aggressive waters.

An interesting study on pitting corrosion of aluminum utensils in two Russian tap waters was made by Pavlov and

Table 9 Aggressiveness of waters related to compositions[10]

Water component	Most aggressive Mossbank, Sask.	Least aggressive Shawinigan Falls, Que.
pH	7.8	7.1
Total solids	1038 ppm	140 ppm
Total hardness	555 ppm	73 ppm
Copper	0.005 ppm	0.04 ppm
Chloride	20 ppm	?
Sulfate	417 ppm	?

Table 10 Ranking of city waters by corrosivity as measured by one year's exposure of 3003 aluminum alloy[27]

	Water analyses, ppm				Corrosion rate, mdd[a]	Maximum pit, mils	Ranking[b] by	
Location	HCO_3	SO_4	Cl	Cu			Corrosion rate	Maximum pit
Youngstown, Ohio	37	94	72	0.01	0.03	0	1	1
Dallas, Texas	0	47	48	0.01	0.86	0	16	2
Oklahoma City, Okla.	26	28	105	nil	0.06	0	3	3
New Orleans, La.	10	60	38	0.01	0.71	14	14	4
Columbus, Ohio	18	...	...	nil	0.98	15	17	5
New York, N. Y.	12	nil	8	0.35	1.32	17	20	6
Toledo, Ohio	137	34	21	...	2.51	19	34	7
Syracuse, N. Y.	114	14	2	...	1.58	24	23	8
Miami, Fla.	260	29	18	0.02	0.18	27	5	9
Richmond, Va.	44	32	18	0.28	1.93	28	29	10
Charlotte, N.C.	18	5	3	...	0.21	28	6	11
Little Rock, Ark.	140	1	6	0.12	1.01	28	18	12
Atlanta, Ga.	13	4	4	...	0.40	29	11	13
Portland, Ore.	110	nil	5	0.06	0.33	29	8	14
Hartford, Conn.	80	trace	7	0.21	1.92	30	28	15
Saginaw, Mich.	72	21	12	nil	2.58	30	35	16
Minneapolis, Minn.	49	28	10	nil	0.04	31	2	17
Boston, Mass.	31	nil	13	0.28	1.77	32	26	18
Wichita, Kansas	108	81	72	0.04	0.33	35	9	19
Corpus Christi, Texas	102	48	130	0.02	1.70	42	24	20
Birmingham, Ala.	69	82	3	...	0.38	46	10	21
Salt Lake City, Utah	75	16	17	0.02	2.36	47	33	22
Milwaukee, Wis.	130	26	11	0.01	1.95	49	30	23
Philadelphia, Pa.	48	103	19	0.20	2.76	51	36	24
Nashville, Tenn.	73	32	5	...	1.52	52	22	25
Los Angeles, Calif.	119	21	27	0.01	1.78	52	27	26
Chicago, Ill.	326	294	9	0.02	0.47	59	12	27
Pittsburgh, Pa.	29	164	27	0.01	0.23	59	7	28
Kansas City, Mo.	28	138	22	0.01	1.46	63	21	29
Washington, D.C.	79	36	16	0.12	1.21	63	19	30
Omaha, Nebr.	170	184	15	...	0.85	69	15	31
Houston, Texas	228	trace	52	0.13	1.70	80	25	32
San Francisco, Calif.	180	50	22	0.02	2.06	84	31	33
Phoenix, Ariz.	161	40	134	nil	0.59	102	13	34

[a] mg/dm/day—based on weight losses.
[b] From least corrosive (1) to most corrosive (34).

Table 11 Aluminum alloys used with fresh waters chemical composition limits (in % maximum unless shown as a range)

									Others		
Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Each	Total	Aluminum
1100	1.0	Si + Fe	0.05–0.20	0.05	...	...	0.10	...	0.05	0.15	99.00
3003	0.6	0.7	0.05–0.20	1.0–1.5	...	...	0.10	...	0.05	0.15	Remainder
3004	0.3	0.7	0.25	1.0–1.5	0.8–1.3	...	0.25	...	0.05	0.15	...
5052	0.45	Si + Fe	0.10	0.10	2.2–2.8	0.15–0.35	0.10	...	0.05	0.15	...
5154	0.45	Si + Fe	0.10	0.10	3.1–3.9	0.15–0.35	0.20	0.20	0.05	0.15	...
5056	0.30	0.40	0.10	0.05–0.20	4.5–5.6	0.05–0.20	0.10	...	0.05	0.15	...
5456	0.40	Si + Fe	0.10	0.50–1.0	4.7–5.5	0.05–0.20	0.25	0.20	0.05	0.15	...
6061	0.40–0.8	0.7	0.15–0.40	0.15	0.8–1.2	0.04–0.35	0.25	0.15	0.05	0.15	...
6063	0.20–0.6	0.35	0.10	0.10	0.45–0.9	0.10	0.10	0.10	0.05	0.15	...

Soboleva.[23] Continuous immersion in city waters at Moscow and Kuibishev produced less pitting than alternating immersion and drying. Nucleation of pitting was promoted by scratching the metal. Even the purest aluminum pitted, but less than less pure metal. The addition of 0.5% magnesium plus 0.5% manganese to the metal reduced sensitivity to pitting, as did the addition of 0.5% magnesium plus 0.2% titanium. They suggested pits initiated at locations of $FeAl_3$ inclusions.

Terai and Baba[24] tested condenser tubes in water at pH 7.2 flowing at 2–5 m/sec for up to 126 days. Alloys tested included 1140, 1120, 3003, 5052, 5454, and alclad 3003. The number of pits was least for the 5052 alloy, but the alclad 3003 proved to be the best material.

Field tests in municipal waters at 34 locations in the United States have shown a wide range of corrosive actions on alloy 3003. In these tests, replicate coupons of 3003 sheet alloy were exposed for periods of one week, one month, three months, and one year in bathroom flush tanks. Temperatures of exposure were those of household cold water taps, and periodic flushing the bathroom bowls changed the water in the tanks. Weight losses for the coupons were used to calculate the corrosion rates. The deepest pits were measured for triplicate coupons for each exposure period. The analyses of test waters and corrosive effects are listed in Table 10. The least corrosive city waters are found in Youngstown, Ohio; Dallas, Texas; and Oklahoma City, Oklahoma—the most severe waters at Houston, Texas; San Francisco, California; Phoenix, Arizona. A number of aluminum alloys are commonly used with tap waters. These are shown, along with compositions, in Table 11.[27]

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