

# A Preliminary Study of Aluminum as a Culvert Material

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This investigation was initiated because there appeared to be a possibility of an economic or engineering advantage in the use of aluminum as a culvert material. The project was sponsored by the Bureau of Public Roads, and the investigation was performed by the Materials and Research Department of the California Division of Highways starting in 1961.

On the basis of this accelerated investigation, it is estimated that under favorable conditions, aluminum may have a service life up to an estimated 25 years. The anticipated favorable conditions for the use of aluminum are described with regard to the use of protective coatings, limits for the hydrogen-ion and the resistivity of the soil and water, and the influence of abrasion on the durability of the metal.

Because this was an accelerated investigation, the durability of aluminum as a culvert material should be continuously verified so as to confirm or modify the results with actual field experience.

•THE POSSIBILITY of an economic or engineering advantage in the use of aluminum as a culvert material has resulted in this investigation by the California Division of Highways in cooperation with the Bureau of Public Roads.

The investigation was initiated on March 31, 1961, under Laboratory Project Authorization 71-R-6244 and more recently, under R-53097. The cost of the investigation has been borne by the California Division of Highways and the Bureau of Public Roads. The actual investigation and associated tests were performed by the Materials and Research Department of the California Division of Highways. This work supplements previous investigations of culvert materials.

This report not only contains information on the field performance of test culverts, but also includes the results of laboratory testing and presents recommendations for the use of corrugated aluminum pipe.

## SUMMARY AND CONCLUSIONS

Field test sites and laboratory tests were selected or designed to provide as much information as possible on the probable corrosion and abrasion resistance of aluminum in the short time available to reach early decision on usage.

Empirical equations for projecting data developed by other investigators demonstrates the inconsistencies that are possible in predicting corrosion rates (see Figure 29). For this reason, all data obtained under this study were projected on a straight-line basis. The purpose of this projection is to assist in the selection of culvert materials in accordance with California practice which allows only those materials that

have an anticipated maintenance-free service life of 25 or 50 years, depending on the highway design criteria. Straight-line projections allow direct comparison of various materials. It is recognized that the final maintenance-free life may be less or greater than the straight-line projection would indicate. For these reasons, the projections of short-time laboratory test results were only given qualitative consideration and were not used alone in making recommendations or in anticipating service life.

In general, the data obtained during this investigation agree with the published literature in that aluminum does not seem to be chemically attacked when the pH of the solution is near neutral (7.0). In addition, there is agreement that within the limits of pH 6.0 to 8.0 aluminum should be chemically stable providing there are no other controlling factors, such as:

1. Waters containing heavy metals;
2. Concentration-cell corrosion;
3. Stagnant or quiescent water; and
4. Water containing large quantities of dissolved chemicals.

It is a conclusion of this study that these foregoing factors can be successfully controlled by requiring an aluminum culvert protected by means of a bituminous or other approved organic type of coating.

At the pH ranges of 5.0 to 6.0, and 8.0 to 9.0, the chemical stability of aluminum does not appear to be as clearly defined as when the pH range is 6.0 to 8.0. Therefore, whenever aluminum culverts are to be used in the environmental pH ranges of 5.0 to 6.0, and at 8.0 to 9.0, they should also be protectively coated on the basis of pH alone.

Although this investigation did not determine any direct relationship between the resistivity of a soil or water and the corrosion rate of aluminum, it did indicate resistivity values below which corrosion is more likely to occur.

Published data indicate that at those locations where the in-place soil resistivities were less than 1,500 ohm-cm, the corrosion of an aluminum pipeline was controlled by the application of cathodic protection. Also, published aluminum culvert test results based on observations over a maximum of 3.5 years of exposure indicated that corrosion from the flow was observed to be almost nil when the in-place soil or the water resistivity had a mean value of approximately 3,100 ohm-cm. Other reports have indicated that aluminum has been attacked when the water contained more than 181 parts per million of calcium carbonate.

On the basis of the foregoing, it is apparent that a resistivity limitation is required because it is a guide to the relative chemical content of the environment.

Because crossdrains are generally located in the more critical locations, when aluminum is used, it should be protectively coated regardless of pH. In addition, the minimum resistivity should not be less than 2,000 ohm-cm, unless the invert is also paved. This resistivity value implies that the total dissolved solids in the water or soil is approximately 450 parts per million, which can include a total of approximately 125 parts per million of sulfates as  $\text{SO}_4$  and chlorides as Cl ions.

In culvert locations which are not as economically critical as crossdrains, changes in the pH, resistivity limits, and coating requirements could be made so as to gather further experience with this material.

The test results of this investigation indicate that aluminum is sensitive to abrasion. In fact, the corrosion-inhibiting cladding on the aluminum specimens was penetrated in all of the laboratory corrosion-abrasion tests as would have been the case with zinc coatings on steel. The specimens in this test had a velocity of 5 fps, and the abrading material was Ottawa sand. The field data agree with the laboratory tests that aluminum is not as abrasion resistant as a steel culvert. Therefore, at this time, it appears necessary to restrict aluminum from indiscriminate use in streams of high flow velocities containing an abrasive bed load.

This investigation also indicates that flow velocity per se may not be a controlling factor in the abrasion process. It appears that the degree of abrasion suffered by a culvert will not only be a function of the velocity, but also of the size, quantity, and shape of the bed material. Severe abrasion was observed in the test culvert where the

bed contained shattered and angular rocks. Conversely, at another culvert site with similar calculated flow velocities, a minor amount of abrasive destruction was observed where the material consisted of rounded boulders.

On the basis of this accelerated investigation, it is estimated that under favorable conditions, aluminum may have an anticipated maintenance-free service life of 25 years. However, the durability of the material should be continuously verified so as to confirm or modify the recommendations since they are partially based upon laboratory data.

### RECOMMENDATIONS

It is recommended that the durability of aluminum culvert material be continuously monitored so as to confirm or modify, through added field experience, the culvert use recommendations that are shown in Table 1.

Current practice of the California Division of Highways establishes the following minimum design service lives for culvert materials:

A.	Crossdrains under high-type pavements	50 yr
B.	Crossdrains under intermediate and low-type pavements	
1.	With less than 10 ft of cover	25 yr
2.	With more than 10 ft of cover	50 yr
C.	Crossdrains under highways on temporary alignment	25 yr
D.	Side drains on all projects except under street connections surfaced with high type pavement	25 yr

A high-type pavement is defined as either asphalt concrete of 0.15 ft or more in thickness or portland cement concrete pavement. An intermediate or low-type pavement is defined as asphalt concrete less than 0.15 ft thick or other pavement of any thickness mixed with liquid asphalt.

The recommended use of aluminum as a culvert material is predicated on analysis of all available data and a judgment to eliminate those environmental factors which could result in earlier maintenance contrary to the established minimum design service lives. Furthermore, because of the lack of long-term field data and the acknowledged

TABLE 1  
RECOMMENDED USE OF MINIMUM GAGE THICKNESS CORRUGATED ALUMINUM PIPE ANTICIPATED  
25-YEAR MAINTENANCE-FREE SERVICE

Location	Protective Coating <sup>1</sup>	pH Range	Flow Conditions <sup>2</sup>						Continuous Flow	Resistivity (ohm-cm), min. value
			Less than 5 FPS		Less than 7 FPS		Greater than 7 FPS			
			Abrasive	Non-Abrasive	Abrasive	Non-Abrasive	Abrasive	Non-Abrasive		
Overside	None	6-8	X	X	X	X	No	X	X	2,000
drain	Bituminous	5-9	X	X	X	X	No	X	X	1,500
Under	None	6-8	X	X	X	X	No	X	X	2,000
drain	Bituminous	5-9	X	X	X	X	No	X	X	1,500
Side	None	6-8	X	X	X	X	No	X	X	2,000
drain	Bituminous	5-9	X	X	X	X	No	X	X	1,500
Cross	Bituminous	6-8	X	X	No <sup>3</sup>	X	No	X	No	2,000
drain	Bituminous plus paved invert	5-9	X	X	X	X	No <sup>3</sup>	X	X	None

<sup>1</sup>When pipe is bituminously coated, backfill to have pH of not less than 5.0 and no resistivity limitation.

<sup>2</sup>'X' in column denotes recommended use.

<sup>3</sup>May be used if metal gage thickness is increased by 2 numbers over minimum loading requirements.

Note: Subject to approval, other thin film type of di-electric coatings may be used in lieu of a thin film bituminous coating. Aluminum is not to be used as a section or extension of a culvert that contains steel sections. In areas where the flow contains heavy metals, aluminum shall not be used unless the invert is paved, irrespective of the pH and resistivity.

uncertainties of the short-term laboratory data and current field experience, no recommendations are made at this time for an anticipated 50-yr maintenance-free service life for corrugated aluminum pipe.

## FACTORS THAT INFLUENCE THE CORROSION OF ALUMINUM IN SOILS OR WATERS

### Hydrogen-Ion Concentration, pH

It has been reported that barring an actual test, aluminum alloys are unsatisfactory for use when the pH of the solution is greater than 10 or less than 3 (1). Other reports have indicated that aluminum is generally inert or inhibited from accelerated corrosion when the pH range of the environment is: 4 to 9 (2), 6 to 8 (3, 4), 5.5 to 7.8 (5), 4 to 8 (6), and 4.5 to 9 (4).

Based on the standard free energies of the constituents, and the deduced electrochemical behavior of aluminum, the oxide of the metal (hydrargillite,  $\text{Al}_2\text{O}_3 \cdot \text{H}_2\text{O}$ ) is theoretically chemically stable within a pH range of 4 to 8.6, providing the solution is free of substances which can form soluble complexes or insoluble salts of the metal (5).

As indicated by the foregoing, it is apparent that aluminum is chemically stable in the near-neutral range of pH (7.0). However, it has been emphasized in the literature that the pH of a solution or soil is not the primary control, or a completely reliable basis for predicting the chemical stability of aluminum (2, 3, 7, 8).

From the preceding, it is apparent that the knowledge of the pH of a solution or soil can be a valuable tool in predicting the durability of aluminum, but other factors must be considered.

Because of the relatively long service of steel culverts and pipe, the relative influence of the pH of the environment to the rate of corrosion of this metal has been determined (10, 11, 12, 13).

### Chemicals

It has been reported that in sodium carbonate solutions of greater than 0.001 normal concentrations (approximately 60 parts per million), aluminum is significantly attacked (9). When the mineral acid concentration is less than 0.001 normal, aluminum is resistant to corrosion (9). In acid solutions containing only one anion, the rate of corrosion increases in the following order: (a) acetate, (b) phosphate, (c) sulfate, (d) nitrate, (e) chloride (9).

The presence of heavy metals, copper, mercury, cobalt and nickel in waters has been reported as a cause of the corrosion of aluminum (1, 3, 4, 8).

Aluminum which does not have the highly corrosion resistant cladding has been observed to have accelerated corrosion when a water contains 0.09 ppm of copper, 0.08 ppm cobalt, and 0.03 ppm nickel (3).

It has been generally observed that aluminum corrodes in "hard" waters. Although no correlation was determined between the relative hardness of a water and the corrosion rate of aluminum, the reported data indicate that a "very hard" water contains approximately 180 parts per million or more of carbonates that are calculated as calcium carbonate (8). Of the nine tests of aluminum in different natural waters containing more than 180 ppm of hardness, seven of these samples were found to have a pit depth of 40 mils in less than 6 months (8). The greatest reported concentration of copper found in the survey of these seventeen natural waters was 0.11 ppm (8).

From the preceding data, it appears that either a complete chemical analysis should be made of the soils or waters to which aluminum would be exposed or an economical means for testing these environments for mineral content should be considered.

### Electrical Resistivity of the Environment

The electrical resistivity has been found to be an indicator of the relative concentration of chemicals in a soil or water (10, 11). The greater the electrical resistivity, the less the concentration of soluble chemicals.



Generally, no correlation has been found between relative values of resistivity and an associated corrosion rate of aluminum (2).

It was reported that on one underground gas pipeline "hot spot" cathodic protection was applied to those sections of the pipe which were embedded in a soil with a resistivity of less than 1,500 ohm-cm (14).

Based upon the preceding lack of data, it appears that the electrical resistivity of an environment is thus far only of academic interest with regard to inferring a possible corrosion rate of aluminum. The electrical resistivity of an environment may be of use when considering that it is an indicator of the highly mineralized solutions which can cause the corrosion of aluminum and steel.

The chemical contents in parts per million of solutions and soils may be estimated by the following formulas (18 and 11, respectively):

$$\text{Total dissolved solids} = \frac{900,000}{R} \quad (1)$$

$$\text{Sum of sulfates and chlorides (SO}_4 + \text{Cl)} = \frac{784,000}{R^{1.15}} \quad (2)$$

where R = resistivity in ohm-cm.

### Bimetallic Corrosion

When aluminum is electrically connected to steel, approximately 1.2 volts can be initially developed and can result in an accelerated corrosion rate of the aluminum (15, 16). Aluminum has been used as a sacrificial anode for galvanically inhibiting the corrosion of steel (17).

The degree of galvanic corrosion of an aluminum culvert would be considered minor if the steel in contact with the aluminum were limited to just a bolt. Conversely, if the situation were reversed with an aluminum bolt in a steel culvert, the aluminum could corrode rapidly.

From this, it is obvious that judgment must be exercised when coupling dissimilar metals to aluminum. A steel bolt used in a culvert band coupler would not seriously affect the aluminum culvert. The intermixing of steel and aluminum culvert sections should not be done as there could be rapid corrosion of the aluminum over an extensive area. The zinc on a galvanized steel culvert is generally anodic and will generally corrode when electrically coupled to aluminum in most neutral or acid solutions. Once the zinc is gone, the steel then can cause the aluminum to corrode.

### Concentration Cell and Crevice Corrosion

Concentration cell corrosion is generally defined as an electrolytic corrosion cell which is caused by a difference in the concentration of the electrolyte, or differences in the concentration of metal ions in solution (1, 16).

In effect, a concentration cell can be the initial cause of corrosion, or as a result of corrosion started by other causes (1), it can be the mechanism by which the corrosion process can continue.

Crevice corrosion is generally considered as a corrosion cell which is the result of differential aeration of the solution (1). A crevice type of corrosion cell can result in severe corrosion of the aluminum because the voltage of an active/passive cell can be superimposed upon the voltage of the differential aeration cell (1). Although structural steel is greatly affected by differential aeration corrosion cells (16), it is unlikely that this metal could be generally susceptible to what is commonly called an active/passive corrosion cell in the normal soil or water (19).

In general, the aggressive types of corrosion cells may be caused to form on aluminum by the following factors:

1. Bolted or riveted construction (1, 20);
2. Pockets or locations of liquid entrapment (1, 20);
3. Nonuniform soil compaction (2);
4. Differential aeration (1);
5. Stagnant pools of water (21); and
6. Electrical connection to ferrous metals (16, 20).

### CURRENT RESULTS OF FIELD TESTS

The test results of the eight field test culvert installations are given in detail in Tables 2 through 4, and shown in Figures 1 through 23. These test sites were chosen because some are the most highly corrosive and abrasive conditions to which an actual highway culvert will be or has been placed. This was a means of getting accelerated results. An exception was the culvert at I-Hum-35-C in the northwestern part of California near Bridgeville. This culvert site is exposed to the environmental conditions typical of the geographic area, and these conditions are considered to be only moderately aggressive.

TABLE 2  
FIELD SITE TEST DATA

Locations	I-Hum-35-C Bridgeville	II-Sha-3-B Redding	III-But-21-B Oroville	IV-SC1-5-C Los Gatos	IV-SCR-5-A Scotts Xing	X-SJ-53-C Rio Vista	XI-SD-2-Nat. Cty Sweetwater Br.	XI-Imp-187-F Salton Sea
Installed	8-20-61	11-16-61	8-21-61	10-19-61	10- 3-62	8-16-61	9-26-61	9-29-61
Last inspection	8-21-63	5- 2-63	5- 3-63	3- 4-63	8-16-63	1-30-64	5-21-63	5-22-63
Test time (yr)	2.0	1.5	1.7	1.4 <sup>1</sup>	0.83 <sup>2</sup>	2.4	1.7	1.7
Average pH	6.6	3.3	2.7	7.7	3.7	4.5-6.3	8.3	7.5
Min. resistivity	2,500	650	165	3,500	330	620-973	39	6.5
Na + K (as Na), ppm	—	14	7	65	—	178	12,300	99,740
Ca, ppm	—	44	266	102	470	65	170	12,300
Mg, ppm	—	88	328	19	—	26	504	2,170
CO <sub>3</sub> , ppm	—	Nil	Nil	Nil	Nil	Nil	Nil	Nil
HCO <sub>3</sub> , ppm	—	Nil	Nil	204	—	9	170	180
Cl, ppm	—	Nil	50	516	26	144	14,920	41,520
SO <sub>4</sub> , ppm	—	996	13,800	132	2,246	356	2,220	7,920

<sup>1</sup>This installation was removed during the last inspection. <sup>2</sup>Steel CMP was in place approximately 1 year prior to installation of aluminum test pipe.

TABLE 3  
CULVERT SITE TEST RESULTS<sup>1</sup>

Location	Metal	Time in Test (yr)	pH	Minimum Resis- tivity (ohm-cm)	Estimated Years to Perforation Based on Metal Loss at: <sup>2</sup>			
					Minimum Cross-Section Loss	Upstream Surface of Corrugation		Downstream Surface or Valley of Corrugation (corrosion surface)
						Abrasion	Pitting	
I-Hum-35-C	Steel	2.0	6.6	2,500	6.1	41	6.4	18
	Aluminum				3.6	3.6	—	6.9
II-Sha-3-B	Steel	1.5	3.3	650	2.3	—	—	2.3
	Aluminum				0.33	—	—	0.33
III-But-21-B	Steel	1.7	2.7	165	0.56	—	—	0.56
	Aluminum				0.56	—	—	0.56
IV-SCR-5-A	Steel	0.83	3.7	330	0.83	No test culvert		0.83
	Aluminum				1.3	—	—	—
IV-SC1-5-C	Steel	1.4	7.7	3,500	1.3	1.3	—	—
	Aluminum				0.14	0.14	—	—
X-S.J-53-C <sup>3</sup>	Steel	2.4	4.5 to 6.3	620 to 973	49	—	—	49
	Aluminum				12	—	—	12
XI-Imp-187-F <sup>3</sup>	Steel	1.7	7.5	6.5	6.7	—	—	6.7
	Aluminum				12	—	—	17
XI-SD-2-Nat. Cty <sup>3</sup>	Steel	1.7	8.3	39	25	—	—	33
	Aluminum				4.8	—	—	6.6

<sup>1</sup>All test results are based upon metallographic analysis of culvert samples.

<sup>2</sup>Estimated years to perforation for all samples were calculated on the basis of a 16-gage metal thickness.

<sup>3</sup>Corrosion loss measured on the soil side of the pipes.

TABLE 4  
AVERAGES OF ESTIMATED YEARS TO PERFORATION  
FOR 16-GAGE METAL

Metal	Max. Cross-Section Loss	Abrasion	Corrosion
(a) All Seven Comparative Field Test Sites			
Galvanized steel	13	21	18
Aluminum	4.8	1.9	8.6
(b) Estimated <sup>1</sup> for Five Test Sites with pH Between 4.5 and 8.3			
Galvanized steel	18	21	27
Aluminum	6.5	1.9	13

<sup>1</sup>Test site with pH of 4.5 has a pH range of 4.5 to 6.3.

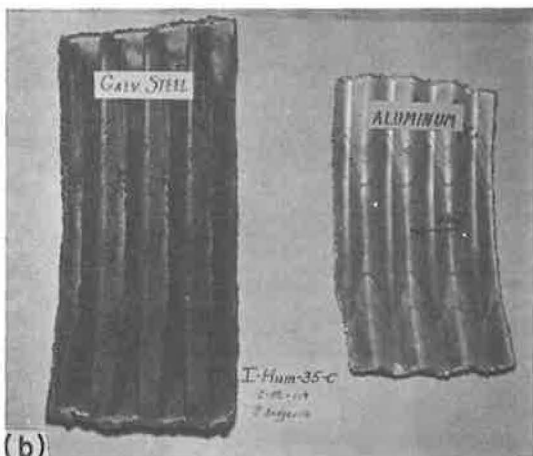


Figure 1. Field test site, I-Hum-35-C, mile 1.19: (a) inlet of test pipe--aluminum section; (b) samples removed from invert after 2-yr exposure.

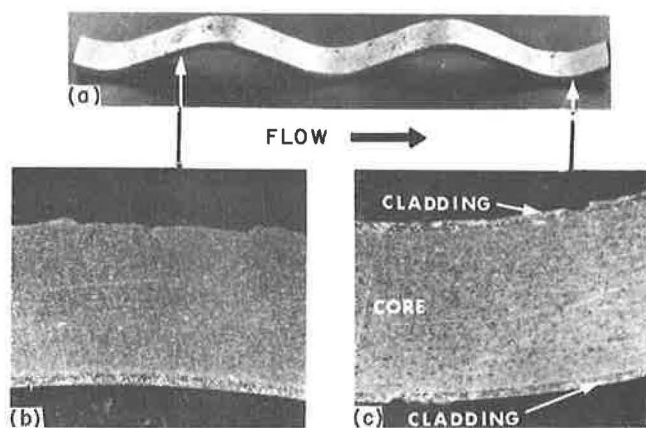


Figure 2. Field test site--aluminum, I-Hum-35-C, mile 1.19: (a) sample from invert of aluminum culvert; (b) typical loss of cladding at abrasion surface--2 yr; (c) cladding intact--2 yr.

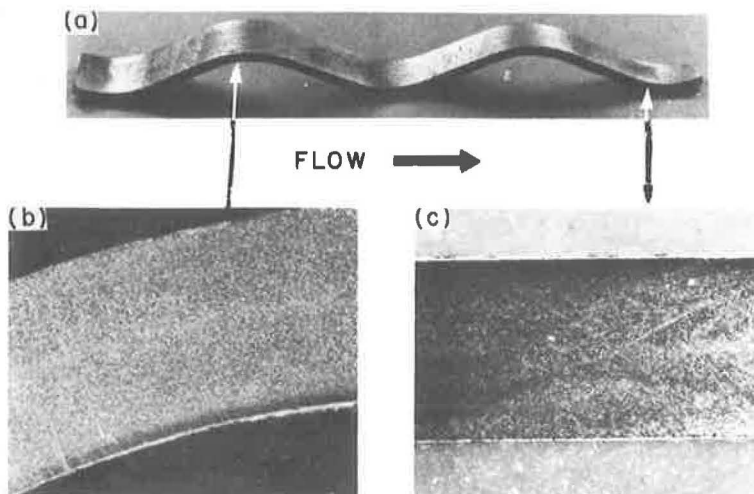


Figure 3. Field test site—steel, I-Hum-35-C, mile 1.19: (a) sample from invert of galvanized steel culvert; (b) note loss of zinc and minor loss of steel at abrasion surface—2 yr; (c) zinc abraded but intact—2 yr.

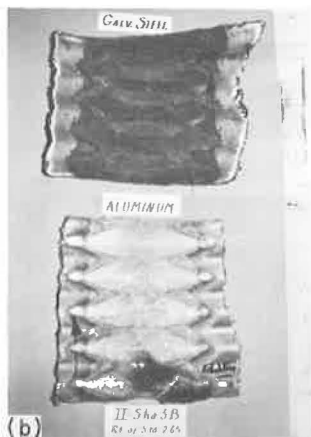


Figure 4. II-Sha-3-B, right of Sta. 265±: (a) field test site; (b) typical invert samples removed after approximately 1.5 yr of test.

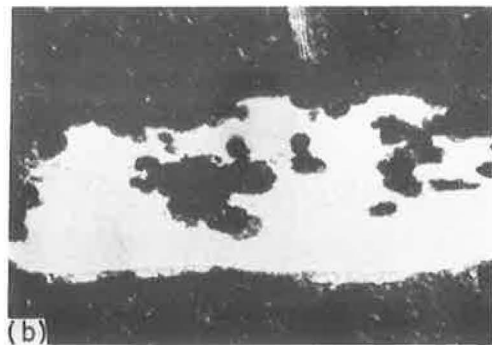
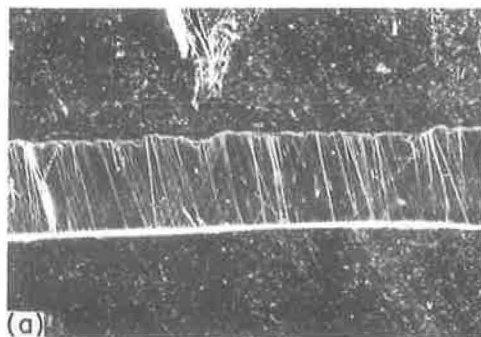
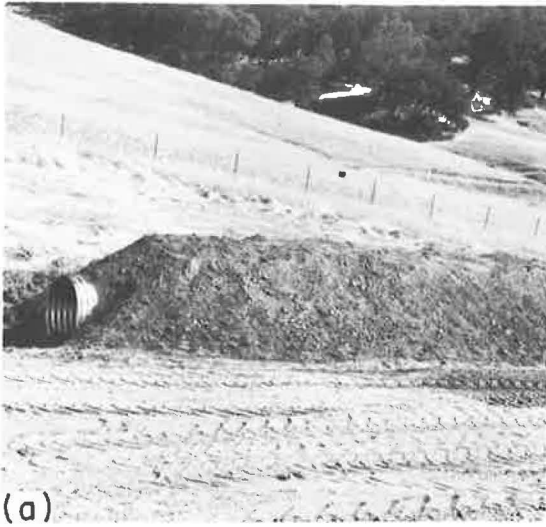
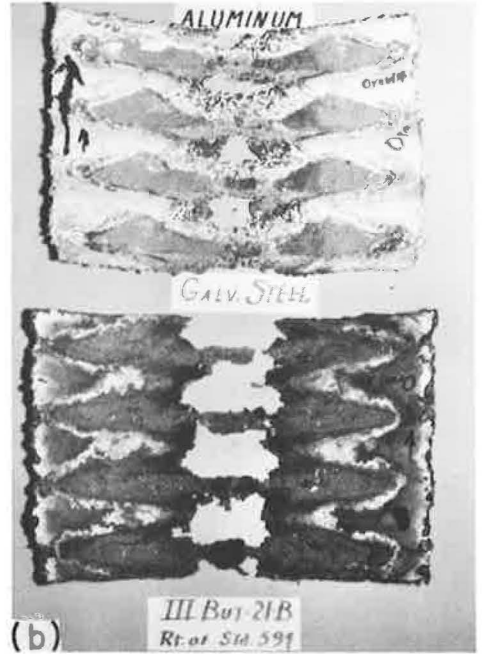


Figure 5. II-Sha-3-B, right of Sta. 265±: (a) cross-section of steel after 1.5 yr of test; (b) cross-section of aluminum.



(a)



(b)

Figure 6. III-But-21-B, right of Sta. 594±: (a) field test site; (b) invert samples removed after approximately 1.7 yr of test (highly corrosive exposure).

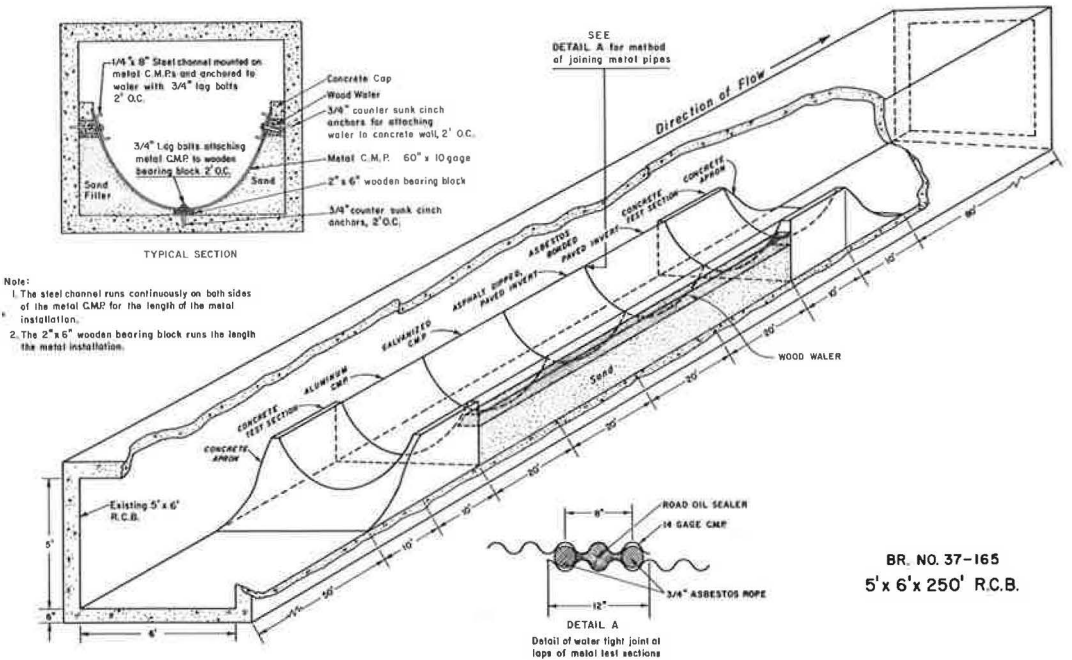


Figure 7. Abrasion test site, IV-SCI-5-C, Trout Creek.



Figure 8. Abrasion test site, IV-SC1-5-C, Sta. 250+25, Bridge No. 37-165: (a) "as built" concrete test section at inlet section of test culvert; (b) appearance of concrete test section after 1.4 yr of service showing severe abrasion; (c) view showing loss of approximately  $\frac{1}{2}$  in. of concrete in the concrete test section at the outlet (note deposit of culvert).



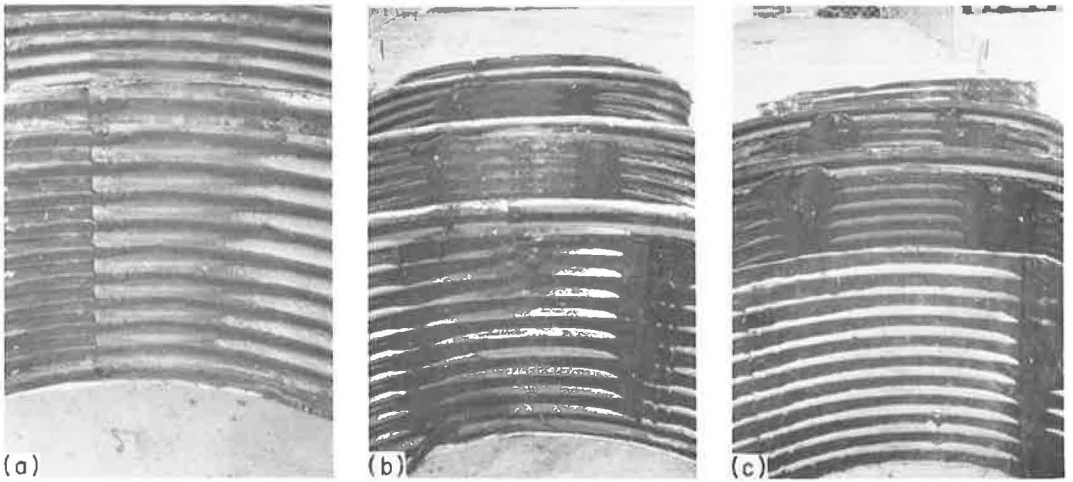


Figure 9. Abrasion test site, IV-SC1-5-C, Sta. 250+25, Bridge No. 37-165. Samples of the invert from: (a) galvanized steel section (note wear of rivet heads); (b) A.D.P.I. section (note loss of rivets at joint); (c) A.B.A.D.P.I. section.

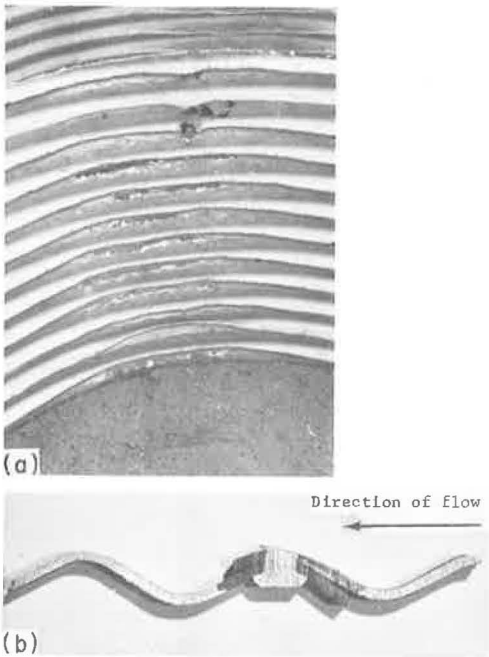


Figure 10. Abrasion test site, IV-SC1-5-C, Sta. 250+25, Bridge No. 37-165: (a) severe abrasion of aluminum after 1.4 yr of service; (b) severe abrasion of galvanized steel after 1.4 yr of service (note loss of head of rivet).

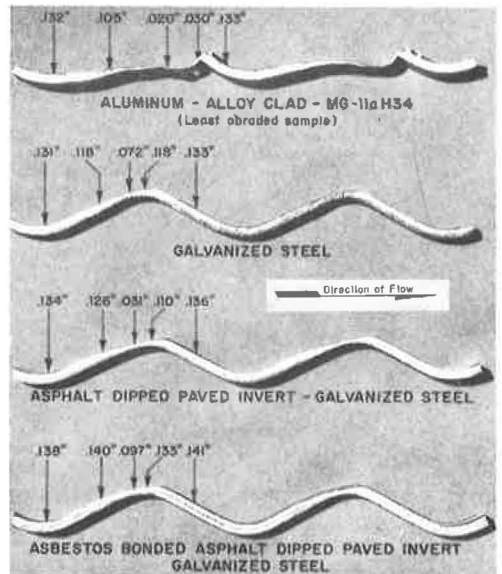


Figure 11. Results of abrasion tests, IV-SC1-5-C, Sta. 250+25, Bridge No. 37-165. Typical cross-sections of pipe invert after test exposure. (Note: All C.M.P. samples were 10 gage (0.140±). Steel samples are typical of the most abraded pipe sections.)

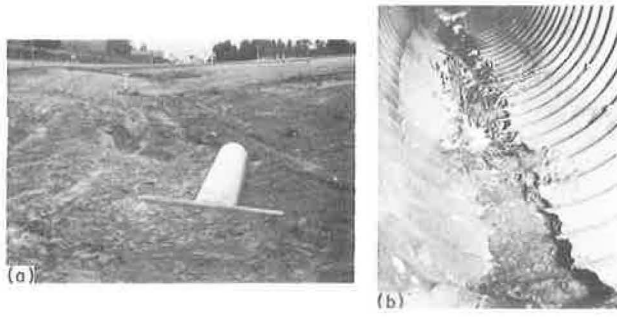


Figure 12. Field test site, IV-SCr-5-A, right of Sta. 530±: (a) aluminum culvert, field test site (exposed pipe subsequently backfilled); (b) existing galvanized C.M.P., approximately 2 yr of service (not placed as part of test program).

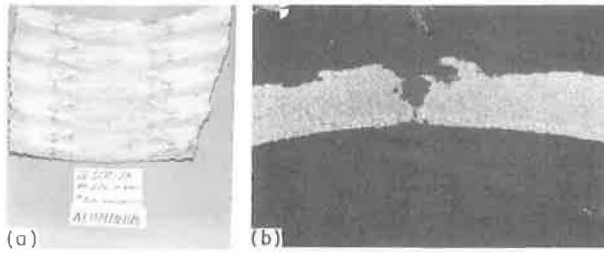


Figure 13. Field test site, IV-SCr-5-A, right of Sta. 530±: (a) aluminum invert sample approximately 0.8 yr of test; (b) cross-section of aluminum, nonperforated section.

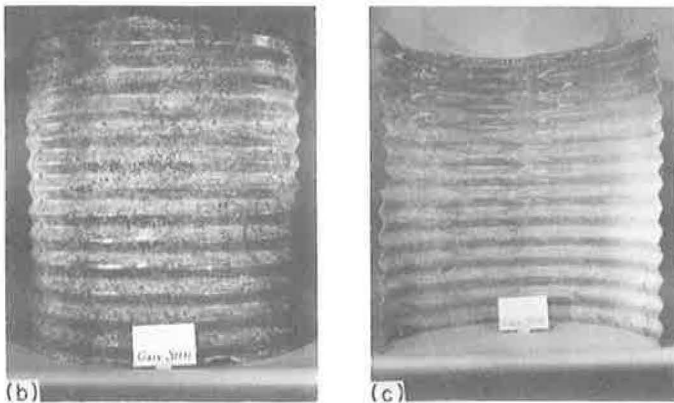


Figure 14. Field test site, X-SJ-53-C, right of Sta. 6±: (a) field test site: (b) backfill side: (c) inside (invert). Appearance of cleaned galvanized steel samples after 2.4 yr of test.

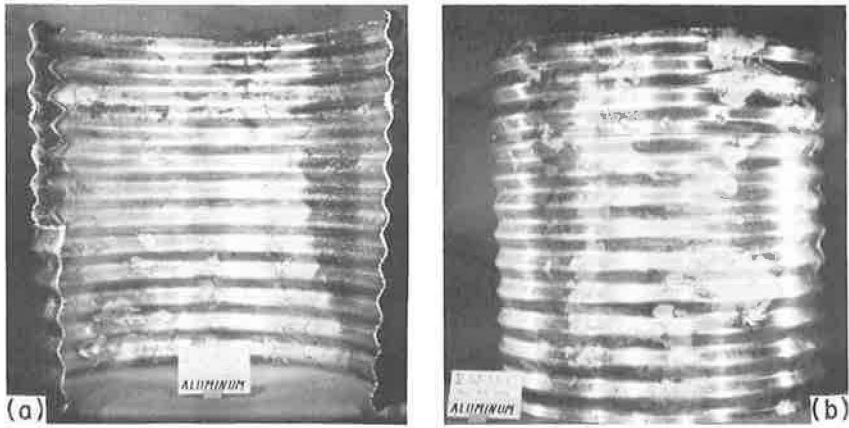


Figure 15. Field test site, X-SJ-53-C, right of Sta. 6±: (a) appearance of inside of aluminum sample after cleaning (invert); (b) appearance of soil side of aluminum sample after cleaning.

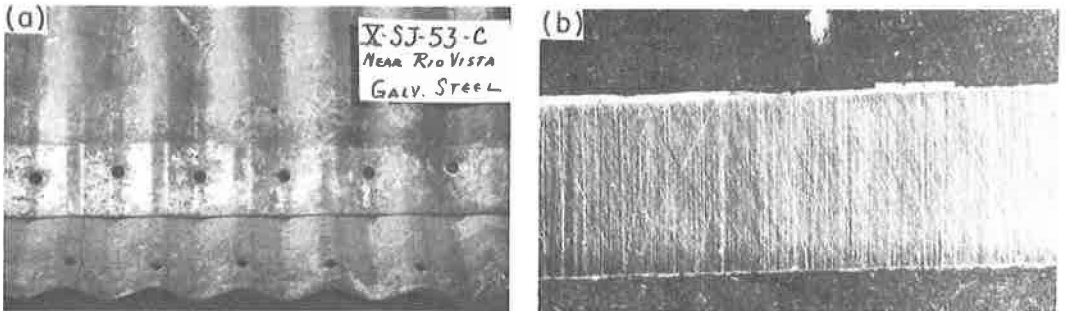


Figure 16. Field test site, X-SJ-53-C, right of Sta. 6±: (a) appearance of galvanized steel joint after cleaning; (b) cross-section of steel (note partial loss of galvanizing on both sides).

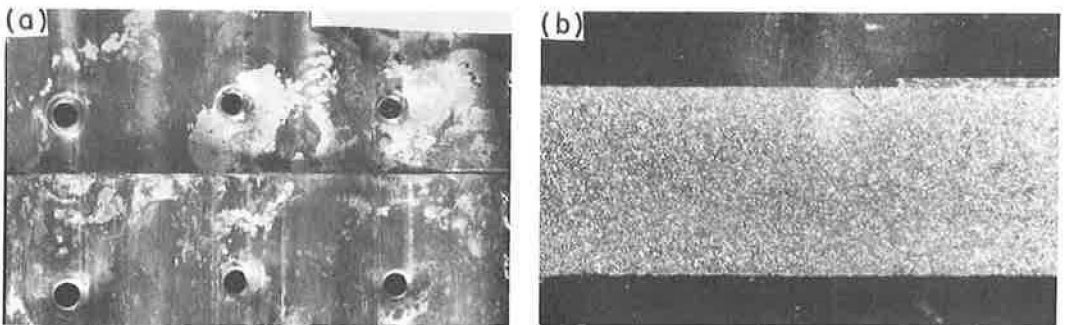
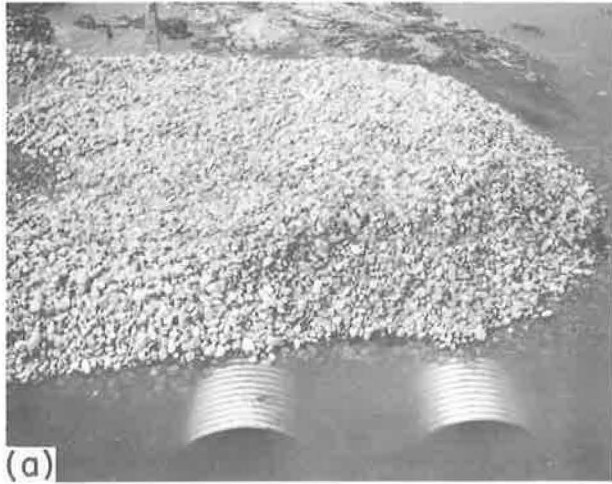
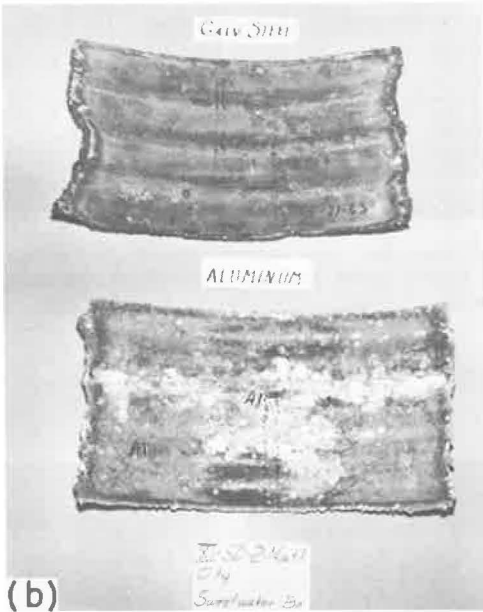


Figure 17. Field test site, X-SJ-53-C, right of Sta. 6±: (a) appearance of aluminum joint after cleaning—light-colored areas are corroded sections of pipe; (b) cross-section of aluminum (note loss of cladding on both surfaces).



(a)



(b)



(c)

Figure 18. Field test site, XI-SD-2-Nat.Cty at Sweetwater Creek: (a) field test site at high tide; (b) sample removed from culvert inverts after approximately 1.6 yr of test; (c) backfill side of same culvert samples.

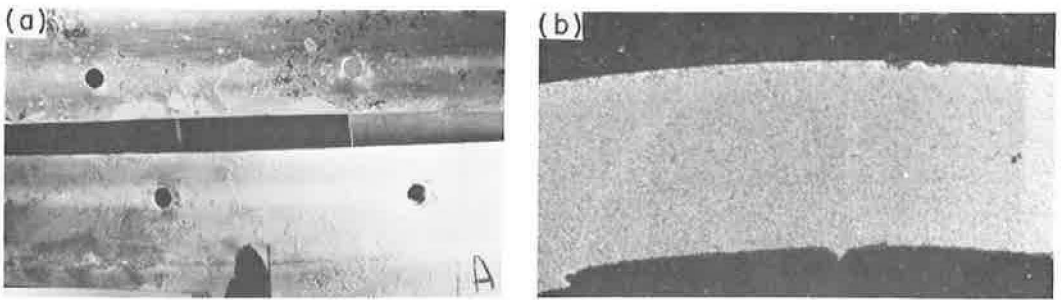


Figure 19. Field test site, XI-SD-2-Nat.Cty at Sweetwater Creek: (a) appearance of aluminum after cleaning—1.6 yr of test; (b) cross-section of aluminum (note loss of cladding and penetration into base metal on backfill side of pipe at bottom of photo).

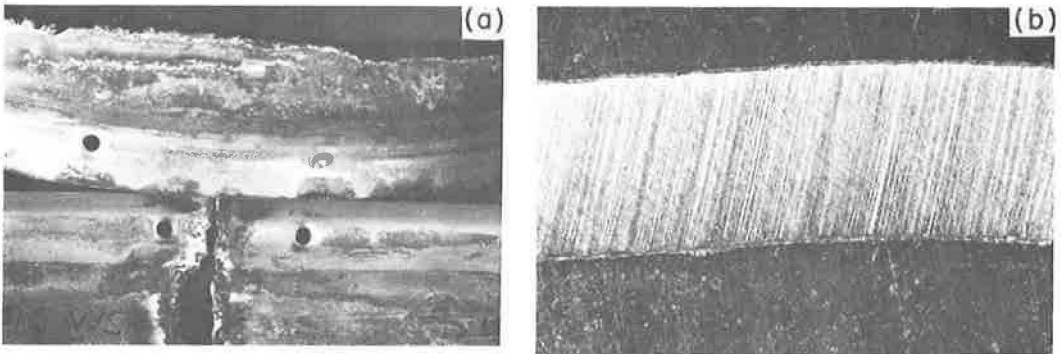


Figure 20. Field test site, XI-SD-2-Nat.Cty at Sweetwater Creek: (a) appearance of galvanized steel after cleaning—1.6 yr of test; (b) galvanizing penetrated at localized spots (top surface of photo).

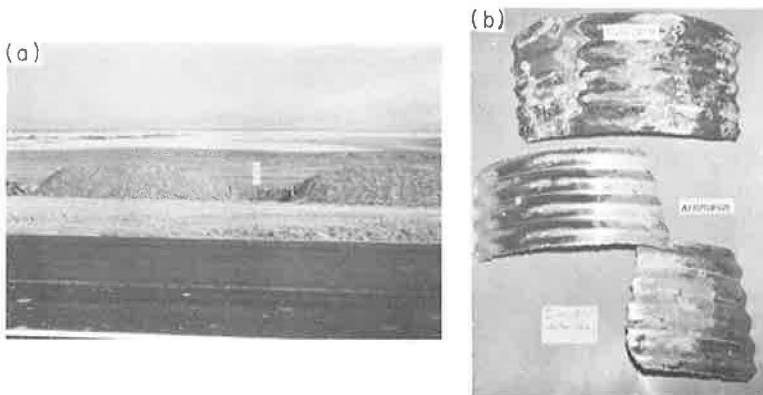


Figure 21. Field test site, XI-Imp-187-F, left of Sta. 498±: (a) field test site: (b) backfill side of culvert samples—approximately 1.7 yr of exposure. (Dark areas on steel and light areas on aluminum are locations of corrosion.)

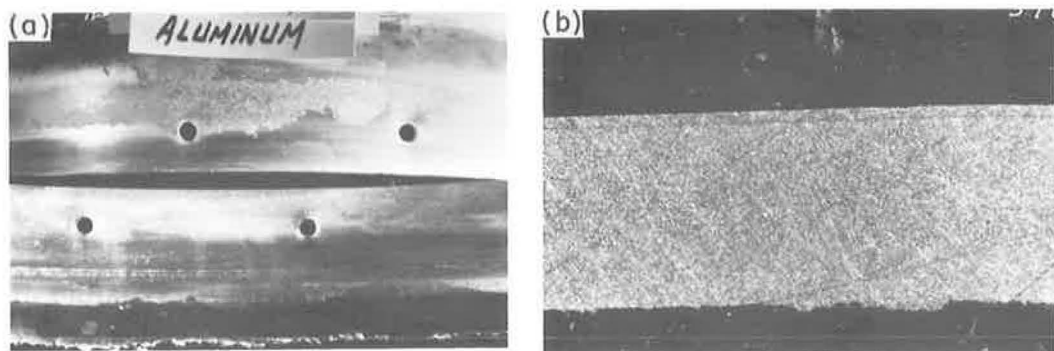


Figure 22. Field test site, XI-Imp-187-F, left of Sta. 498±: (a) appearance of aluminum joint after cleaning; (b) section through aluminum (note loss of cladding and penetration of base metal on soil side of aluminum culvert at bottom of photo).

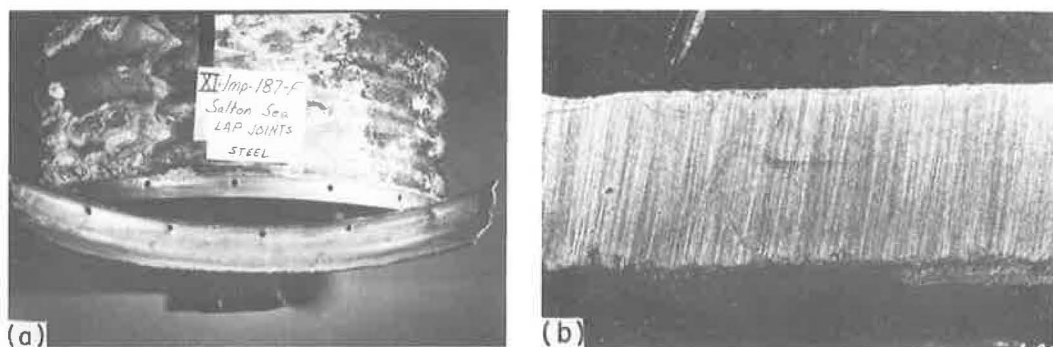


Figure 23. Field test site, XI-Imp-187-F, left of Sta. 498±: (a) appearance of galvanized steel joint after cleaning—dark areas are rust; (b) section through steel (note loss of galvanizing and penetration at localized areas).

### Abrasion Test Results

The details of the results of the comparative field abrasion tests are shown in Figures 1 through 3 and Figures 7 through 11 (also see Tables 3 and 4). Specifically, the culverts located at I-Hum-35-C and IV-SC1-5-C are the only culverts which could be considered to have an abrasive environment. From past experience, the former culvert is considered only an average abrasion culvert, and the latter is known to be highly abrasive.

The rate of metal loss of the aluminum indicates that it will perforate by abrasion in approximately one-tenth the time as a steel culvert (Tables 3 and 4).

At periods of a high yearly flow, both abrasion test culverts carry a bed load of rocks. However, the flow velocity at the test culvert at I-Hum-35-C would range from 10 to 14 fps or about one-half the velocity at the other site. Because of the apparent 2:1 difference in the calculated flow velocities, it would be tempting to assign this velocity difference as the cause of the approximately 30:1 difference in severity of abrasion damage to the two culverts.

Although not a part of this program, an investigation of a culvert condition was made in the mountainous vicinity of Redding. This particular 48-in. diameter galvanized steel culvert was observed to have minor abrasion damage after approximately 7 years of service.



Cobbles of approximately 6-in. diameter were observed lying in the invert at the outlet end of this pipe. The calculated flow velocity in the pipe is in the range of 20 to 25 fps.

The reader should be aware that the results of erosion are exceedingly difficult to explain and formulate objectively to a mathematical certainty. For instance, the severely damaged test pipe located at IV-SCL-5-C may have had a calculated flow velocity in the range of 25 to 30 fps with a bed load of shattered rocks. The minor abrasion damaged culvert near Redding (II-Tri-20-A, Sta. 582+73) has a calculated flow velocity in the range of 20 to 25 fps and has a bed load of rounded boulders. Therefore, it is obvious that even though flow velocities are highly important, the size and shape (rounded or shattered) and hardness of the bed material may be of greater consequence in the subsequent degree of abrasion of a culvert.

For all practical purposes, no commonly used culvert coating or material would offer a maintenance-free service life at the highly abrasive test site, IV-SCL-5-C.

### Corrosion Test Results

The details of the corrosion field test results are given in Tables 2, 3, and 4, and shown in Figures 1 through 6 and 12 through 23. Even though some of the test sites are regarded as being highly corrosive to steel, only three sites had a pH of less than 4.5, and the remaining five culverts were installed in sites with a pH range of 4.5 to 8.3. In effect, one-half of the culverts were subjected to a flow or soil which had a pH that ranged between 6.6 and 8.3. For all seven comparative corrosion tests culverts, the field test data indicate that on the average, the aluminum will be perforated by corrosion in less time than will galvanized steel.

For the five test sites in which the pH of the soil or flow ranged between 4.5 and 8.3, the data again indicated that aluminum would be perforated by corrosion in less time than will galvanized steel.

As shown by the photographs (Figs. 1 through 23), the removed sections of aluminum are not generally attacked by small areas of random pitting, but at large areas of the pipe surface. Therefore, the corrosion is not considered to be the result of a minor and localized imperfection in the protective oxide film on the surface of the aluminum. Instead, the appearance of the large areas of corrosion on the soil contacting surface of the pipe, inside the laps, around the rivet holes, and beneath silt, strongly suggests that the corrosion is the result of a concentration cell. This concentration cell appears to be the result of the soil causing a partial shielding of the metal from oxygen and in one case (XI-Imp-187-F) further complicated by the result of a differential concentration of soil salts in direct contact with the culvert.

With the exception of the culverts carrying the highly acid runoff, the corrosion attack of the aluminum was most severe on the backfill side of the pipes and in the joints.

## LABORATORY TESTS

### Corrosion-Abrasion Test

In an attempt to compare the relative corrosion-abrasion resistance between galvanized steel and aluminum, these metals were separately exposed to solutions of various pH and resistivity. The testing equipment (dubbed the "wash machine") is shown in Figure 24. In each test, four each of the 4 × 8-in. similar metal specimens were clamped so as to rotate with the drum at a speed of approximately 5 fps. These specimens were electrically isolated from direct metallic contact to the drum by means of rubber spacers attached to the ends of the specimen. In addition, electrical isolation was further accomplished by the plexiglass multipurpose observation and access windows which were also used to clamp the samples in place during the test.

Prior to testing, all specimens were degreased with benzene, washed, and scrubbed with soap, and then thoroughly rinsed with Sacramento city tap water.

Some pilot testing of galvanized steel indicated that the corrosion rate of this composite material would change so rapidly with time that each test would probably require more than two weeks. Therefore, to expedite results, the zinc was prestripped from

TABLE 5  
LABORATORY CORROSION-ABRASION TEST DATA

Test No.	Metal	Designated pH	Solution Measurements		Distilled Water (gm)	Ottawa <sup>1</sup> Sand (gm)	Chemicals Used in Test	
			Max. Range of pH	Resistivity (ohm-cm)			Formula	Grams
3	Aluminum	9.0	7.7-9.8	100	4,000	4,000	Na <sub>2</sub> CO <sub>3</sub>	40
4	Aluminum	8.8	8.6-9.6	100	4,000	4,000	NaCl	25
							CaCO <sub>3</sub>	4
5	Aluminum	8.7	8.7-9.5	100	4,000	4,000	NaCl	25
							CaCO <sub>3</sub>	20
6	Aluminum	10.5	10.3-10.7	100	4,000	4,000	NaCl	25
							Na <sub>2</sub> CO <sub>3</sub>	60
7	Aluminum	8.0	7.3-8.2	100	4,000	4,000	NaCl	25
8	Aluminum	3.9	2.2-5.6	100	4,000	4,000	CH <sub>3</sub> COOH	845
							NaCl	25
9	Aluminum	3.6	3.5-3.9	100	4,000	4,000	C <sub>76</sub> H <sub>52</sub> O <sub>46</sub>	32
							NaCl	25
10	Aluminum	6.3	6.2-6.4	100	4,000	4,000	NaOH	1.6
							KH <sub>2</sub> PO <sub>4</sub>	4.9
11	Aluminum	5.0	4.2-6.7	100	4,000	4,000	NaCl	25
							NaOH	7.47
12	Steel + zinc	9.2	7.9-9.8	100	4,000	4,000	K <sub>2</sub> C <sub>8</sub> H <sub>5</sub> O <sub>7</sub> H <sub>2</sub> O	46.04
							NaCl	25
13	Steel + zinc	6.3	6.2-6.4	100	4,000	4,000	HCl	30
							Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub> · 10 H <sub>2</sub> O	40
14	Steel	6.3	6.2-6.5	100	4,000	4,000	NaCl	25
							NaOH	1.6
15	Steel	8.8	8.6-9.3	100	4,000	4,000	KH <sub>2</sub> PO <sub>4</sub>	49
							NaCl	25
16	Steel	7.5	7.0-8.8	100	4,000	4,000	CaCO <sub>3</sub>	20
							NaCl	25
17	Steel	4.5	3.4-4.9	100	4,000	4,000	NaCl	25
							C <sub>76</sub> H <sub>52</sub> O <sub>46</sub>	32
18	Steel	5.2	5.1-5.6	100	4,000	4,000	NaCl	25
							KH <sub>2</sub> PO <sub>4</sub>	60
19	Steel	6.7	5.5-9.9	1,000	4,000	4,000	NaOH	0.5
							NaCl	25
20	Steel	7.5	7.2-7.9	1,000	4,000	4,000	KH <sub>2</sub> PO <sub>4</sub>	5.0
							NaCl	2.2
21	Steel	9.1	8.9-9.6	1,000	4,000	4,000	CaCO <sub>3</sub>	20
							NaCl	2.1
22	Steel	4.4	4.1-6.3	1,000	10,000	4,000	KHC <sub>8</sub> H <sub>4</sub> O <sub>4</sub>	20
23	Aluminum	4.8	4.1-5.5	1,000	10,000	4,000	KHC <sub>8</sub> H <sub>4</sub> O <sub>4</sub>	20
24	Aluminum	9.1	8.8-9.4	1,000	4,000	4,000	CaCO <sub>3</sub>	2.0
							NaCl	2.0
25	Aluminum	7.5	7.2-7.7	1,000	4,000	4,000	NaCl	2.1
26	Steel	7.5	7.2-7.8	5,000	10,000	4,000	NaCl	1.08
27	Steel	9.1	9.0-9.8	5,000	10,000	4,000	CaCO <sub>3</sub>	40
							NaCl	0.5
28	Steel	7.4	7.1-7.4	1,000	10,000	4,000	NaCl	4.4
29	Aluminum	7.5	7.0-7.5	1,000	10,000	4,000	NaCl	4.4
30	Aluminum	7.5	6.8-7.9	5,000	10,000	4,000	NaCl	0.4 to
								1.0
31	Aluminum	9.0	9.0-9.7	5,000	10,000	4,000	NaCl	0.33
							CaCO <sub>3</sub>	40
32	Aluminum	7.5	6.8-8.5	1,000	10,000	4,000	NaCl	4.1

<sup>1</sup>Ottawa sand is: Standard Sand 20-30, ASTM designation C-190.

all galvanized specimens with a solution of hydrochloric acid which was chemically inhibited from attacking the steel. In this manner, the average testing period for each sample was reduced to approximately 8 days.

The details of the chemicals, etc., used in this test are shown in Table 5. The pH of the test solutions varied from the designated values. The designated pH value is that value at which the solution was maintained for the greatest period of time.

TABLE 6  
LABORATORY CORROSION-ABRASION TEST RESULTS OF STEEL

Test No.	pH	Days of Test	Resistivity (ohm-cm)	Years to Perforation—16 Gage			
				100% Weight Loss	Minimum Cross-Section	Abrasion Surface	Corrosion Surface
14	6.3	9.9	100	4.39	0.41	0.41	1.66
15	8.8	9.2	100	0.48	0.07	0.08	0.09
16	7.5	7.5	100	0.21	0.06	0.08	0.12
17	4.5	7.9	100	0.24	0.16	0.27	0.58
18	5.2	10.6	100	1.76	0.11	0.25	0.13
19	6.7	7.8	1,000	1.76	0.24	0.52	0.37
20	7.5	7.7	1,000	0.18	0.09	0.14	0.14
21	9.1	10.1	1,000	0.98	0.11	0.17	0.15
22	4.4	8.0	1,000	0.22	0.38	0.54	0.74
26	7.5	7.8	5,000	3.24	0.20	0.29	0.24
27	9.1	7.8	5,000	1.05	0.44	1.31	1.31
28	7.4	8.6	1,000	0.53	0.10	0.11	0.18

Note: No galvanized steel used in this test. Except for perforation by weight loss, all test results are based upon metallographic analysis of samples. Abrasion surface is the upstream side of the corrugation. Corrosion is downstream side or valley of corrugation.

TABLE 7  
LABORATORY CORROSION-ABRASION TEST RESULTS OF ALUMINUM

Test No.	pH	Days of Test	Resistivity (ohm-cm)	Years to Perforation—16 Gage			
				100% Weight Loss	Minimum Cross-Section	Abrasion Surface	Corrosion Surface
3	9.0	15.6	100	4.22	0.47	0.86	0.47
4	8.8	14.9	100	0.53	0.70	0.81	1.63
5	8.7	6.8	100	3.01	0.56	0.45	0.56
6	10.5	9.1	100	0.12	0.10	0.20	0.12
7	8.0	9.8	100	2.34	0.46	0.46	1.07
8	3.9	3.6	100	0.34	0.09	0.17	0.14
9	3.6	7.3	100	0.75	0.20	0.30	0.34
10	6.3	7.9	100	2.22	0.43	0.52	1.30
11	5.0	7.7	100	0.24	0.23	0.36	0.36
23	4.8	7.8	1,000	1.36	0.23	0.29	1.28
24	9.1	7.8	1,000	1.14	0.43	0.26	1.29
25	7.5	10.0	1,000	2.48	0.41	0.41	0.82
29	7.5	9.9	1,000	1.92	0.36	0.40	1.08
32	7.5	36.2	1,000	3.24	0.91	1.32	1.48
30	7.5	8.3	5,000	1.62	0.34	0.34	0.68
31	9.0	7.6	5,000	0.94	0.19	0.19	0.84

Note: Except for perforation by weight loss, all test results are based upon metallographic analysis of samples. Cladding was penetrated on abrasion surface in all tests. Abrasion surface is the upstream side of the corrugation. Corrosion surface is the downstream side or the valley of the corrugation.

It should be noted when referring to Tables 6 and 8 that initial pilot testing of the galvanized specimens also indicated that within the allotted short testing period, the zinc coating could protect the steel from corrosion where abrasion would be less severe such as on the downstream side of the corrugation. Thus, it is expected the estimated years to corrosion perforation for steel would be greater than those shown in the fore-mentioned tables had the specimens been galvanized.

Test Results—Corrosion.—The details of the corrosion-abrasion tests for each metal are shown in Tables 6, 7, and summarized in Table 8. The extrapolated years to perforation are presented on the basis of four types of measurements:

TABLE 8  
SUMMARY OF LABORATORY CORROSION-ABRASION  
TESTS, 16-GAGE METAL

Metal	Max. Cross-Section Loss	Abrasion Surface	Corrosion Surface	Weight Loss
(a) Averages of Estimated Years to Perforation				
Plain steel	0.20	0.35 <sup>a</sup>	0.48	1.3
Aluminum	0.39	0.46	0.84	1.7
(b) Averages of Estimated Years to Perforation for pH of 6.0 to 8.0 Only				
Plain steel	0.18	0.26 <sup>a</sup>	0.45	1.72
Aluminum	0.40	0.43	0.99	2.12

<sup>a</sup>Generally corrosion pits and not metal loss from simple abrasion.

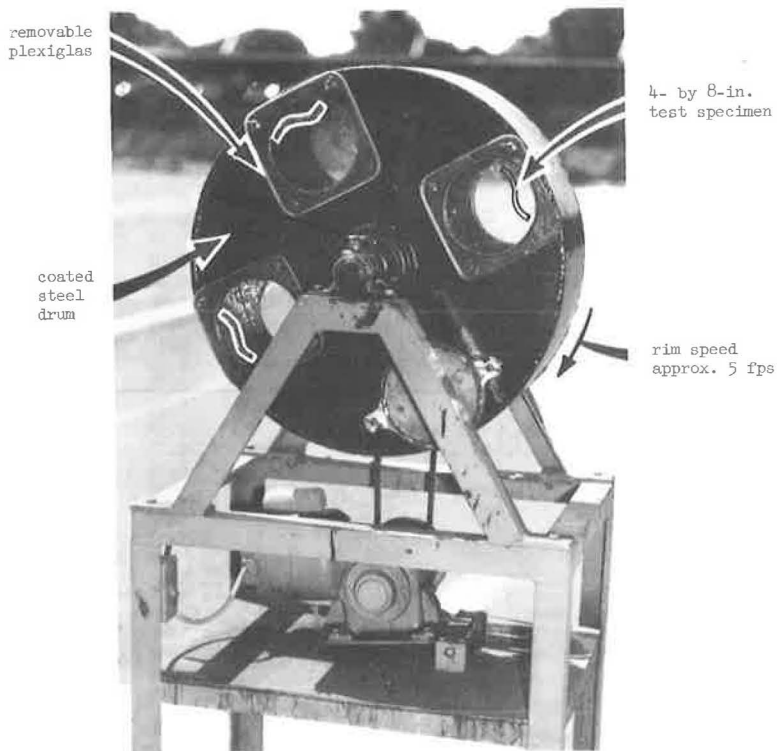


Figure 24. Corrosion-abrasion testing machine (steel drum 24 in. in diameter, 8 in. deep).

1. Maximum cross-section loss;
2. Just the abrasion surface or the upstream side of the corrugation which had initial contact with the sand;

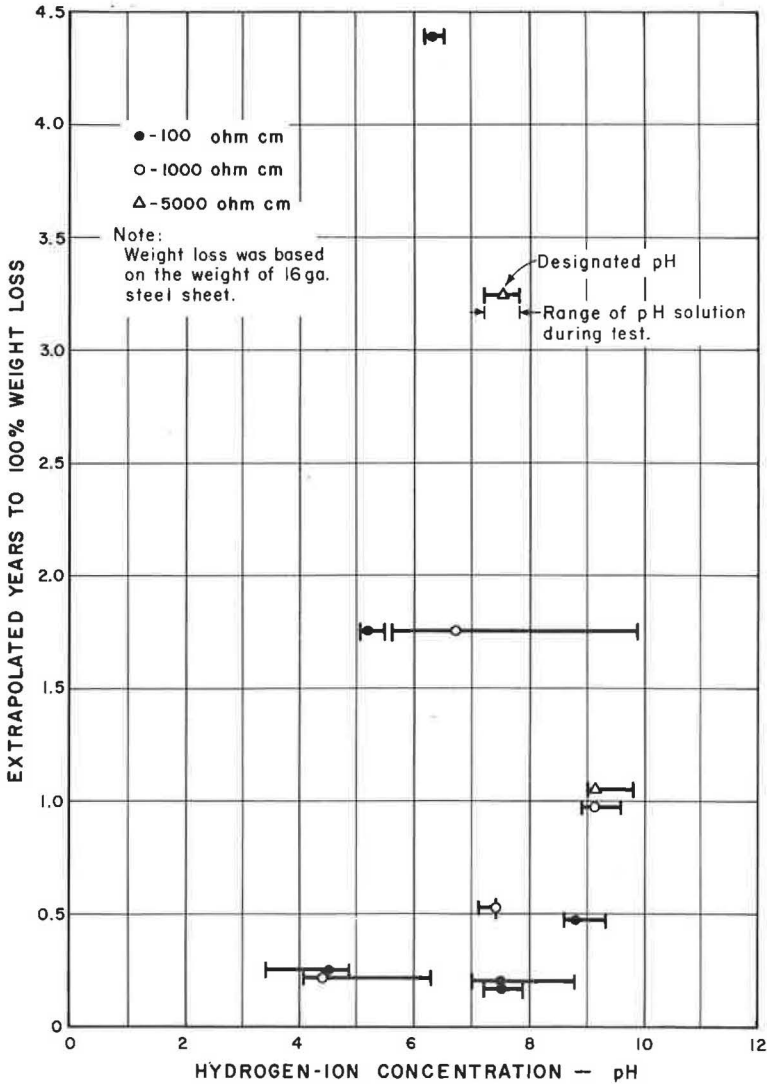


Figure 25. Laboratory corrosion-abrasion test of steel, extrapolated years to 100% weight loss vs pH.

3. The corrosion surface which is any section of the corrugation except the abrasion surface; and

4. By means of 100 percent weight loss of the specimen.

In this particular laboratory corrosion-abrasion test with highly aerated solutions, aluminum generally showed twice the resistance to perforation from corrosion as did plain or bare steel. However, this procedure did not test the effect of concentration cell-type corrosion on aluminum or steel, nor did it show the benefit that might be gained had the steel specimens been galvanized.

Because of the corrosion characteristics of these two metals, it would be expected that aluminum would not be as adversely affected by an aerated solution as would steel. Conversely, in quiescent solutions, the corrosion resistance of aluminum is reduced as was indicated by other tests performed.

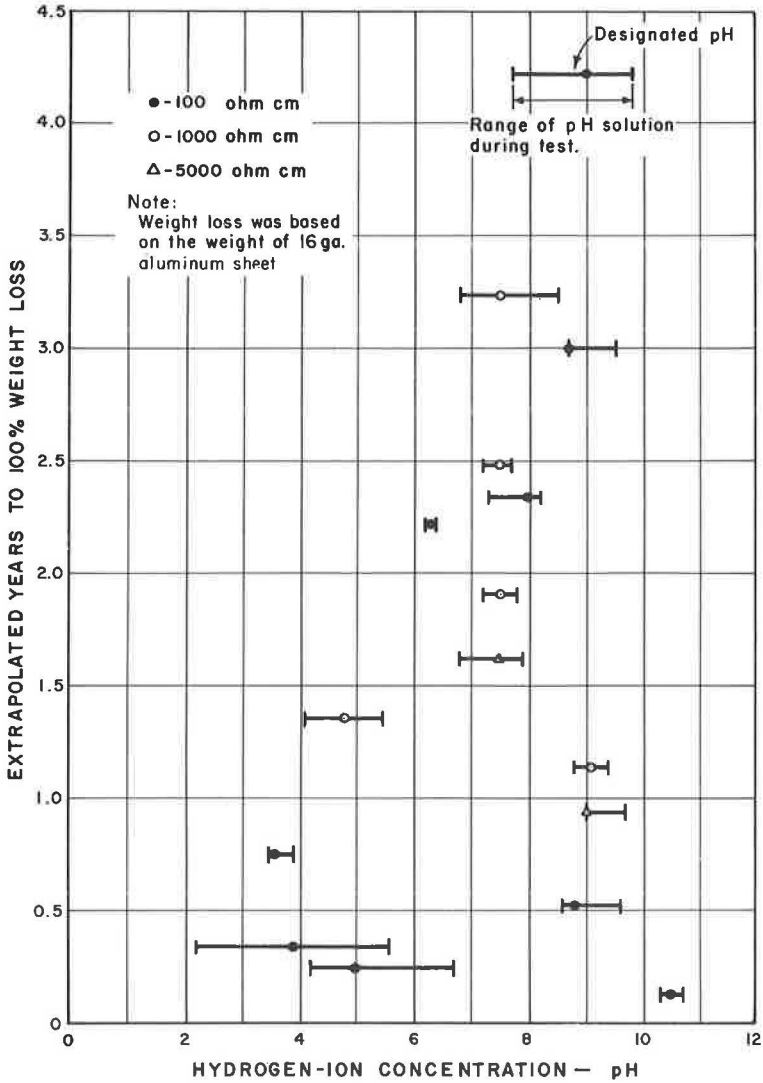


Figure 26. Laboratory corrosion-abrasion test of aluminum, extrapolated years to 100% weight loss vs pH.

Disregarding the resistivity of a solution, the data in Figure 25 indicate that steel could rapidly corrode in aerated solutions where the pH is less than approximately 5.0 and greater than 7.0. However, in the case of steel, it is misleading to infer that steel has its greatest corrosion resistance when it is subjected to an environment with a pH range between 5.0 and 7.0. Further analysis of these data show that for the steel test series, the pH of the solution is an important factor in the corrosion rate only when the pH is less than approximately 7.3. At pH values of less than approximately 7.3, the resistivity and the pH of the solution are the controlling factors. At greater pH values (7.3 or greater), the resistivity is the primary control of the relative corrosion rate of steel.

The data in Figure 26 indicate that aluminum is more resistant to corrosion in the pH range of approximately 5.5 to 8.5. An analysis of the data did not indicate any clear-cut trend in the influence of resistivity on the rate of corrosion. It is suspected



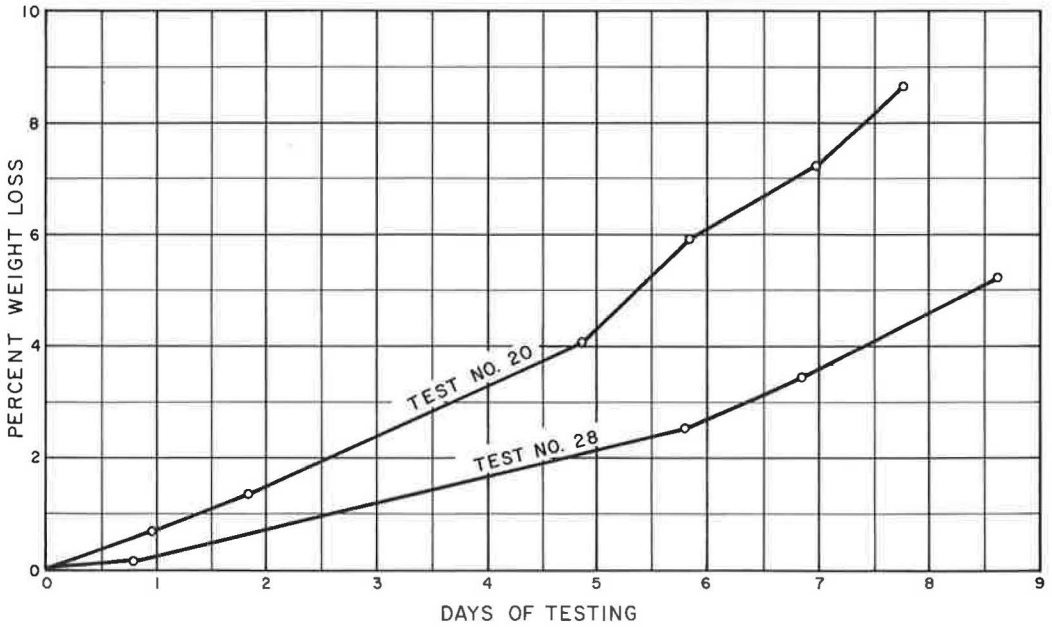


Figure 27. Laboratory corrosion-abrasion test, reproducibility of plain steel.

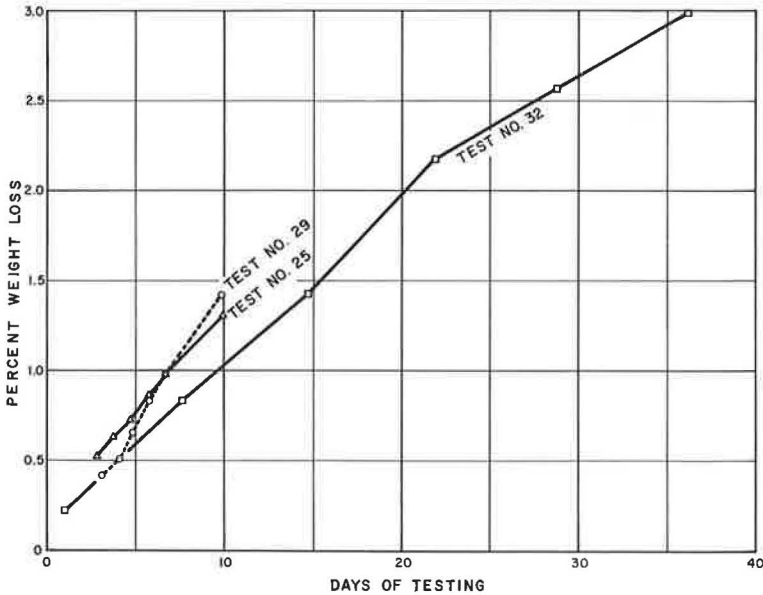


Figure 28. Laboratory corrosion-abrasion test, reproducibility of aluminum.

that the aluminum was more sensitive to the types of chemicals than to the concentrations of the different chemicals used in this test.

Figures 27 and 28 are shown to depict the accuracy in reproducing a single type of test. From these data, it is obvious that the individual test results probably have a test accuracy of  $\pm 20$  percent.

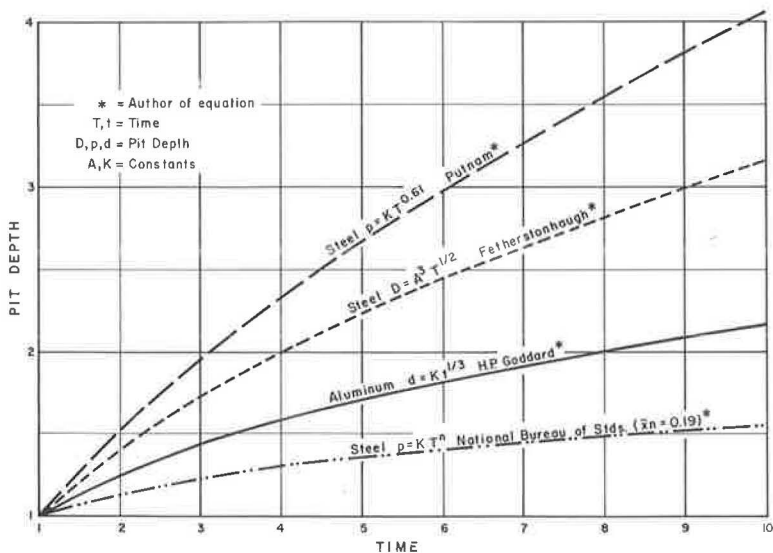


Figure 29. Time vs depth of pitting.

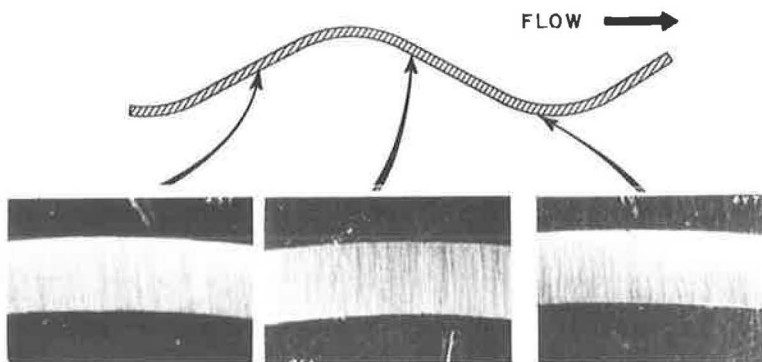


Figure 30. Laboratory corrosion-abrasion test, steel. Cross-sections of plain steel test sample after approximately 8 days of testing. Note minor abrasion loss of metal (left photo) which was caused by Ottawa sand and a specimen velocity of approximately 5 fps. Note lack of corrosion in this test.

All of the reported test data were extrapolated on a straight-line proportional basis to the particular end point; i.e., metal perforation or 100 percent weight loss. Such methods of extrapolation of data are not recommended as being highly accurate but are a means for comparison of test results. An equation which includes a factor of decreasing rate of corrosion with time was not used. Therefore, these data imply an exaggeration of the numerical difference of the corrosion rates which were measured at the end of each test.

Since equations are available which include a factor describing the decrease in the corrosion rate with time, Figure 29 shows that there is a choice of three for steel (24, 25, 26) and one for aluminum (8).

Figure 29 should not be construed to indicate that the corrosion rate of one metal is clearly less than the other. This is because the required constant for each equation may be many-fold greater or less than the other. Therefore, when the constants are included in the equations, the result could be that one metal may perforate in a few days while the other metal may require years to perforate.

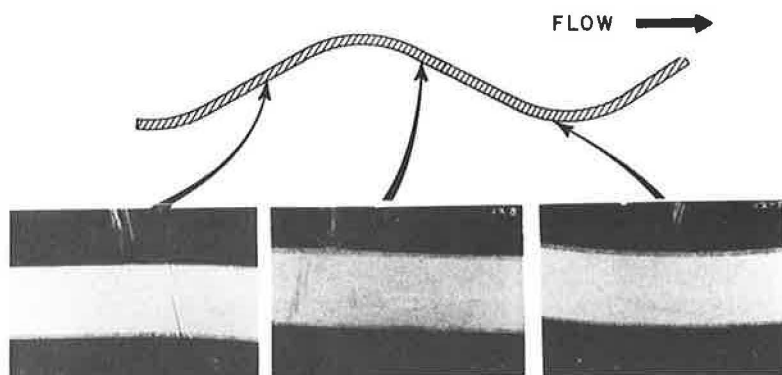


Figure 31. Laboratory corrosion-abrasion test, aluminum. Cross-sections of aluminum test sample after approximately 8 days of testing. Note typical loss of cladding (left photo) which was caused by Ottawa sand and a specimen velocity of approximately 5 fps. Note lack of corrosion in this test.

TABLE 9  
SOLUTIONS USED IN THE CONTINUOUS SUBMERSION TESTS

Test No.	pH	Resistivity (ohm-cm)	Tap Water (gm)	Chemical	Grams of Chemical
1	4.3	1,000	10,000	$\text{KHC}_8\text{H}_4\text{O}_4$	22
2	7.5	1,000	10,000	NaCl	5.2
3	9.0	1,000	10,000	$\text{CaCO}_3$	10
				NaCl	5.0

TABLE 10  
CHEMICAL ANALYSIS OF SACRAMENTO CITY TAP WATER

Total Solids	Hardness	Alk.	Cl	$\text{SO}_4$	Ca	Mg	Na	Fe	N	F
83 to 113	36 to 76	20 to 78	3 to 21	11 to 19	8 to 18	4 to 8	Nil	0.1	Nil	Nil

Resistivity = 8,000 ohm-cm.

pH = 7.2.

Milligrams per liter.

Chemical analysis from California Domestic Water Supplies, Department of Public Health, 1962.

**Test Results—Abrasion.**—Figures 30 and 31 show the results of abrasion on plain steel and aluminum when corrosion was practically absent. In all tests there was no noticeable wear on the abrasion surface of the steel. The abrasion surface is the upstream surface of the corrugation. Generally, the steel pitted on the abrasion as well as on other surfaces of the steel.

**TABLE 11**  
**RESULTS OF CONTINUOUS SUBMERSION TEST<sup>a</sup>**  
**(Estimated Years to Perforation for 16-Gage Metal)**

Metal	Sample	pH	Years
Galvanized steel	1	4.3	Steel was unaffected
	2	4.3	
Aluminum	1	4.3	2.9
	2	4.3	2.9
Galvanized steel	1	7.5	Steel was unaffected
	2	7.5	
Aluminum	1	7.5	2.9
	2	7.5	3.7
Galvanized steel	1	9.0	Steel was unaffected
	2	9.0	
Aluminum	1	9.0	2.9
	2	9.0	3.3

<sup>a</sup>Test solutions had a resistivity of 1,000 ohm-cm and test period was 70 days.

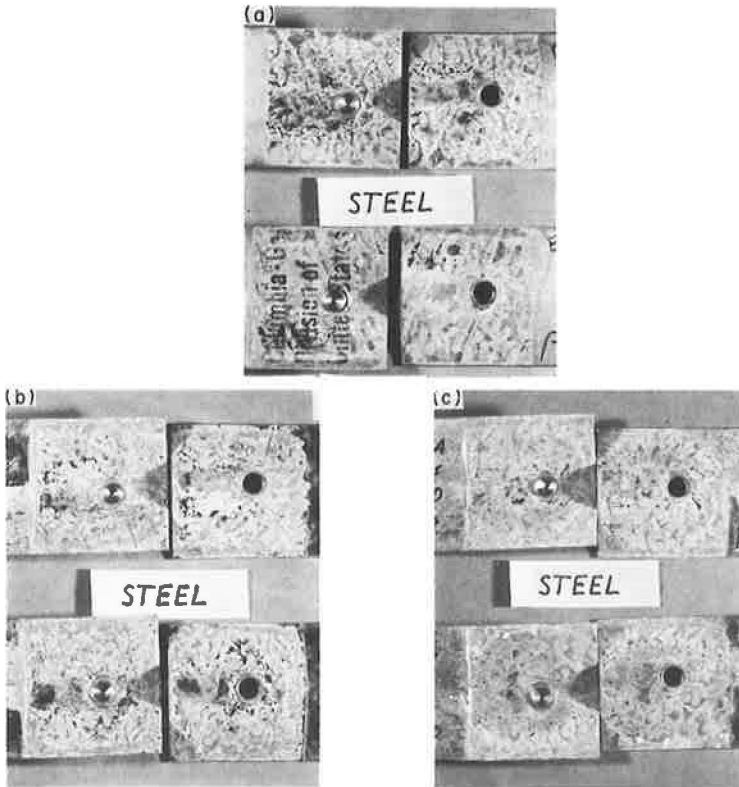


Figure 32. 70-day laboratory test of continuous submersion of galvanized steel: (a) pH = 4.3, resistivity = 1,000 ohm-cm, galvanizing intact, no corrosion of steel; (b) pH = 7.5, resistivity = 1,000 ohm-cm, galvanizing intact, no corrosion of steel; (c) pH = 9.0, resistivity = 1,000 ohm-cm, galvanizing intact, no corrosion of steel.

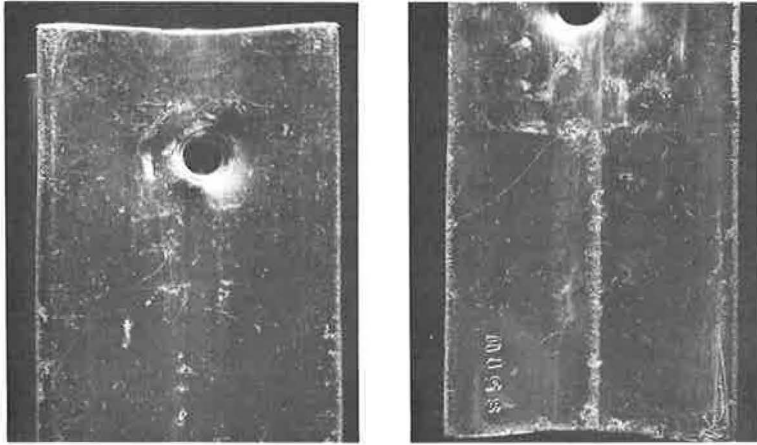


Figure 33. 70-day laboratory test of continuous submersion of aluminum—solution pH = 4.3, resistivity = 1,000 ohm-cm. Note corrosion at edges near rivet hole, role marks and where the two pieces of aluminum overlapped (right photo).

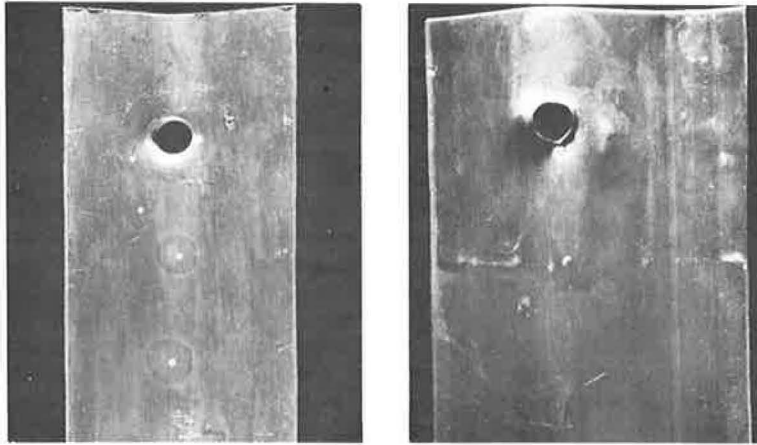


Figure 34. 70-day laboratory test of continuous submersion of aluminum—solution pH = 17.5 resistivity = 1,000 ohm-cm. Note corrosion at edges near rivet hole and where the two pieces of aluminum overlapped (right photo).

The typical loss of the aluminum cladding on the abrasion surface after an average of 8 days of testing is shown in Figure 31. At the conclusion of Test No. 32 (36 days), the face of the sheared leading edge of the aluminum test panels peeled back for a distance of approximately  $\frac{1}{16}$  in. as a result of the impact of the specimen with the Ottawa sand at a velocity of approximately 5 fps.

After the mounting and polishing of all metallographic specimens, the steel was etched for 30 seconds with a solution of nitric acid ( $\text{HNO}_3$ ) and amyl alcohol ( $\text{C}_5\text{H}_{11}\text{OH}$ ). The aluminum specimens were etched for approximately 10 minutes with concentrated sodium hydroxide ( $\text{NaOH}$ ) solution.

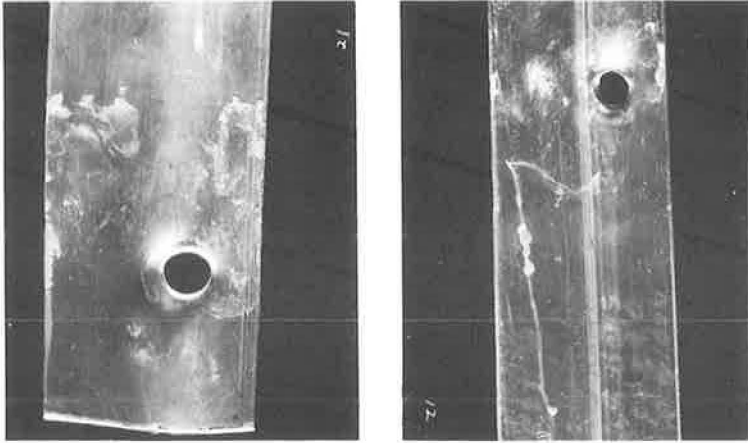


Figure 35. 70-day laboratory test of continuous submersion of aluminum—solution pH = 9.0, resistivity = 1,000 ohm-cm. Note corrosion at edges near rivet holes where the two pieces of aluminum overlapped (left photo), and corrosion in the long scratch (right photo).

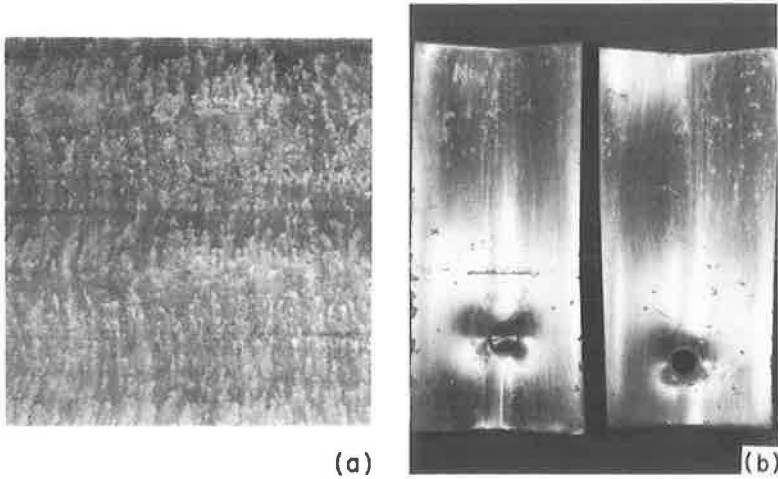


Figure 36. Laboratory test in fog room: (a) approximately 1 yr of exposure of galvanized steel and no corrosion of steel; (b) 117 days of exposure of aluminum (note corrosion at edges near rivet holes and at the line where the two pieces of aluminum overlapped).

### Continuous Submersion

The results of this laboratory test are given in detail in Tables 9, 10 and 11, and shown in Figures 32 through 35.

The corrosion rate of the metal in this test was determined by micrometer measurements rather than by metallographic analysis. Basically this test consisted of submerging duplicate specimens of either riveted aluminum or riveted galvanized steel metal in a plastic container containing the described test solutions. There was no intermixing of galvanized steel or aluminum in any container. Both metals were culvert stock and were riveted by a commercial culvert fabricator. The culvert sheet metal and rivet materials are those which are commercially specified as culvert stock.



The pH and resistivity of the solutions were maintained to the proper level by periodic additions of the chemical additives. After the first 30 days of test, all of the solutions were replaced with a fresh test solution. There was no stirring or attempt to aerate the test solution.

An effort was made to have the test specimens in a quiescent water which would be similar to that found in bogs or marsh areas. Also, the resistivity was kept at a constant value of 1,000 ohm-cm. On the basis of steel corrosion, a solution resistivity value of 1,000 ohm-cm is generally not considered as being highly corrosive, but it is also not disregarded as being non-corrosive.

In all cases the zinc on the galvanized steel is intact and there is no corrosion of the underlying steel after 70 days of testing (Fig. 32).

In all cases, the aluminum was attacked at the metal laps, edges of the plate, near the rivet hole, and sometimes at scratches and also sheet rolling marks due to the corrugating process (Figs. 33, 34, and 35).

The overall corrosion of the aluminum was less in the solution of pH 7.5 than in the 4.3 and 9.0.

The results of this test indicate that among other variables, a concentration cell type of corrosion attack is a common denominator in the causes of corrosion of aluminum in quiescent solution. Also, aluminum can aggressively corrode in solution of pH 4.3 and 9.0.

#### Laboratory Test in Fog Room

The fog room used for this test is a concrete curing room which is maintained at approximately 73.4 F and 100 percent relative humidity by means of temperature controls and water fogging equipment. The fog room can be construed as a misnomer as droplets of water are continuously being dispersed throughout the chamber and seem more like rainfall.

The pH of the atomized water is 8.2 and the resistivity is 6,300 ohm-cm.

Figure 36 shows the appearance of galvanized steel after approximately one year of testing and the zinc is intact. Also shown is the typical result of 117 days and also 94 days of exposure of the riveted aluminum samples to the fog environment. In this case, the aluminum has been attacked near the rivet hole, cut edges where the plates were in contact, and also at the line where the two pieces overlapped. Apparently this corrosion attack is the result of a concentration cell.

By means of a micrometer, the depth of corrosion was determined and extrapolated on a straight-line proportional basis to a calculated time to perforation. The results of these measurements are given in Table 12.

TABLE 12  
RESULTS OF FOG ROOM TEST

Metal	Sample	Days of Test	Est. Years to Perforation for 16-Gage Metal
Galvanized steel	1	+365	Steel was unaffected <sup>a</sup>
Aluminum	1	94	3.2
	2	94	3.2
	3	94	3.2

<sup>a</sup>Sample was from previous testing.

## OTHER FIELD TESTS OF ALUMINUM CULVERTS

An excellent and comprehensive study of the field performance of aluminum culverts was reported by Lowe and Koepf (2). Although the authors did not report any rates of corrosion, they did include their observations on the appearance of the culverts. The reported condition of the pipes visually ranged from an unaffected condition to the extreme where the pipe wall was perforated. In many cases, the resistivity of the in-place soil or flow and also the pH was tabulated.

As was indicated (2), it is obvious that the majority of the reported installations had no problems involving corrosion because approximately 60 percent of their data indicate that the visual condition of the culvert was unaffected or the metal was stained. It is assumed that stained aluminum is not evidence of corrosion and indicates a relatively unaffected condition (3).

The authors (2) did not mathematically present their findings regarding the influence of soil pH or resistivity on the corrosion rate of aluminum. However, there appear to be some general mathematical relationships which could be of value.

For instance in Table 13, the reported condition of the culverts has been listed in an assumed rank of corrosion severity that varies from unaffected to perforated. In rank-

TABLE 13  
NATIONWIDE FIELD TEST RESULTS OF ALUMINUM CULVERTS (2)

Reported Culvert Condition	Average Acid pH	Average Alkaline pH	Mean <sup>1</sup> Resistivity (ohm-cm)	Estimated <sup>2</sup> Rate of Corrosion	Average Acid pH	Average Alkaline pH	Mean <sup>1</sup> Resistivity (ohm-cm)
Unaffected	6.2	7.9	2,100	Nil	6.0	7.8	3,100
Staining	5.9	7.7	3,300				
Etching	5.5	8.0	600	Light to moderate	5.6	7.8	2,000
Pitting	5.7	7.7	4,700				
Cladding removed	2.8	—	150	Severe	3.0	—	250
Perforated	3.1	—	300				

<sup>1</sup>Geometric Mean.

<sup>2</sup>This estimate is speculation. The estimated rate of corrosion is entirely based upon the terminology that was used in the report for describing the visual appearance of the culverts. No rates of corrosion were reported.

Maximum years of service of reported culverts were 3.5.

TABLE 14  
CULVERT SITE TEST RESULTS BASED ON INSPECTION OF NOVEMBER 23, 1964<sup>1</sup>  
(Addendum; see also Table 3)

Location	Metal	Time in Test (yr)	pH	Minimum Resistivity (ohm-cm)	Estimated Years to Perforation Based on Metal Loss at: <sup>2</sup>			
					Minimum Cross-Section Loss	Upstream Surface of Corrugation		Downstream Surface or Valley of Corrugation (corrosion surface)
						Abrasion	Pitting	
I-Hum-35-C	Steel	2.0	6.6	2,500	6.1	41	6.4	18
	Aluminum				3.6	3.6	—	6.9
II-Sha-3-B <sup>3</sup>	Steel	1.5	3.3	650	2.3	—	—	2.3
	Aluminum				0.33	—	—	0.33
III-But-21-B <sup>4</sup>	Steel	1.7	2.7	165	0.56	—	—	0.56
	Aluminum				0.56	—	—	0.56
IV-SCr-5-A <sup>3</sup>	Steel	0.83	3.7	330	0.83	No test culvert		0.83
	Aluminum				—	—	—	
IV-SCl-5-C <sup>3</sup>	Steel	1.4	7.7	3,500	1.3	1.3	—	—
	Aluminum				0.14	0.14	—	—
X-SJ-53-C <sup>5</sup>	Steel	2.4	4.5 to 6.3	620 to 973	49	—	—	49
	Aluminum				12	—	—	12
XI-Imp-187-F <sup>5</sup>	Steel	3.2	7.5	6.5	24	—	—	24
	Aluminum				34	—	—	37
XI-SD-2-Nat. Cty	Steel	3.2	8.3	39	8.0	—	—	8.4
	Aluminum				8.8	—	—	11

<sup>1</sup>All test results are based upon metallographic analysis of culvert samples.

<sup>2</sup>Estimated years to perforation for all samples were calculated on the basis of a 16-gage metal thickness.

<sup>3</sup>Aluminum only perforated within test time.

<sup>4</sup>Aluminum and galvanized steel perforated within test time.

<sup>5</sup>Corrosion loss measured on the soil side of the pipes.

TABLE 15  
COMPARATIVE FIELD TEST SITES BASED  
ON INSPECTION OF NOVEMBER 23, 1964  
(Addendum; see also Table 4)

Metal	Max. Cross- Section Loss	Abrasion	Corrosion
(a) All Seven Comparative Field Test Sites			
Galvanized steel	13	21	17
Aluminum	8.5	1.9	11
(b) Estimated <sup>1</sup> for Five Test Sites with pH Between 4.5 and 8.3			
Galvanized steel	18	21	25
Aluminum	12	1.9	17

<sup>1</sup>Test site with pH of 4.5 has a pH range of 4.5 to 6.3.

ing the relative condition of the culverts, the more severe condition noted was arbitrarily assigned to represent the rank of the culvert. For instance, if the culvert was reported as "mottled stain. No attack. Random pitting of clad in invert," this culvert was assigned to the "pitting" classification in Table 13. For each of these culvert conditions, the acidic pH's of less than 7.0 were arithmetically averaged. The same was true of pH's that were greater than 7.0. In addition, the least resistivity of the in-place soil or water were averaged on the basis of the computed geometric mean (27) which is

$$\text{Geometric mean} = \sqrt[n]{X_1 X_2 \dots X_n} \quad (1)$$

where  $n$  = number of observations, and  $X$  = observed value.

The geometric mean of the resistivity values was used because of the extremes in values that are normally found in resistivity measurements.

Although the validity of this analysis of data in Table 13 has not been verified, it is interesting to note that there seems to be a reasonably implied correlation of the data. This is implied by the observation that the severity of corrosion increases with decreasing pH and resistivity.

In the subject report (2), it was stated that extensive experience has indicated that if aluminum is not attacked by corrosion after periods of a year or more, then the aluminum metal may be considered to be relatively inert to the environment. Conversely, it should also be true that if significant corrosion of the aluminum occurs at an early exposure period, then aluminum should sustain some rate of corrosion until disintegration.

From Table 13, it appears that the anticipated performance of aluminum could be satisfactory when the pH ranges between 6.0 and 7.8. It is highly probable that when the pH of the environment exceeds these values, the aluminum could corrode at a rate that would vary from minor to severe.

The resistivity measurements were determined for the most part on an in-place soil. Therefore, they may not be accurately reproducible owing to the fact that these values are highly dependent upon the seasonally variable moisture content of the soil.

Normally, soil resistivity measurements used in culvert corrosion technology are based on the minimum value. The minimum resistivity is normally less than the in-place soil resistivity. Therefore, care should be exercised when directly comparing the in-place field values to the minimum resistivity of a soil (10).

#### REMARKS

There are few published data concerning the service life of aluminum when used underground or as a culvert. The longest reported service life for this material as a culvert is 3.5 years (2).

For underground applications of aluminum pipe, reports of up to 15 years have been published (22). As reported, the 388 total miles of aluminum pipeline with an estimated average of seven years of service, only 8 to 9 miles have had to be replaced because of corrosion. None of the failed pipe was coated or received cathodic protection. Of this total reported pipe length of 388 miles, approximately 25 percent of its total length is protectively coated. In addition, approximately 30 percent of the total length of the pipelines received cathodic protection. Cathodic protection was not necessarily applied to coated pipe. The reported wall thickness of these pipelines varied from an equivalent

corrugated metal pipe gage of approximately 16 to a reported maximum which would be approximately equivalent to 8-gage thickness. Thin-gage pipe wall thickness was in the minority.

The review of the literature shows that some aluminum facilities have corroded when placed underground or as a carrier of water. Except for broad generalities, specific criteria for predicting the service life of aluminum as a culvert are not available.

Past experience with the use of galvanized steel culverts without a means for estimating service life, resulted in 63 percent of all of the culverts (7,000) in just one of the eleven California highways districts needing replacement or repair within 30 years of service (23). From this past experience, it is obvious that caution has to be exercised before a material should be allowed to be used randomly in large quantities on highway projects.

Because of the concentration-cell type of corrosion which has been observed in the laboratory and on the backfill side of the culverts in the field test sites, no aluminum cross-drains should be placed in critical locations without being bituminously or otherwise protectively coated.

[Tables 14 and 15 are addenda to original paper.]

#### ACKNOWLEDGMENTS

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The authors wish to express their appreciation to J. L. Beaton, Materials and Research Engineer, for his advice and direction during this study; also to the numerous personnel of the California Division of Highways and those of the Materials and Research Department who extended their aid and cooperation during this study.

#### REFERENCES

1. Pryor, M. J. The Corrosion of Wrought Aluminum Alloys. Richland, Washington; A lecture in March 1954 Educational Program of the Columbia Basin Chapt. of the ASM, and a publication of Kaiser Aluminum and Chemical Corp., Dept. of Met. Res., March 1955.
2. Lowe, T. A., and Koepf, A. H. Corrosion Performance of Aluminum Culvert. Highway Research Record No. 56, pp. 98-115, 1964.
3. Sawyer, D. W., and Brown, R. H. Resistance of Aluminum Alloys to Fresh Waters. Corrosion, Vol. 3, No. 9, p. 443, 1947.
4. Haygood, A. J., and Minford, J. D. Aluminum Cooling Towers and Their Treatment. Corrosion, Vol. 15, No. 1, p. 36, Jan. 1959.
5. Deltombe, E., and Pourbaix, M. The Electrochemical Behavior of Aluminum. Corrosion, Vol. 14, No. 11, p. 16, Nov. 1958.
6. Shatalov, A. Y. Effet de pH sur le Comportement Electrochimique des Metaux et Leur Resistance a la Corrosion. Nauk, U.S.S.R., Doklady Akad, Vol. 86, p. 775, 1952.
7. Lorking, L. F., and Mayne, J. E. O. The Corrosion of Aluminum. Jour. Appl. Chem., Vol 11, p. 170, May 1961.
8. Godard, H. P. The Corrosion Behavior of Aluminum in Natural Waters. Canadian J. Chem. Eng., p. 167, Oct. 1960.
9. McKee, A. B., and Brown, R. H. Resistance of Aluminum to Corrosion in Solutions Containing Various Anions and Cations. Corrosion, Vol. 3, No. 12, p. 595, Dec. 1947.
10. Beaton, J. L., and Stratfull, R. F. Field Test for Estimating Service Life of Corrugated Metal Pipe Culverts. Highway Research Board Proc., Vol. 41, pp. 255-272, 1962.
11. Stratfull, R. F. Field Method of Detecting Corrosive Soil Conditions. Univ. of Calif., L.A., Proc. 15th Calif. Street and Highway Conference, I.T.T.E., p. 158, 1963.

12. Stratfull, R. F. A New Test for Estimating Soil Corrosivity Based on Investigation of Metal Highway Culverts. *Corrosion*, Vol. 17, No. 10, p. 115, Oct. 1961.
13. Stratfull, R. F. Highway Corrosion Problems. *Materials Protection*, Vol. 2, No. 9, p. 8, Sept. 1963.
14. Whiting, J. F., and Wright, T. E. Cathodic Protection for an Uncoated Aluminum Pipeline. *Corrosion*, Vol. 17, No. 8, p. 9, Aug. 1961.
15. U. S. Dept. of Commerce, Office of Technical Services. Corrosion Prevention, Part M. of Maintenance and Operation of Public Works and Public Utilities. NAVDOCKS, TP-Pw-30.
16. H. H. Uhlig (ed.). *Corrosion Handbook*. New York, John Wiley and Sons, 1948.
17. Verink, E. D., Reid, K. K., and Diggins, E. R. Current Output of Light Metal Galvanic Anodes as a Function of Soil Resistivity. Paper published in *Cathodic Protection*, by the Nat. Assoc. of Corrosion Engineers, 1949.
18. *Betz Handbook of Industrial Water Conditioning*. Philadelphia, Penn., W. H. and L. D. Betz, 1953.
19. Pourbaix, M. Corrosion, Passivity and Passivation from the Thermodynamic Point of View. *Corrosion*, Vol. 5, No. 4, p. 121, April 1949.
20. Evans, U. R. *The Corrosion and Oxidation of Metals*. New York, St. Martins Press Inc., 1960.
21. Whiting, J. F., and Godard, H. P. The Corrosion Behavior of Aluminum in the Construction Industry. *Canada, The Eng. Jour.*, June 1958.
22. Aluminum Pipeline Case History Data. NACE, Tech. Unit. Comm. T-2M and Task Group T-2M-1, *Materials Protection*, Vol. 2, No. 10, p. 101, Oct. 1963.
23. Beaton, J. L., and Stratfull, R. F. Corrosion of Corrugated Metal Culverts in California. *Highway Research Board Bull.* 223, pp. 1-13, 1959.
24. Putnam, J. F. Soil Corrosion. *Proc. Am. Petroleum Inst.* (IV) 16, 66, 1935.
25. Fetherstonhaugh, E. P. Discussion of Underground Corrosion. *Proc. Am. Soc. Civil Engr.* Vol. 101, p. 828, 1936.
26. Logan, K. H., Ewing, S. P., and Denison, I. A. Soil Corrosion Testing. Philadelphia, Penn. Symposium on Corr. Test Procedures, ASTM, 1937.
27. ASTM Manual on Quality Control of Materials. ASTM, Spec. Tech. Publ. 15-C, Jan. 1951.

### *Discussion*

HUGH P. GODARD, Aluminium Laboratories Limited, Kingston, Ontario, Canada.— On the basis of an accelerated investigation, Messrs. Nordlin and Stratfull concluded that, under favorable conditions, aluminum culverts may have a service life of up to 25 years. They decided that to obtain this life, certain criteria for pH, water and soil resistivity must be adhered to. These authors realized the uncertainty of their conclusions, since they recommended periodic examination of existing culverts to confirm or modify their views.

By contrast, I will endeavor to support the view that aluminum culverts will last far in excess of 25 years in the great majority of waters and soils, even without paint or other protection. I suggest also that the criteria selected by Nordlin and Stratfull are not applicable or necessary for predicting the service life of aluminum culverts.

### Introduction

In any problem involving the possible corrosion of a metal, it is necessary first to select the criterion by which the extent of corrosion should be judged. This is important, since although too mild a criterion may lead to premature failure, too severe a criterion will lead to an unreasonably expensive structure. In the case of metal culverts, it is suggested that the sole criterion of corrosion is the continued ability of the culvert to support the overburden and normal live loads for which it was designed.

In natural waters and soils, most aluminum alloys, and certainly all of those which would be considered for culvert construction, do not suffer uniform or general corrosion. That is to say they do not waste away by general thinning. If corrosion attack does take place, it is localized, and usually in the form of pitting, in a random pattern over the surface of the metal. Further the pits are of small diameter—usually less than  $\frac{1}{8}$  in. The effect of a pit on the mechanical strength of a sheet is in proportion to the cross-sectional area of metal removed, which is negligibly small compared to the total cross-section. Accordingly, it can be safely predicted that the pitting of an aluminum culvert will have no appreciable influence on the load-bearing capacity of the culvert unless the pits become so numerous and so large that an appreciable cross-section of the metal is consumed—a very improbable condition as the available evidence will demonstrate.

Most of the literature on the use of aluminum in water and soil pertains to pipelines. For this use, the primary criterion of corrosion is perforation, since even the first hole causes a loss of the fluid conveyed, and must be repaired promptly and at some expense. As just pointed out, this is not the case with culverts. In reviewing the literature, the authors failed to appreciate this distinction, and as a result have included criteria such as water composition, water resistivity, and soil resistivity. These give no information on the loss of strength due to pitting, although they have some value in predicting the tendency to pitting and the rate of penetration.

Water composition (which determines water resistivity) affects the incidence and rate of pitting of aluminum and is important when considering pipelines, tanks and water handling equipment, but is of little consequence in the case of culverts for which small perforations would be unimportant.

Soil resistivity also affects the incidence and rate of pitting. In addition, it gives information on soil battery effects which occur in the case of pipelines which traverse several soil types. By contrast, metal culverts are normally relatively short, and buried in one type of soil. This further reduces the value of soil resistivity readings in culvert considerations.

The influence of pH on the corrosion of aluminum alloys is dependent on the specific ions which cause the pH, and hence, pH by itself, is not a reliable criterion in judging the corrosivity of an environment to aluminum. For example, aluminum is fully resistant to concentrated nitric acid at pH 1, to acetic acid at pH 3, and to ammonium hydroxide at pH 13. Even in concentrated sodium carbonate solution at pH 11, after an initial period of activity, a protective surface film forms on aluminum which then becomes highly resistant. In studies of aluminum corrosion, pH has not been found to be a significant variable in either waters or soils.

The authors described the corrosion on 8 aluminum culvert installations in California. Concern was expressed in that patches of aluminum surface were corroded, as distinct from point pitting. The authors apparently did not realize that this is the normal behavior of an Alclad aluminum surface in soil. An unclad product would have shown only pin-point pitting attack. The corroding area was protecting the core alloy exposed by the pits. Experience on the rate of consumption of cladding in seawater suggests that the rate of cladding consumption drops sharply with time, and that a linear projection of several years data is unduly pessimistic.

Unfortunately, the data given for the California culverts in Tables 3 and 4 are not presented in a form that can be appreciated. However, it would appear that the loss of cross-section of aluminum culverts due to corrosion was appreciably less than that for galvanized steel. The method of extrapolating to obtain years to perforation was not given, but in my experience this cannot be calculated from early corrosion data on a clad aluminum product, since the rate of consumption of cladding is not known, the minimum area of cladding that must be removed to permit pitting into the exposed core metal is not known, nor is the rate of penetration of the exposed core metal.

The laboratory erosion and corrosion tests described are of very dubious value in predicting the field service life of aluminum culvert. It is suggested that examination of typical installations cited by Lowe and Koepf (28) would be far more rewarding.

### Corrosion of Aluminum by Surface Waters

The corrosion of aluminum by natural surface waters has been described by Sawyer and Mears (29), Godard (30) and Sverepa (31). There is no general thinning of the metal. If corrosion does occur it takes the form of small diameter pits. The rate of perforation decreases with time, according to a cube root curve (30). Seligman and Williams (32), Porter and Hadden (33), Davies (34), and others have made laboratory studies on the influence of water composition on the pitting of aluminum in water.

However, the pitting action of natural water on aluminum is of limited importance in culvert considerations in view of the small influence of the pits on load bearing strength.

### Corrosion of Aluminum by Soils

There is rather less information on the corrosion of aluminum by soils, but there is sufficient to draw some general conclusions that can be applied to culverts.

Logan (35) and later Romanoff (36) reported corrosion data for 2- × 6-in. sheet coupons of three aluminum alloys in five soils after 10 years. The maximum pit depths are given in Table 16, along with the loss of weight of the 2- × 6-in. specimens, expressed as a percentage loss of the original weight (based on 0.062 inch sheet).

TABLE 16  
NATIONAL BUREAU OF STANDARDS 10-YEAR TEST—ALUMINUM  
BURIED IN FIVE SOILS

Soil No.	Alloy 1100		Alloy 3003	
	Max. Pit Depth (mils)	Wt. Loss (% of original)	Max. Pit Depth (mils)	Wt. Loss (% of original)
13	21	1.2	45+	5.4
29	62+	100	62+	13.8 <sup>a</sup>
42	62+	5.0	14	2.8
43	6	2.6	13	3.2
45	46+	6.8	20	4.6

<sup>a</sup>Second sample destroyed.

TABLE 17  
BRITISH IRON AND STEEL RESEARCH ASSOCIATION—ALUMINUM  
BURIED IN FIVE SOILS<sup>a</sup>

Location	Max. Pit Depth (mils)		Wt. Loss (% of original)	
	Sheet	Pipe	Sheet	Pipe
Benfleet	66	41	1.0	1.6
Pitsea	39	33	0.2	0.2
Rothamstead	0	0	0.1	0.2
Gotham	86	30	0.1	0.2
Corby <sup>b</sup>	125+	—	6.4	—

<sup>a</sup>1100 Alloy: 10- × 15- 0.125-in. sheet; 1-in. diam., 15 in. long, 0.062-in. wall pipe.

<sup>b</sup>Cinder embankment.



TABLE 18  
BRITISH NON-FERROUS METALS RESEARCH ASSOCIATION  
TEN-YEAR TEST—ALUMINUM BURIED IN SIX SOILS<sup>a</sup>

Location	Alloy	Max. Pit Depth (mils)	Wt. Loss (% of original)
Benfleet	1100	43	4.3
	2014 Alclad	20	6.0
Pitsea	1100	32	1.9
	3003	0	1.2
	5154	0	1.2
	2014 Alclad	24	1.9
Corby	1100	122	64.9
	2014 Alclad	187+	90.8
Edinburgh	1100	87	3.4
	3003	24	12.5
	5154	49	8.2
	2014 Alclad	67	3.5
Woburn	1100	0	2.4
Wye	1100	47	0.9

<sup>a</sup>4- x 8- x 0.187-in. sheet specimens.

TABLE 19  
ALCOA 7- TO 8-YR TEST IN ONE LOCATION  
(New Kensington, Pa.)

Alloy	Maximum Pit Depth (mils)		
	2 Yr	4 Yr	7 to 8 Yr
3003	30	58	50
6061-T6	35	73	78
6063-T5	64	98	80
6063-T5 Alclad	5	6	6 <sup>a</sup>

<sup>a</sup>Although almost all of the attack was confined to the clad layer, 3 or 4 small diameter pits did occur to a maximum depth of 73 mils where areas of cladding were eaten away.

While at first sight the destruction of 3 of 4 aluminum samples in soil 29 might be regarded as serious, it should be realized that this was the most corrosive of 47 soils tested (to steel) and is thus hardly an average American soil.

The sheet specimens were too thin to determine maximum pit depths for both alloys in 3 of the other 4 soils, but conversion of the weight losses due to pitting to percent loss of the original specimen weight indicates that, except for soil 29, less than 7 percent of the metal was corroded in 10 years. If this is applied to culverts, which are exposed to soil on only one side, the figure is then 3.5 percent in 10 years.

TABLE 20  
SOILS INCLUDED IN ALCAN TESTS

No.	Location	Soil Type	Resistivity (ohm-cm)
1	Arvida, Que.	Stiff clay	-
2	Kingston, Ont.	Clay-silt	2,000
3	Toronto, Ont.	Sandy	-
4	Shawinigan, Que.	Sandy	-
5	Wetaskiwin, Alta.	Solodized solonetz	1,700
6	Wetaskiwin, Alta.	Angus Ridge loam	1,800
7	Wetaskiwin, Alta.	Solonetz drag	1,750
8	Guelph, Ont.	Rocky clay	165,000
9	Hespeler, Ont.	Sandy loam	210,000
10	Brampton, Ont.	Clay loam	185,000
11	Fredericton, N.B.	Sandy and clay loam	165,000
12	Aulac Station, N.B.	Salt marsh	600

TABLE 21  
 FIRST ALCAN 5-YR TEST—ALUMINUM BURIED IN FOUR SOILS  
 (1948-1953)

Soil No.	Alloy											
	1100		3003		3003 Alclad		5052		6063-T5		6061-T6	
	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)
1	29	0.2	31	0.1	3	0.4	3	0.1	42	0.3	32	0.5
2	27	0.4	22	0.2	4	0.2	4	0.2	31	0.4	20	1.0
3	33	0.1	24	0.1	1	0.1	1	0.1	32	0.1	64+	0.6
4	2	0.5	2	0.4	1	0.5	1	0.4	2	0.4	36	0.7

TABLE 22  
 SECOND ALCAN 5-YR TEST—ALUMINUM BURIED IN EIGHT SOILS  
 (1958-1963)

Soil No.	Alloy									
	3003		3003 Alclad		5083 Type		6061-T6		6061 Alclad	
	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)	Max. Pit Depth (mils)	Wt. Loss (% of orig.)
5	0	0.2	0	0.1	5	0.1	22	0.1	0	0.3
6	35	0.7	2	0.6	0	1.0	25	0.7	0	1.0
7	7	0.1	5	0.2	5	0.1	10	0.1	0	0.2
8	15	0.2	0	0.1	16	0.1	64+	0.1	12	0.4
9	15	0.1	0	0.1	6	0.1	11	0.1	0	0.1
10	0	0.1	0	0.1	0	0.1	18	0.1	19	0.2
11	24	0.2	0	0.2	43	0.2	64+	0.3	50+	0.3
12	64+	5.1	64+	20.3	64+	6.4	64+	12.2	50+	7.7

TABLE 23  
BURIAL PLOT VALUES

Site No.	Resistivity (ohm-cm)	
	Well Drained	Poorly Drained
5	1,700	600
8	165,000	14,000
11	165,000	20,000

Gilbert and Porter (37) reported weight losses and pit depths for 1100 aluminum alloy tubing and sheet buried five years in five soils in Great Britain (Table 17).

Perforation occurred only at Corby (soil 5) where the site was located in a cinder embankment (between tracks on a railroad siding). Here too the weight loss was appreciably higher, though still moderate, especially when halved for one side corrosion. Cinders are known to be corrosive to metal due to sulfuric acid produced from residual sulfur.

Only last month Campbell (41) reported ten-year results from another series of

tests at three of these sites, and three others for AA1100 alloy, plus results on a few other alloys at two sites (Table 18).

Once again the Corby cinders proved very aggressive to aluminum, while corrosion elsewhere was small (maximum 6.25 percent—one side, at Edinburgh).

Sprowls and Carlisle (38) have reported 7- to 8-yr burial tests on several aluminum alloys at one location (New Kensington, Pa.). The specimens were 5-ft lengths of 1 $\frac{1}{4}$ -in. diameter pipe with a wall thickness of 0.280 in. The maximum pit depths are given in Table 19. The results suggest a decrease in the rate of penetration with time, and appreciable protection by the cladding alloy. Although some penetration of the cladding did occur, it was limited to a few areas.

The present writer has obtained pit depth and weight loss results on many aluminum alloys buried for 5 years in the 12 Canadian soils given in Table 20 (39).

Table 21 gives maximum pit depths and percentage weight losses for the first test series. Perforation of the 0.064-in. sheet occurred only in 6061-T6 alloy in one location. The prevention of penetration by cladding was also demonstrated. Taken together, the pit depth and weight losses indicate that while some pitting occurred the loss of metal was negligible.

In a second series (1958-63) 0.064-in. sheet specimens were buried at 8 sites across Canada, selected with the help of the Canadian Department of Agriculture as representing the main soil types. The maximum pit depths for a number of alloys and the percentage weight losses are given in Table 22.

With the exception of site 12, which was land reclaimed from the sea, weight losses were negligible, as with the four central Canadian soils tested previously. At sites 5, 8 and 11 burials were made in both well and poorly drained soils of the same composition and structure at nearby locations. To indicate the lack of correlation between corrosivity and soil resistivity, the values for the burial plots are given in Table 23. In all cases corrosion was appreciably less (both maximum pit depths and weight losses) in the poorly drained soil.

### Summary

In 26 soils (6 American, 12 Canadian and 8 British), corrosion of aluminum alloys that might be used for culverts was negligible in 23 soils, and appreciable in only 3. One of these was salt marshland reclaimed from the sea, another was the most corrosive (to steel) of 47 tested by the Bureau of Standards, and the other was a cinder embankment. It is significant that there are well over 200 miles of unprotected buried aluminum pipe in western Canada in a wide variety of soils. There are also over 150 buried thin wall (0.060 in.) irrigation systems across Canada protected only by a single coat of bituminous paint. There is also an appreciable mileage of unprotected buried aluminum pipelines in the U.S.A. (40).

On this evidence, together with the examination of 500 actual aluminum culverts (of 20,000 installed) presented by Lowe and Koepf (28), the writer contends that the large majority of aluminum culverts will have a service life far in excess of the 25 years tentatively suggested without conviction by Nordlin and Stratfull.

## References

28. Lowe, T. A., and Koepf, A. H. Corrosion Performance of Aluminum Culvert. Highway Research Record 56, pp. 98-115, 1964.
29. Sawyer, D. W., and Brown, R. H. Resistance of Aluminum Alloys to Fresh Waters. Corrosion, Vol. 3, pp. 443-456, 1947.
30. Godard, H. P. The Corrosion Behaviour of Aluminum in Natural Waters. Can. Jour. Chem. Eng., Vol. 38, pp. 167-173, 1960.
31. Sverepa, O. Corrosion of Aluminum and Its Alloys in Waters of Various Composition. Werk. u. Korr., Vol. 9, pp. 533-535, 1958.
32. Seligman, R., and Williams, P. The Action on Aluminum of Hard Industrial Waters. Jour. Inst. Met., Vol. 23, pp. 159-192, 1920.
33. Porter, F. C., and Hadden, S. E. Corrosion of Aluminum in Supply Waters. Jour. Appl. Chem., Vol. 3, pp. 385-409, 1953.
34. Davies, D. E. Pitting of Aluminum in Synthetic Waters. Jour. Appl. Chem., Vol. 9, pp. 651-660, 1959.
35. Logan, K. H. Underground Corrosion. U. S. Nat. Bur. Stds. Circ. C-450, p. 127, 1945.
36. Romanoff, M. Underground Corrosion. U. S. Nat. Bur. of Stds. Circ. 579, April 1957.
37. Gilbert, P. T., and Porter, F. C. Tests on the Corrosion of Buried Aluminum, Copper, and Lead. British Iron and Steel Res. Assoc., Spec. Rept. No. 45, pp. 55-74, July 1952.
38. Sprowls, D. O., and Carlisle, M. Resistance of Aluminum Alloys to Underground Corrosion. Corrosion, Vol. 17, pp. 125-132, 1961.
39. Godard, H. P. Unpublished Results, Series 1—1948-1953, 4 locations; Series 2—1958-1963, 8 locations.
40. Dalrymple, R. S. Aluminum Pipeline Case History Data. Materials Protection, pp. 101-104, Oct. 1963.
41. Campbell, H. S. Corrosion and Protection of Aluminum Alloys Underground. Jour. Inst. Met. (U.K.). Vol. 93, pp. 97-105, 1963.

E. F. NORDLIN and R. F. STRATFULL, Comments.—Hugh P. Godard's discussion contains numerous comments and supporting data. We believe it is necessary to make specific reference to the major points involved. For this reason we have used an unusual format for our closure wherein we comment on each major point.

### Statement 1 (Godard)

"In the case of metal culverts, it is suggested that the sole criterion of corrosion is the continued ability of the culvert to support the overburden and normal live loads for which it was designed."

### Comments

It is agreed that one criterion of the results of corrosion is the continued adequacy of culvert as a structure. However, there are two other criteria which should be included if a culvert is perforated by corrosion. These criteria are (a) the penetration of water through corrosion perforations can increase the moisture content of the overburden (embankment) and thus could reduce its structural strength in supporting loads, and (b) when significant areas of the culvert are perforated by corrosion, the exposed backfill material may be removed by scour. Whether or not these latter criteria are applicable or could be critical will depend on the particular culvert site. As an example, we are now designing a freeway in which a critical problem is to prevent the contact of drainage waters with the soils on which this highway will be built. After inundation of

the foundation soil, a test section at this location settled approximately 14 ft below its original elevation. In this general area, a county road was temporarily closed because runoff water contacted the embankment causing foundation settlement which disrupted the roadbed. A temporary closure of a freeway must be prevented. A corrosion-caused hole in a culvert on this freeway would be considered to be serious even though the pipe were still structurally adequate.

#### Statement 2 (Godard)

"However, the pitting action of natural water on aluminum is of limited importance in culvert considerations in view of the small influence of the pits on load bearing strength."

#### Comments

In our report, Figures 4, 6, and 13 show the complete loss of sections of the aluminum culvert invert. At the present time, the aluminum culvert shown in Figure 4, II-Sha-3-B, has complete losses of metal in the bottom of the pipe which range up to 1 ft in length. The waters which flow through these three culverts are natural waters. They do not emanate from a mine or a commercial source. These particular test culverts were placed in the same drainage channels in which metal culverts were previously used when corrosion testing was not practiced in the normal course of highway construction.

#### Statement 3 (Godard)

"They decided that to obtain this life, certain criteria for pH, water and soil resistivity must be adhered to." . . . "I suggest also that the criteria selected by Nordin and Stratfull are not applicable or necessary for predicting the service life of aluminum culverts." . . . "In studies of aluminum corrosion, pH has not been found to be a significant variable in either waters or soils."

#### Comments

No. 1. Lowe and Koepf, in their report on aluminum culverts (2), state: "The pH range of 4.0 to 9.0 removes the prospect of chemical attack on the oxide film."

No. 2. Godard states (48), "The oxide film on aluminum generally is stable in the pH range 5-8."

No. 3. A conclusion of Technical Committee T-4E of the National Association of Corrosion Engineers is: "Conclusion 4. Aluminum is not resistant to waters containing copper salts or with a pH less than about 6-6.5." (42)

No. 4. A handbook published by an aluminum company states: "Aluminum is readily attacked by strong alkaline or strong acid solutions with the exception of nitric acid and some concentrated organic acids." (43)

The definition of a strong acid has been implied to be a number greater than 4.5 by Lowe and Koepf (2) in Table 4 of their paper as indicated by the following:

Very strongly acid to slightly acid	(pH 4.0-6.5)
Very strong acid to neutral	(pH 4.5-7.3)
Extremely acid to neutral	(pH 3.0-7.3)
Extremely acid to neutral	(pH 4.0-7.0)

No. 5. If the corrosion testing criteria are not applicable or employed, then with the resultant lack of specific information an aluminum company advises: "Aluminum pipe offers excellent resistance to corrosion by many soils. However, some soils may cause corrosion; and in the absence of specific information, it is advisable to protect aluminum pipe by suitable coatings and wrappings similar to those used for steel pipe." (44)

No. 6. "This laboratory's experience is that fairly hard, mildly alkaline water such as in the Great Lakes System tends to pit aluminum, while soft, mildly alkaline or mildly acid waters do not." (47)

Statement 4 (Godard)

"Accordingly, it can be safely predicted that the pitting of an aluminum culvert will have no appreciable influence on the load-bearing capacity of the culvert unless the pits become so numerous and so large that an appreciable cross-section of the metal is consumed. . . ."

Comment

No criteria are given by which to predict safely the pitting density of aluminum when it is used as a culvert.

Statement 5 (Godard)

"Soil resistivity also affects the incidence and rate of pitting. In addition, it gives information on soil battery effects which occur in the case of pipelines which traverse several soil types. By contrast, metal culverts are normally relatively short and are buried in one type of soil. This further reduces the value of soil resistivity readings in culvert considerations."

Comments

Lowe and Koepf (2) state in their report on aluminum culverts: Tentative Conclusion 3. "The corrosion attack observed on the soilside surface of some aluminum culvert is believed to be the result of nonuniform soil compaction rather than of borderline pH or resistivity conditions. Such lack of uniformity causes concentration cells whose activity is influenced by soil resistivity. Good compaction at the time of installation can reduce attack from such cells." . . . "That resistivity influences the processes of corrosion of buried metals is seldom disputed. There are many cases, however, indicating that other factors play an equal or perhaps more significant role in corrosion of buried culverts."

Statement 6 (Godard)

The following are H. P. Godard's comments regarding the N.B.S. underground tests of aluminum. (45)

"The sheet specimens were too thin to determine maximum pit depths for both alloys in 3 of the other 4 soils, but conversion of the weight losses due to pitting to percent loss of the original specimen weight indicates that, except for soil 29, less than 7 percent of the metal was corroded in 10 years. If this is applied to culverts, which are exposed to soil on only one side, the figure is then 3.5 percent in 10 years."

Comments

No. 1. Soil can be deposited on the inside of a culvert by the flow as shown by Figure 8 of our paper.

Comment on these data by the National Bureau of Standards (45): "The aluminum alloys were susceptible to intergranular corrosion. In the advanced stages, this type of attack caused ridges and blisters to occur on the surface, beneath which was a white powder on some of the specimens. The unalloyed specimens were the best of the group. Table 56 shows the loss of weight and maximum penetration of the thin aluminum specimens, exposed approximately 10 years, and similar data for the same soils on zinc and iron for comparison. None of the thin materials was satisfactory for use unprotected in the corrosive soils to which they were exposed. Great strides have been made during recent years in the development of aluminum alloys which might be more corrosion resistant than the specimens buried at the Bureau's test sites."

[Authors' Note: The thickness of the aluminum test specimens at the N.B.S. site was 0.062 in. which is thicker than the equivalent 16-gage aluminum culvert sheet (0.060 in.).]

No. 2. C. J. Walton, in his discussion (50), has stated, "Loss in weight measures the total amount of corrosion; but such data often do not measure reliably the effect of the corrosion on other properties, such as actual depth of attack or actual loss in tensile properties. In case of the aluminum alloys, depths of attack calculated from weight losses were always much less than that measured by microscopic examination of cross-sections; and the losses in strength calculated from weight loss data were much less than the actual losses in strength as determined by tension tests. Thus, weight loss data provide a basis for comparing the total amount of corrosion of different kinds of metals, but are not adequate for evaluating the relative effects of the corrosion on other properties."

No. 3. Included in Table 24 are some of the results of the ASTM atmospheric tests (50) where the changes in the physical properties of several aluminum alloys are compared to the results of corrosion. It is of interest for the reader to compare the amount of corrosion (Table 24) and those amounts of corrosion of aluminum when placed underground as submitted by Godard in his discussion. In culvert applications, a significant loss of elongation within one year conceivably could contribute to structural failure of a culvert.

#### Statement 7 (Godard)

"There are also over 150 buried thin wall (0.060 in.) irrigation systems across Canada protected only by a single coat of bituminous paint."

#### Comments

The majority of culverts which are used in highway construction are 16-gage or in the case of aluminum would be 0.060-in. thick. With the exception of invert paving, the protective coating recommendations in the paper only include a single coat of bituminous or other suitable material.

#### Statement 8 (Godard)

"On this evidence, together with the examination of 500 actual aluminum culverts (of 20,000 installed) presented by Lowe and Koepf (28), the writer contends that the large majority of aluminum culverts will have a service life far in excess of the 25 years tentatively suggested without conviction by Nordlin and Stratfull."

#### Comments

No. 1. None of the tabulated data submitted as evidence by Godard has a reported testing time of greater than 10 years.

No. 2. None of these data submitted by Godard for up to 10 years of reported testing were correlated to demonstrate that a large majority of the specimens will have a service life far in excess of 25 years.

No. 3. From the corrosion data submitted by Godard in Tables 16 through 19 and 21 through 22, it is obvious that the majority of specimens were not destructively corroded within 10 years. However, it is also of prime importance to know the magnitude of the minority which were seriously corroded. In Figures 37 through 40 we have plotted on probability paper the data submitted by Godard. The plotting positions of the data were calculated in a recommended manner. (46, 48)

In all cases, the tabulated weight loss data were corrected to a culvert wall thickness of 0.060 in. by direct proportion. This was done because in some cases the reported percentage of weight loss in Godard's tables was for sheets as thick as 0.280 in. Therefore, these weight losses were corrected to a thickness of 0.060 in. because if a reported weight loss of an 0.280-in. thick material was approximately 21 percent, then



TABLE 24  
RESULTS OF ATMOSPHERIC CORROSION TESTS OF SEVERAL ALUMINUM ALLOYS AND RELATED  
CHANGES IN STRUCTURAL PROPERTIES (50)

Alloy	Actual Loss in Tensile Strength (%) <sup>a, b</sup> (20 yr)		Calculated Loss in Tensile Strength (%) <sup>b, c</sup> (20 yr)		Max. Pit Depth Mils, Microscopic Exam. <sup>d</sup> (20 yr)		Loss in Elongation (%) <sup>e</sup>			
	New York	La Jolla	New York	La Jolla	New York	La Jolla	Pre-Machined Tension Spec. (1 yr)		Panels (20 yr)	
							New York	La Jolla	New York	La Jolla
Alclad 2017-T3	0	0	3.5	2.6	1.4	2.9	1.5	4.1	1	4
3003-H14	8.3	7.0	3.4	2.6	6.4	10.2	31	42	+2	34
1100-H14	6.8	8.2	4.4	2.8	8.4	14.0	19.7	69.9	14	54
6051-T4	11.6	19.6	4.1	3.5	6.7	12.1	38.9	76.7	30	64
2017-T3	6.9	19.9	5.9	10.4	7.1	20.3	46.3	91.7	15	58
Avg.	6.7	10.9	4.3	4.4						

<sup>a</sup>Actual loss in tensile strength was measured on tension specimens machined from panels.  
<sup>b</sup>From Table IV (50).  
<sup>c</sup>Calculated from weight loss data, assuming corrosion to be perfectly uniform.  
<sup>d</sup>From Table D (50).  
<sup>e</sup>From Table C (50).

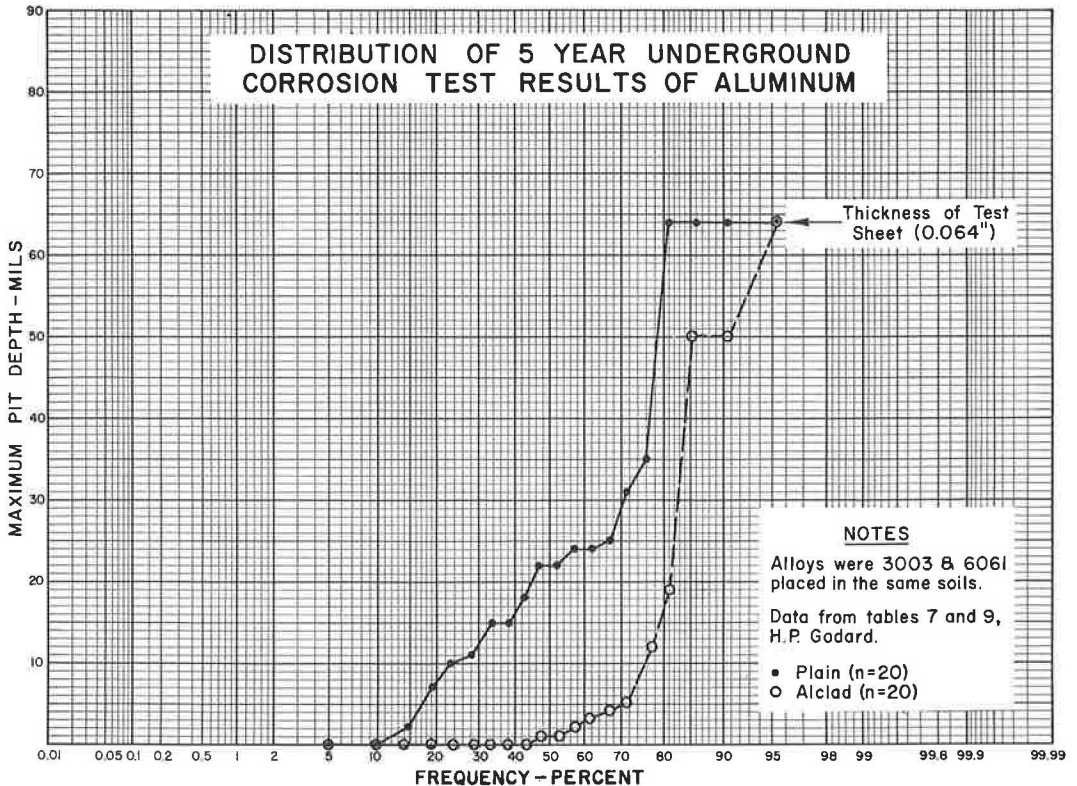


Figure 37.



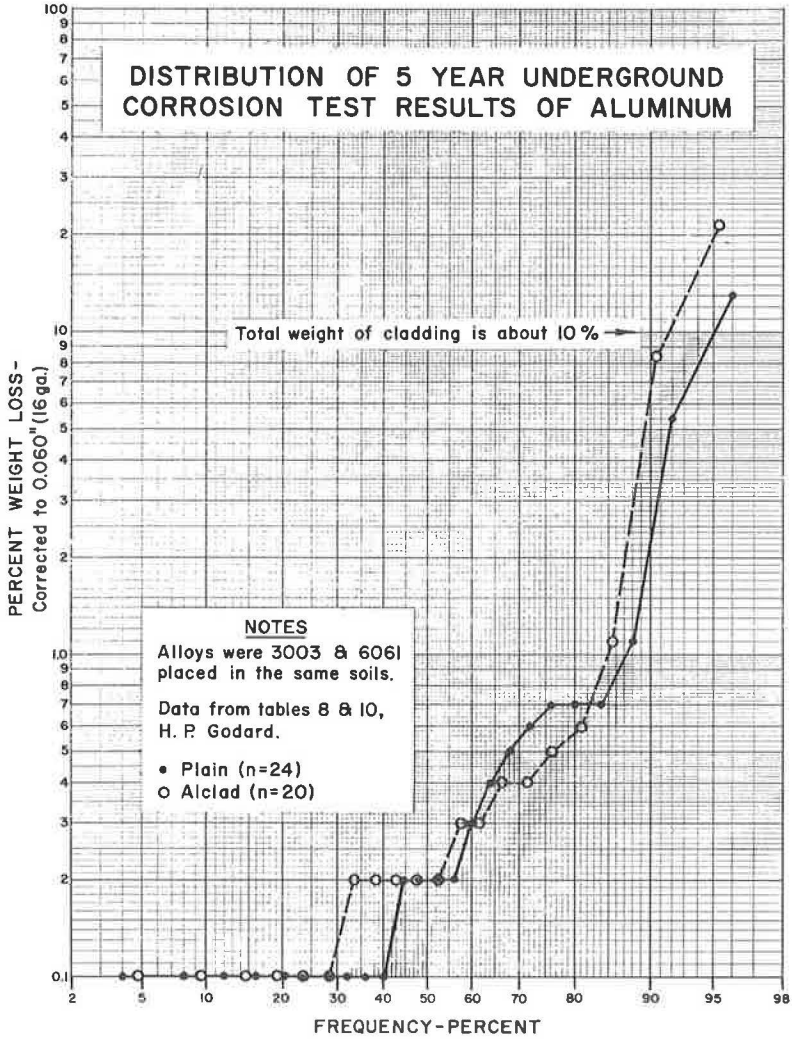


Figure 38.

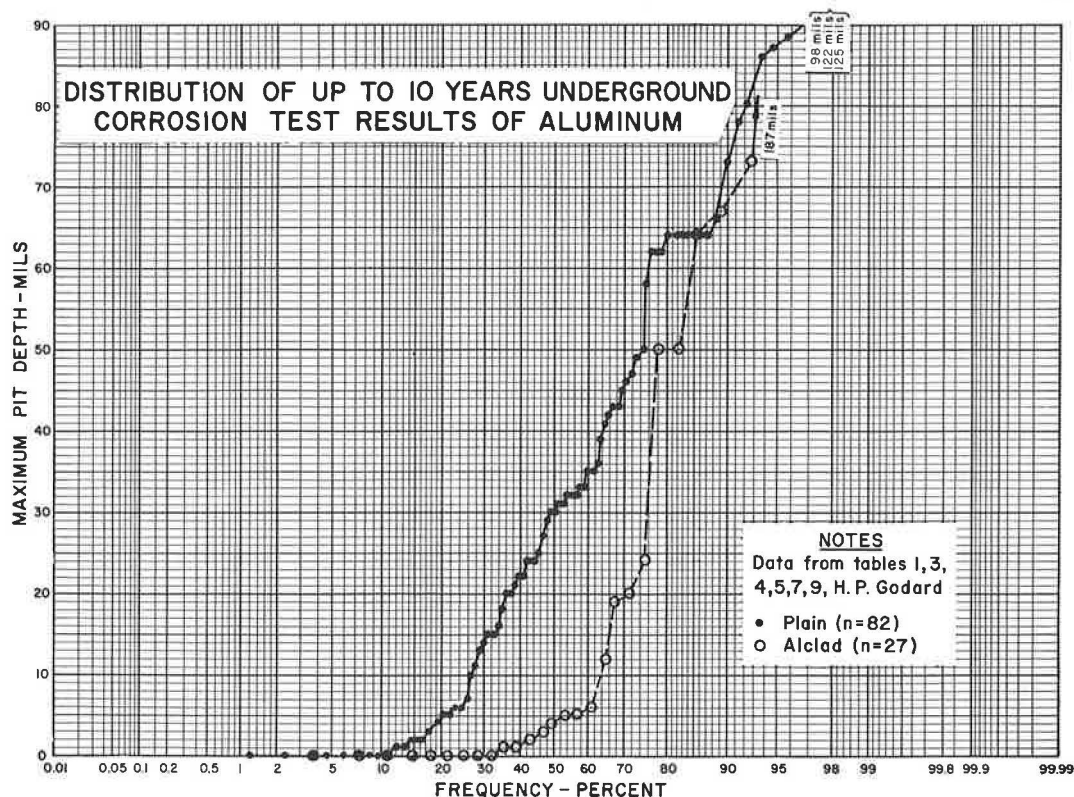


Figure 39.

this would be the approximate equivalent of 100 percent weight loss for an 0.060-in. thick specimen. Other than the preceding thickness correction and the plotting, no other mathematical conversions of the reported data were performed.

In the foregoing analysis, the following assumptions were made:

1. The data submitted by Godard is a representative and random sample of the expected performance of aluminum in soils.
2. The random data demonstrate that the large majority of aluminum culverts will have a service life far in excess of 25 years.
3. The data for all listed alloys and soils verify that corrosion criteria are not applicable or necessary for predicting the service life of aluminum culverts.

On the basis of the preceding assumptions, the random placement of aluminum culverts without corrosion testing or culvert coatings could result in the following:

1. The random use of aluminum culverts of 0.060 in. indicate the possibility that up to approximately 20 percent of the culverts will be perforated by pitting within approximately 5 years of service (Fig. 37).
2. The random use of aluminum culvert of 0.060-in. thickness indicates the possibility that approximately 10 percent of the culverts can have a weight loss of greater than 5 percent within 5 years of service (Fig. 38).
3. The random use of aluminum culverts with a wall thickness of 0.060 in. indicate the possibility that up to approximately 25 percent of the culverts will be perforated by pitting within approximately 10 years of service (Fig. 39).
4. A small percentage of culverts could have a 100 percent weight loss of metal within 10 years. If the weight loss of 7 percent (see Godard's Statement 7 with Com-

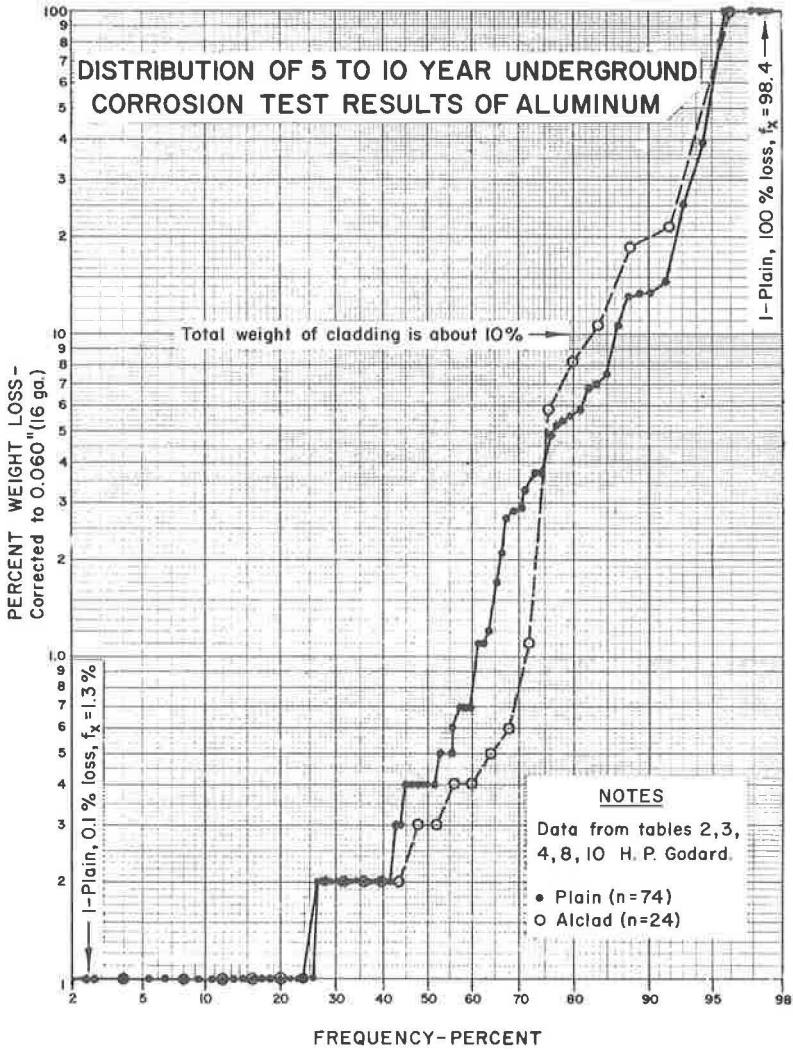


Figure 40.

ment No. 1) is used, then it seems to be possible that up to approximately 20 percent of the culverts with a wall thickness of 0.060 in. will probably be in an unsatisfactory condition for use within approximately 10 years of service (Fig. 40).

The evidence of the corrosion test results of aluminum indicates that corrosion control measures are necessary if one does not wish to accept a significant percentage of culverts with perforations and significant weight loss in less than 10 years.

#### References

42. Service Life of Pipe Exposed to Domestic Waters. N.A.C.E. Tech. Comm. Rept., Publ. 60-11. Corrosion, Vol. 16, p. 453t, Sept. 1960.
43. Sheet and Plate Product Information. Kaiser Aluminum and Chemical Sales, Inc., Copyright, 1953.
44. Process Industries Applications of Alcoa Aluminum. Copyright, 1955.
45. Romanoff, M. Underground Corrosion. Circular 579, Nat. Bur. of Stds., p. 92, 1957.
46. U. S. Bur. of Pub. Roads, Office of Research and Development. Contract CPR 11-8718, M-W Tech. Rept. No. 201. Raleigh, N. C., Miller-Warden Assoc., Aug. 1963.
47. Wright, T. E., and Godard, Hugh P. Laboratory Studies on the Pitting of Aluminum in Aggressive Waters. Corrosion, Vol. 10, No. 6, p. 195, June 1954.
48. Godard, Hugh P. The Corrosion Behavior of Aluminum. Corrosion, Vol. 11, No. 12, p. 542t, Dec. 1955.
49. Aziz, P. M. Application of the Statistical Theory of Extreme Values to the Analysis of Maximum Pit Depth Data for Aluminum. Corrosion, Vol. 12, No. 10, p. 495t, Oct. 1956.
50. Walton, C. J., and King, William. Resistance of Aluminum Base Alloys to 20-Year Atmospheric Exposure. ASTM Symp. on Atmospheric Corrosion of Non-Ferrous Metals, ASTM Spec. Tech. Publ. No. 175, p. 21-46, 1955.
51. Putilova, I. N., Balezin, S. A., and Barannik, V. P. Metallic Corrosion Inhibitors. New York, Pergamon Press, p. 122, 1960.
52. Stratfull, R. F. A New Test for Estimating Soil Corrosivity Based Upon an Investigation of Metal Highway Culverts. Corrosion, Vol. 17, No. 10, p. 115-118, Oct. 1961.
53. Walton, C. J., McGeary, F. L., and Englehart, E. T. Compatibility of Aluminum with Alkaline Building Products. Corrosion, Vol. 13, No. 12, p. 807t, Dec. 1957.

THOMAS A. LOWE, Department of Metallurgical Research, Kaiser Aluminum & Chemical Corporation.—This discussion has been prepared with the intent of constructively commenting on a paper entitled "A Preliminary Study of Aluminum as a Culvert Material," by Eric F. Nordlin and R. F. Stratfull. These comments are not intended to stand by themselves, but to complement discussions offered on this paper by Dr. Hugh Godard and by A. H. Koepf. As a corrosion research engineer for a major aluminum-producing company, I have actively and directly participated in the aluminum culvert program. My work started at the inception of the product's development six years ago and has since involved an extensive, thorough, and continuing evaluation of corrosion performance in a large number of culvert installations which encompass many types of soils and service widely distributed throughout the United States.

The results of field tests of aluminum culvert are valuable, since they provide a broader background of experience to compare with recommendations of producers and to compare with results of culvert tests being conducted by other agencies. We are seriously concerned, however, about the conclusions of Nordlin and Stratfull respecting aluminum culvert. If these conclusions are accepted by the highway authorities, the

effect will be to discriminate unfairly against aluminum culvert and to discourage its use. On the basis of our knowledge of aluminum and our experience with the metal, both in general and in the form of culvert, we do not believe the authors' conclusions are justified. We have carefully reviewed the paper, and we disagree with: (1) the interpretation of information and data taken from the literature; (2) the experimental approach; and (3) the analysis of the reported results.

### Summary

The authors' paper should be read in its entirety, and, if possible, the major references, some of which we discuss here, should also be reviewed. Neither the work of Nordlin and Stratfull, nor the papers which they reference, justify the conclusions which the authors have reached.

The narrow limits imposed on the use of aluminum culvert by the State of California are not supported by the data which they have accumulated. Even those data are in question since they involved conditions that are not representative of those normally encountered in culvert installations.

Our inspections of hundreds of bare aluminum crossdrains and sidedrains throughout the United States, in soil conditions varying from purposefully aggressive to the more normal, show no evidence to support these restrictive limits, or the assumedly aggressive conditions which the authors conceive. These many installations, and, in fact, those installed by the State of California, have performed in a manner consistent with what we have come to expect. On the basis of this broader experience, aluminum culvert would be expected to:

1. Provide corrosion performance superior to that of galvanized steel in soils within the pH range of 4.0 to 9.0 and having a minimum resistivity above 1,500 ohm-cm. (Field experience indicates this value can be lowered considerably, but further exposure is needed to confirm it.)
2. Provide better corrosion performance than galvanized steel in installations exposed to flow of brackish or sea water.
3. Suffer attack, as does galvanized steel, in runoff from pyrite areas whose pH at any time drops below 4.0.
4. Be more resistant than galvanized steel to the normal erosion-corrosion cycles encountered by drainage structures in areas of erosive runoff. Our experience in such installations has been reported more fully in the discussion of this paper by A. H. Koepf.

### Literature Reference

For those unfamiliar with the corrosion characteristics of aluminum, it is natural to assume that those characteristics will be similar to other metals commonly used in construction. Such an assumption is not true. Reference to the literature, as attempted by the authors, is an excellent means for familiarizing oneself with the subject of aluminum corrosion. It is important, however, to fully digest the intent of any reference, along with the significance of all data presented.

It would be desirable to discuss each of the references given by Nordlin and Stratfull which concerns aluminum, but space will not allow. Instead, certain references will be selected for comment and are listed again at the end of this discussion. The serious investigator is encouraged to read some of these references so that he might appreciate the danger of misapplying or misinterpreting statements or data from those references.

### Influence of pH

Deltombe and Pourbaix (54) are listed by the authors as setting forth a pH range of 5.5 to 7.8 over which aluminum is inert or "inhibited from accelerated corrosion." This reference reports a chemical thermodynamic treatment through which a potential-pH equilibrium diagram of the system aluminum-water was developed from standard free energies of certain constituents. The general electrochemical behavior of aluminum was deduced from the diagram.

Deltombe and Pourbaix have assumed for their model that hydragillite,  $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ , (usually called gibbsite in the U.S.) is the oxide on the metal surface. With this model, they predict that the gibbsite-covered aluminum surface is passive, or is corrosion resistant, over a pH range of 4.0 to 8.6. The point is that Deltombe and Pourbaix have interpreted the behavior of aluminum in terms of the soluble  $\text{Al}^{+++}$  and  $\text{AlO}_2^-$  species and in terms of the solid  $\text{Al}^0$  and  $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ . They cannot, nor do they attempt, to equate the surface oxide films that normally occur on aluminum with their reference models. These films are too complex, and they vary in composition with the medium in which they are in contact. Therefore, not only have the authors misinterpreted the information contained in this reference, they have incorrectly quoted the pH range of 5.5 to 7.8.

The pH range of 5.5 to 7.8, which Nordlin and Stratfull mention, is actually the range in which Deltombe and Pourbaix found  $\text{Al}(\text{OH})_3$  to have minimum solubility. This range is of no real significance since, as Deltombe and Pourbaix mention, "The aluminum hydroxide gel is not stable. It crystallized eventually to give the monohydrate of boehmite, crystallizing in the rhombohedral system. It then gives the trihydrate or bayerite, crystallizing in the monoclinic system, and finally another trihydrate, hydragillite, crystallizing in the same system. This evolution of the hydroxide of aluminum is known as "aging." The diverse hydrates formed in the course of aging are characterized by greater and greater stabilities, and concomitant variations in all their properties, particularly in their solubilities in acids, bases and pure water."

The paper by Deltombe and Pourbaix and that by Nordlin and Stratfull reference the work of Shatalov (55). Deltombe and Pourbaix reproduce the graphs of Shatalov in their paper which indicate the influence of pH on the rate of corrosion aluminum. These graphs show essentially zero corrosion rates over a pH range wider than the 4.0 to 8.6 suggested by Deltombe and Pourbaix, than the 4.0 to 9.0 recommended by Kaiser Aluminum, and certainly wider than the 6.0 to 8.0 specified by Nordlin and Stratfull. Confirmation for the influence of pH determined by Shatalov is found elsewhere in the literature (56).

Similar detail is in order with respect to Nordlin and Stratfull's interpretation of the pH ranges suggested in other references. Rather than attempt such a detailed discussion, it can be stated that several of the references have been misinterpreted. All but one of them represent the coverage of aluminum performance in applications very different from culvert, nevertheless they support a stability of the aluminum oxide film over a pH range of 4.0 to 9.0.

To summarize our position on pH, we believe that the range suggested by Nordlin and Stratfull has been arrived at arbitrarily. It has no basis of experience, either in their work or in the literature. From a practical standpoint, we know that there are few soils which fall outside the pH range of 4 to 9. Therefore, we must conclude that other factors influence corrosion performance, if we are to explain the few cases of corrosion which have been noted.

### Chemical Compatibility

The reader might gain misleading conclusions from statements under the chemicals section of the paper. A reference is made to attack by sodium carbonate solutions (57). One is warned against accepting data without learning the conditions under which the data were obtained. In the McKee and Brown study (57), also referenced by Nordlin and Stratfull, the one sentence discussing tests with sodium carbonate reads, "Although alkalinity produced by the presence of sodium hydroxide or resulting from hydrolysis of a sodium salt such as the carbonate causes appreciable corrosion, aluminum may or may not be resistant to such solutions, depending upon the nature of other ions present." The important point is that the tests in this study were of only 48 hours' duration. A glance at Figure 41 (Fig. 1, 58) shows that, with time, there is a striking decrease in the corrosion rate of aluminum in a sodium carbonate solution much more concentrated than those used by McKee and Brown (57). A study of corrosion which does not properly assess the influence of time on corrosion rate can give erroneous results, as indicated by the data shown in Figure 41.



AVERAGE CORROSION RATE OF ALUMINUM  
IN SODIUM CARBONATE SOLUTIONS

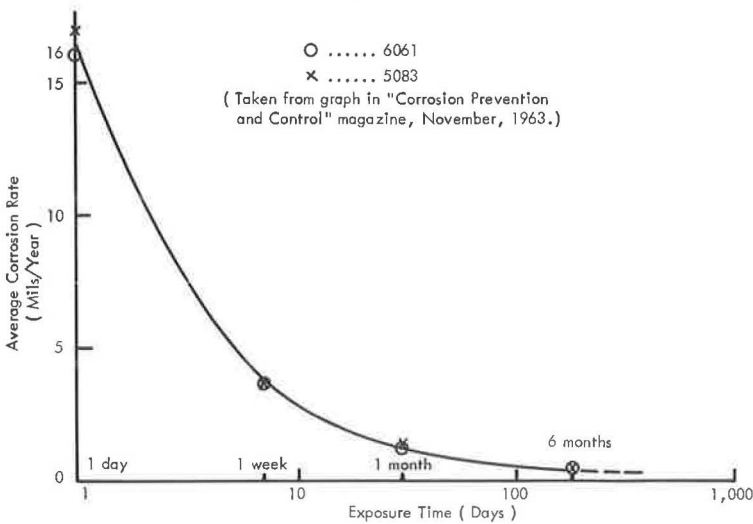


Figure 41. Rapid decrease in corrosion rate with increasing exposure, of aluminum alloys 6061 and 5083 to 10 percent (by wt) and to saturated sodium carbonate solutions at room temperature.

As mentioned by the authors, the presence of heavy metals in waters can cause attack of aluminum. Incidence of attack caused by heavy metals, however, is rare. The case referred to in the paper involved the water supply of Altoona, Pa. An unusually high content of heavy metals was found in this water, which, in combination with other characteristics, caused the water to be particularly aggressive. Since such waters are infrequently encountered, they should receive little consideration. The success of aluminum irrigation tubing, and the absence of detrimental attack during the five years since aluminum culvert was introduced is evidence of aluminum's compatibility with nearly all "natural" waters. (A distinction is made between "natural" and "produced" waters, the former being those in equilibrium with air, such as runoff, lake, or river water, as opposed to the latter which are not, such as spring or well water. Produced waters are not normally encountered in culvert applications.)

The cladding on aluminum culvert is intended to mitigate any attack that might be caused by an unusual water. Such cladding has helped prolong the useful life of aluminum in such applications as cooking utensils (58), hot water heaters, heat exchanger tubing, and irrigation pipe. Attack spreads laterally along the layer of more anodic cladding, rather than into the core alloy. Should subsequent pitting of the exposed core alloy penetrate the metal, it will have an insignificant effect on the strength of the culvert.

While on the subject of cladding, it might be well to comment on the authors' terminology "corrosion inhibiting cladding." The cladding does not, nor is it intended to, inhibit attack. As mentioned above, its function is to control the manner of attack, if any should occur.

### Electrical Resistivity

Nordlin and Stratfull have made a serious misinterpretation of resistivity readings provided in the report by Lowe and Koepf (59). Those readings were made in the field using a Model 263 A Vibroground equipped with a wiring harness for obtaining average resistivities at depths of 2.5, 5.0 and 10 ft. The procedure is given in the original paper.

The Vibroground is the most widely used instrument for making soil resistivity surveys before designing cathodic protection systems for buried oil and gas pipelines. This instrument gives an average reading of a hemisphere of soil whose radius is determined by pin settings. This average will include surface soil as well as soil at the designated depth.

If resistivity values from 2.5 ft to 10 ft are increasing with depth, the more shallow soils have a lower resistivity than indicated by the average. For example, if a soil has a resistivity of 1,000 ohm-cm at 2.5 ft and 5,000 ohm-cm at 10 ft, the surface layers, if isolated, would have a resistivity lower than 1,000 ohm-cm. The soil at the 2.5-ft depth would have a resistivity somewhere between 1,000 and 5,000 ohm-cm, such as 2,500 ohm-cm.

We believe that depths of 2.5, 5.0 and 10.0 ft cover the great majority of culvert installations in existence. We therefore get a reasonable indication of soil resistivity at the culvert depth while getting a "feel" for the complete range of material which may have been used as backfill.

One cannot arbitrarily average the values reported and have a meaningful value. Furthermore, most of the installations which we reported fall below the mean value listed by Nordlin and Stratfull, and these installations, as a whole, are showing excellent performance.

For longer term data, it is interesting to look at results reported by the National Bureau of Standards in their 10-yr test. Four of the five soils included in that program would be classified as aggressive soils by corrosion engineers. Nevertheless, bare, not clad, aluminum is withstanding the rigors of those four environments better than zinc or steel. Based on our knowledge of the corrosion characteristics of aluminum, it would continue to be superior for years to come. Clad aluminum would show even better corrosion performance.

The 1,500 ohm-cm value quoted from another reference (61) concerned a pipeline which was cathodically protected at "hot spots." Long-line currents which gather on pipelines make low resistivity soils a potential hazard. Culverts are not subject to such currents; consequently, there is no need to consider resistivity from that aspect. Furthermore, we have cladding to protect against particularly aggressive soils.

### Bimetallic Corrosion

The concepts which Nordlin and Stratfull present on this subject are generally correct. However, they neglect the influence of surface films on the activity of galvanic cells. Only aluminum alloys specifically designed to provide cathodic protection can be used to protect steel. These alloys will corrode more freely and will not be greatly affected by surface films. Most aluminum alloys will not provide such protection, as evidenced by the literature (62) on aluminized steel. For aluminized steel, aluminum provides some protection only in the presence of significant chloride concentrations, such as in marine environments.

### Concentration Cell and Crevice Corrosion

In the many culverts which we have examined, we have found no problem of preferential corrosion at laps, either circumferential or longitudinal. All common metals of construction, including steel and galvanized steel, are subject to concentration cell and crevice corrosion if conditions exist which promote such attack. As for the possibility of active:passive cells supplementing crevice attack, the reader should understand that any oxygen-passivated metal, such as chromium, stainless steel, or aluminum is subject to such attack. Again we repeat that, even in the culvert exposed to the muck at Gramercy, Louisiana, we have not seen evidence of preferential attack of lapped surfaces in the many field installations examined.

### Laboratory Tests

We do not feel that the compatibility of aluminum, or any other metal, can be realistically evaluated by exposing that metal to chemical solutions in the laboratory. One cannot reproduce the soil electrolyte chemically.



There is the added problem of length of exposure for the tests reported by Nordlin and Stratfull. Short-term tests, particularly with no provision for determining time/rate data, are meaningless. The data in Figure 41 illustrate this point, as does the reaction of concrete on aluminum. After a general etching of 0.001 in. to 0.002 in. during the setting period, aluminum is unaffected when embedded in concrete.

As for the abrasion tests, field performance of a metal exposed to erosive flow is not solely determined by its resistance to abrasion. The ability of the metal to withstand countless erosion-corrosion cycles is the true criterion. Such a criterion requires a time factor not easily included in laboratory evaluations.

Actual installations, observed periodically over a few years, give a true picture of the comparison of galvanized steel and aluminum in such erosive flows. We have had a number of such installations under surveillance, one of which we reported in some detail in a previous paper (59). Similar field tests by another state highway department have provided identical results to those which we have observed. Pictures of the in-place culvert, as well as photomicrographs of cross-sections taken from that installation at the end of 2.0 and 4.3 years were shown during our discussion of this paper at the 44th Annual Meeting of the Highway Research Board.

### Field Tests

It is unfortunate that the authors chose such extreme conditions for their field tests rather than exposures more representative of California soils. Even in the eight sites reported, no indication of the general soil-side performance is provided for the three sulfuric acid sites or for the two abrasion sites. The highly acid runoff would be expected to affect the soil-side of the invert, where it leaks through joints or perforations of the invert. The remainder of the soil-side surfaces would not be so affected. Surely, the soils representative of those three sites will be used as backfill for culverts not exposed to acid runoff, just as the soil in contact with culvert I-HUM-35-C will be in contact with other culverts not exposed to erosive runoff. In effect, soil corrosion is being evaluated at only three of the eight sites, a fact confirmed in the authors' paper, Table 3. Thus, the use of aluminum culvert by the State of California is based on the performance at only three sites.

A further weakness of the California tests is that five or six of the eight test culverts were not installed under normal conditions. Most of these installations were made in ditches adjoining the highway where the culvert was merely covered with a mound of dirt. There was no opportunity for compaction of the "backfill" which a normal installation experiences. The importance of such compaction is pointed out in several references (59, 63).

The authors give no data or description of the comparative performance of the culvert materials from one inspection time to another. Progress of attack, if any, cannot be determined.

It is hoped that the authors will provide more detail concerning inspection results in their next report on the subject. In the meantime, the reader is asked to consider carefully the procedure that he might follow before embarking upon a field test program of any type of material. Test conditions should duplicate those to be experienced in service.

### References

54. Deltombe and Pourbaix. The Electrochemical Behavior of Aluminum. Corrosion, Vol. 14, No. 11, pp. 496t-500t, 1958.
55. Shatalov, A. Y. Effet du pH sur le Comportement Electrochimique des Metaux et Leur Resistance a la Corrosion. U.S.S.R., Doklady Akad. Nauk., Vol. 86, pp. 775-777, 1952.
56. Aluminum in Chemical Engineering. Corrosion Prevention & Control, pp. 41-43, May 1963.
57. McKee, A. B., and Brown, R. H. Resistance of Aluminum to Corrosion in Solutions Containing Various Anions and Cations. Corrosion, Vol. 3, No. 12, pp. 595-612, 1947.

58. Wei, M. W. The Corrosion Rates of Aluminum. Corrosion Prevention & Control, pp. 34-35, Nov. 1963.
59. Lowe, T. A., and Koepf, A. H. Corrosion Performance of Aluminum Culvert. Highway Research Record No. 56, pp. 98-115, 1964.
60. Romanoff, Melvin. Underground Corrosion. Nat. Bur. of Stds. Cir. 579, pp. 92, 19-20; 1957.
61. Whiting, J. F., and Wright, T. E. Cathodic Protection for an Uncoated Aluminum Pipeline. Corrosion, Vol. 17, No. 8, p. 9, Aug. 1961.
62. Evans, Ulick R. The Corrosion and Oxidation of Metals. London, Edward Arnold, pp. 640-641, 1960.
63. Romanoff, Melvin. Corrosion of Steel Pilings in Soils. Jour. of Res. of the Nat. Bur. of Stds., Vol. 66C, No. 3, July-Sept. 1962.

E. F. NORDLIN and R. F. STRATFULL, Comments.—For the most part, Lowe disagrees with almost everything in our report. Generally, he has detailed the reasons for his difference of opinion. Because of the numerous points of disagreement, we are commenting on each major point. However, some of the major points brought out by Lowe were also discussed by Koepf and are included in our comments on the latter discussion.

#### Statement 1 (Lowe)

"On the basis of this broader experience, aluminum culvert would be expected to:  
1. Provide corrosion performance superior to that of galvanized steel in soils within the pH range of 4.0 to 9.0 and having a minimum resistivity above 1,500 ohm-cm."

#### Comments

No. 1. No data have been submitted by Lowe which demonstrate that the corrosion performance of galvanized steel culverts has been studied in all of these soils and that the superior corrosion performance of aluminum culverts has been comparatively determined.

No. 2. No data have been submitted by Lowe which demonstrate that laboratory testing or field data have been mathematically correlated to demonstrate that aluminum culverts would provide corrosion performance superior to that of galvanized steel in soils within a pH range of 4.0 to 9.0 or having a minimum resistivity above 1,500 ohm-cm.

No. 3. In his discussion, Lowe made reference to the published paper (2) he co-authored with Koepf. A paper by Stratfull (52), which was also used as a reference in the paper by Lowe and Koepf (2), defines and describes minimum resistivity to be the result of a laboratory type of test. To our knowledge, no method has been established for correlating an in-place field resistivity obtained by the method employed by Lowe and Koepf (2) with the minimum soil resistivity. In their paper or in his discussion, Lowe has not indicated that they have actually determined the minimum resistivity of a soil.

In their paper (2), Lowe and Koepf, in apparent support of their minimum resistivity recommendations, refer to one paper by Whiting and Wright (14) in stating, "A minimum soil resistivity of 1,500 ohm-cm has been suggested as a threshold value below which corrosion of aluminum may occur (4)." Whiting and Wright (14) make no reference to the term "minimum soil resistivity." There is no other mention of a minimum soil resistivity of 1,500 ohm-cm in the text to the paper (2) by Lowe and Koepf. Therefore we are not aware of the basis for the minimum soil resistivity recommendation of 1,500 ohm-cm.

It should be noted that the application of the type of cathodic protection such as used by Whiting and Wright (14) is not necessarily limited to soils of a particular resistivity. This type of protection is also applied to pipelines where a significant soil resistivity differential exists and the lower limit of resistivity can be much higher than or even less than 1,500 ohm-cm.

### Statement 2 (Lowe)

Deltombe and Pourbaix (54) are listed by the authors as setting forth a pH range of 5.5 to 7.8 over which aluminum is inert or 'inhibited from accelerated corrosion'. . . . "Therefore, not only have the authors misinterpreted the information contained in this reference, they have incorrectly quoted the pH range of 5.5 to 7.8." . . . "This range is of no real significance since, as Deltombe and Pourbaix mention: 'The aluminum hydroxide gel is not stable. . ..'" . . . "Similar detail is in order with respect to Nordlin and Stratfull's interpretation of the pH ranges suggested in other references."

### Comments

No. 1. We do not believe we have misquoted or misinterpreted the information presented in the paper by Deltombe and Pourbaix (5). On Page 499t, they state: "According to laboratory tests the minimum solubility of  $\text{Al}(\text{OH})_3$  lies between pH 5.5 and 7.8."

This paper also states, "When alkali is added to a solution of an aluminum salt, or acid to a solution of an aluminate, one obtains a precipitate, hydroxide gel, corresponding essentially to the composition  $\text{Al}(\text{OH})_3$  and amphoteric in nature." . . . "The last stage of aging of the aluminum hydroxide gel in caustic soda corresponds, according to Fricke and Meyring, to the formation of hydrargillite  $\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$ , of which Fricke and Jucaitis have calculated the solubility product  $(\text{AlO}_2^-)(\text{H}^+) = 2.5 \times 10^{-15}$  or  $10^{-14.60}$ ."

In relating the work of Shikkor, Messrs. Putilova, Balezin and Barannik (51) state: "Shikkor also established that the solution rate of aluminum in alkalies is almost independent of the purity of the metal, and on the basis of his experiments concluded that the solution rate is determined not by the formation of micro-galvanic cells but, most probably, by the production of a film of amorphous aluminum hydroxide on the metal surface and its subsequent slow dissolution."

No. 2. McKee and Brown (9) state: "In direct contrast to sodium hydroxide solutions, low rates of attack were obtained with ammonium hydroxide solutions. This wide difference in corrosion rates in two different alkaline solutions can be explained by the great difference in the solubility of the corrosion product in the two solutions."

Figure 17 in the McKee and Brown paper (9) shows the effect of potassium nitrate and ammonium nitrate on the solubility of aluminum hydroxide  $\text{Al}(\text{OH})_3$  in ammonium hydroxide.

From the preceding it appears that other authors attach importance to aluminum hydroxide.

No. 3. Lowe's statements are based upon the following sentence in our paper, and we quote: "Other reports have indicated that aluminum is generally inert or inhibited from accelerated corrosion when the pH range of the environment is: 4 to 9 (2), 6 to 8 (3, 4), 5.5 to 7.8 (5), 4 to 8 (6), and 4.5 to 9 (4)."

This sentence as written does not contain an incorrect quotation because we have not directly quoted any references as specifically stating "generally inert or inhibited from accelerated corrosion." The listed pH ranges will be found in the cited references.

The authors believe they are justified in using the nonspecific terms, "generally inert or inhibited from accelerated corrosion," because reference was made to five publications that varied not only in scope but also in the terminology which was used in reporting their observations.

The use of the word "indicated" in a sentence without quotation marks does not necessarily imply a direct quotation. In fact, the use of the word "indicated" may imply that a further analysis of data is being reported.

For example, the following two statements are contained in two papers (2, 53) that comment on the results of the same investigation (9). The published paper, itself, by McKee and Brown (9), does not show data or contain text that describe the corrosion

rate test results or the effect on the oxide film in terms of ranges of pH values per se. In this subject paper, the criterion of good corrosion resistance was stated to be below 5 mils/year.

(a) Statement by T. A. Lowe and A. H. Koepf (2): "Aluminum oxide is generally inert to chemical attack within the range of pH 4 to <sup>9</sup>(10)."

(b) Statement by C. J. Walton, F. L. McGeary, and E. T. Englehart (53): "It has been indicated by McKee and Brown<sup>4</sup> that in exposures to neutral or nearly neutral solutions, pH 4.5 to 8.5, the film is fortified by the formation of additional hydrated alumina to increase its resistance to the new environment."

It will be noted that statement (b) included the word "indicated," and neither statement (a) or (b) had contained quotation marks.

#### Statement 3 (Lowe)

"Deltombe and Pourbaix reproduce the graphs of Shatalov in their paper which indicate the influence of pH on the rate of corrosion of aluminum. These graphs show essentially zero corrosion rates over a pH range wider than the 4.0 to 8.6 suggested by Deltombe and Pourbaix, than the 4.0 to 9.0 recommended by Kaiser Aluminum, and certainly wider than the 6.0 to 8.0 specified by Nordlin and Stratfull."

#### Comment

With reference to the reproduced graphs of Shatalov, Deltombe and Pourbaix (5) conversely state: "In Figure 3b, these same results have been transferred to a graph with linear co-ordinates, which emphasizes the slow rate of corrosion between pH 4 and pH 8, and the rapid increase outside these limits."

#### Statement 4 (Lowe)

"One is warned against accepting data without learning the conditions under which the data were obtained. In the McKee and Brown study (57), also referenced by Nordlin and Stratfull, the one sentence discussing tests with sodium carbonate reads, 'Although alkalinity produced by the presence of sodium hydroxide or resulting from hydrolysis of a sodium salt such as the carbonate causes appreciable corrosion, aluminum may or may not be resistant to such solutions, depending upon the nature of other ions present.'"

#### Comment

Under Conclusions in the McKee and Brown study (9 or 57) to which Lowe refers, the following sentence related to sodium carbonate may also be found: "Conclusion 9. Aluminum is resistant to sodium carbonate solutions up to 0.001 normal concentrations, either in the presence or in the absence of sodium chloride, but in higher concentrations, the behavior is similar to that in sodium hydroxide solutions."

In our paper, the sentence regarding the corrosion of aluminum in sodium carbonate reads: "It has been reported that in sodium carbonate solutions of greater than 0.001 normal concentrations (approximately 60 parts per million), aluminum is significantly attacked (9)."

#### Statement 5 (Lowe)

"Produced waters are not normally encountered in culvert applications."

#### Comment

Lowe in his discussion defines a spring and well water as produced water. In California it is not unusual for culverts to convey spring water or for underdrains to intercept subterranean water.

#### Statement 6 (Lowe)

"While on the subject of cladding, it might be well to comment on the authors' termi-

nology 'corrosion inhibiting cladding.' The cladding does not, nor is it intended to, inhibit attack."

#### Comments

No. 1. In H. P. Godard's discussion of our paper, he states: "In natural waters and soils, most aluminum alloys, and certainly all of those which would be considered for culvert construction, do not suffer uniform or general corrosion. That is to say they do not waste away by general thinning. If corrosion attack does take place, it is localized, and usually in the form of pitting, in a random pattern over the surface of the metal."

Based upon the pitting criterion stated by Godard, Figures 37 and 39 indicate that the percentage of clad aluminum samples which had zero mils of pitting was far greater than those samples which were not clad. With zero mils of pitting, the cladding cannot be acting galvanically to the base material. Therefore, as corrosion did not occur on the cladding in more cases than it did on unclad aluminum, it appears that the cladding may be correctly termed "corrosion inhibiting."

No. 2. Lowe states in his discussion: "The cladding on aluminum culvert is intended to mitigate any attack that might be caused by an unusual water." From this statement it also seems reasonable to assume that the cladding is "corrosion inhibiting."

#### Statement 7 (Lowe)

"One cannot arbitrarily average the values reported and have a meaningful value. Furthermore, most of the installations which we reported fall below the mean value listed by Nordlin and Stratfull and these installations, as a whole, are showing excellent performance."

#### Comment

Table 25 indicates that we find most of the readings published by Lowe and Koepf (2) do not fall below the reported mean value which is shown on Table 12 in our report.

The mean resistivity values listed in Table 13 of our paper were based upon the one which was the least in-place soil resistivity value reported by Lowe and Koepf (2) for each culvert site. In addition, these values were segregated according to what appeared to be the corrosion condition of the pipe. Approximately 40 percent of the least in-place resistivity values resulted in a mean of 2,000 ohm-cm or less. In 33 out of 39 cases, Lowe and Koepf show three in-place soil resistivity values for each culvert site.

In Table 25, every resistivity value was used without regard to the condition of the culvert or the pH of the environment.

#### Statement 8 (Lowe)

"We believe that depths of 2.5, 5.0, and 10.0 ft cover the great majority of culvert installations in existence. We therefore get a reasonable indication of soil resistivity at the culvert depth while getting a 'feel' for the complete range of material which may have been used as backfill."

#### Comment

In California we have had difficulty in duplicating field resistivity measurements that are obtained during different seasons of the year.

#### Statement 9 (Lowe)

"Nordlin and Stratfull have made a serious misinterpretation of resistivity readings in the report by Lowe and Koepf (59). Those readings were made in the field using a Model 263 A Vibroground equipped with a wiring harness for obtaining average resistivities at depths of 2.5, 5.0 and 10 ft."

TABLE 25

TOTAL RESISTIVITY READINGS (2)  
ABOVE AND BELOW MEAN VALUE

Mean Value (ohm-cm)	Number Above	Number Below
3, 100	54	53
2, 000	60	47
250	103	4
Total	217	104

Comments

We do not agree that we have made a serious misinterpretation of Lowe and Koepf's published (2, or 59) resistivity readings.

Reference (12) in our paper relates the work of Stratfull wherein he empirically correlates the culvert corrosion test method (10) of pH and minimum soil resistivity to test methods which utilize the average soil resistivity. The latter is the method employed by Lowe and Koepf (2). The test method published by Stratfull (12) was found to be a more accurate test for estimating soil corrosivity.

In our paper under discussion, we have shown by the following statements that average soil resistivities as obtained by Lowe and Koepf (2) can be significantly different than the "minimum soil resistivity." "Although the validity of this analysis of data in Table 13 has not been verified, it is interesting to note that there seems to be a reasonably implied correlation of data." . . . "The resistivity measurements were determined for the most part on an in-place soil. Therefore, they may not be accurately reproducible owing to the fact that these values are highly dependent upon the seasonally variable moisture content of the soil. Normally, soil resistivity measurements used in culvert corrosion technology are based on the minimum value. The minimum resistivity is normally less than the in-place soil resistivity. Therefore, care should be exercised when directly comparing the in-place field values to the minimum resistivity of a soil (10)."

Statement 10 (Lowe)

"Only aluminum alloys specifically designed to provide cathodic protection can be used to protect steel." . . . "Most aluminum alloys will not provide such protection, as evidenced by the literature (62) on aluminized steel. For aluminized steel, aluminum provides some protection only in the presence of significant chloride concentrations, such as in marine environment."

Comments

No. 1. H. P. Godard states (48): "It is well known that aluminum stands high in most galvanic series and hence provision must be made to avoid galvanic corrosion when using aluminum in contact with other metals. This is one of the most common practical corrosion problems with aluminum and one that can be eliminated if attention is given to joint design and care of construction."

No. 2. It is our understanding that the cladding used on aluminum culvert sheets is specifically designed to provide cathodic protection.

Statement 11 (Lowe)

"In effect, soil corrosion is being evaluated at only three of the eight sites, a fact confirmed in the authors' paper, Table 3. Thus the use of aluminum culvert by the State of California is based on the performance at only three sites."

Comment

Of the eight aluminum culvert sites, four were shown (see Figs. 4, 6, 10, and 13) to be perforated by corrosion or destroyed by abrasion. Because of this destruction, we assumed that the observations of corrosion on the backfill side of the culverts had been misleadingly influenced by the flow leaking through the perforations.



Statement 12 (Lowe)

"The authors give no data or description of the comparative performance of the culvert materials from one inspection time to another."

Comment

Tables 2, 14, and 15 in our paper report the results of two inspections on some culverts.

Statement 13 (Lowe)

"These comments are not intended to stand by themselves, but to complement discussions offered on this paper by Dr. Hugh Godard and by A. H. Koepf."

Comments

It appears that the comments by T. A. Lowe also contradict the discussion by H. P. Godard with regard to pH and resistivity limitations for aluminum culverts. For example, Lowe states: "On the basis of this broader experience, aluminum culvert would be expected to: 1. Provide corrosion performance superior to that of galvanized steel in soils within the pH range of 4.0 to 9.0 and having a minimum resistivity above 1,500 ohm-cm."

Conversely, H. P. Godard states: "In studies of aluminum corrosion, pH has not been found to be a significant variable in either waters or soils." . . . "To indicate the lack of correlation between corrosivity and soil resistivity, the values for the burial plots are given in Table 23." . . . "I suggest also that the criteria selected by Nordin and Stratfull are not applicable or necessary for predicting the service life of aluminum culverts."

A. H. KOEPF, Kaiser Aluminum.—The paper, "A Preliminary Study of Aluminum as a Culvert Material," has been prepared to describe data from a first inspection of eight culvert sites where aluminum alloy and galvanized steel culverts were exposed to aggressive environments. Several laboratory tests relating aluminum alloy to steel were also conducted. From the data obtained, the authors have estimated service life expectancy of aluminum alloy culvert.

Discussion of the report is required in two stages. First is a general review of the background fundamentals upon which this report appears to be based, for in this area, the authors' method of analysis is open to question. Errors in understanding and extrapolating results noted negate most of the value which may be attached to the conclusions of the authors. Second in discussion is a review of the report details. In this area, there is much to be learned from the data, particularly when stripped of opinion so the data may be judged from the merits of their compilation. In spite of differences of opinion, however, the authors are to be complimented for the presentation of field data in a subject where more knowledge is necessary.

General Discussion

Several major points need to be established. (1) The report is based solely upon performance of only eight sites, all of which were so placed to develop data for extreme exposures; yet the pattern of the paper is to rely heavily on statistical averaging of these few extremes for predictions of life. These two conditions, one of exposure and a second of analysis cannot be reconciled, and certainly do not represent a normal approach to research. (2) The progression of corrosion behavior of alclad aluminum alloys follow a distinct pattern which can be quite different from the progression of galvanized steel. The authors did not recognize this in their analysis and opinions, creating impressions which vary widely from the behavior expectations of aluminum

TABLE 26  
ESTIMATED YEARS-TO-PERFORATION OF GALVANIZED  
STEEL FIELD TEST CULVERTS  
(Based upon a method of predicting years-to-perforation  
adopted by the California Division of Highways)

Culvert Site	Location	Installation Conditions for Corrosion Evaluation	Estimated Years-to-Perforation by (16 gage) Corrosion (10)
A	I-HUM-35-C Bridgeville	Average coastal soil, mild acid moderate abrasion site	22
B	II-SHA-3-B Redding	Strong sulfuric acid flow from sulfide soil leaching	0
C	III-BUT-21-B Oroville	Very strong sulfuric acid flow from sulfide soil leaching	0
D	IV-SCL-5-C Los Gatos	Abrasion site—not considered in corrosion summary as sand backing used	50
E	IV-SCR-5-A Scotts Crossing	Sulfuric acid flow from leaching silty peat backfill elsewhere	0
F	X-SJ-53-C	Silt much in invert area only this area reported	2-14
G	XI-SD-2-NAT CTY National City	Clay muck in invert area and granular select backfill elsewhere with both Urban runoff and salt water tidal flow. Only invert area and stream on soil side reported	8
H	XI-IMP-187-F Salton Sea	Salt saturated alkaline	3
Average years-to-perforation of seven corrosion sites (Site D not included)			= 5.0 to 6.8 years
Average years-to-perforation of four corrosion sites with pH in 4.5 to 8.3 range (Sites B, C, D, E, not included)			= 8.7 to 11.7 years

alloy. (3) The cumulative mechanisms of wastage of galvanized steel and aluminum alloys in erosive, abrasive, and abusive flows are not the same. The authors indicate they have no way to rate these conditions, yet categorically conclude culvert performance life across the same full range of bedloads. (4) The data obtained on galvanized steel, supported by previous work by the authors, showed short life expectancy at these sites; while the same work acknowledges areas of long life exposure on steel under less severe exposures. This disparity may also be applied to aluminum alloy culvert, but was not done in this instance.

#### The Eight Field Sites

A description of the location of the eight test sites cited in the paper is contained in Table 26. The soil or water properties existing at each of these sites is charted in Figure 42. The recommended lower limits for galvanized steel for 25- and 50-yr time for perforation established by the Division of Highways (10) are shown along with the



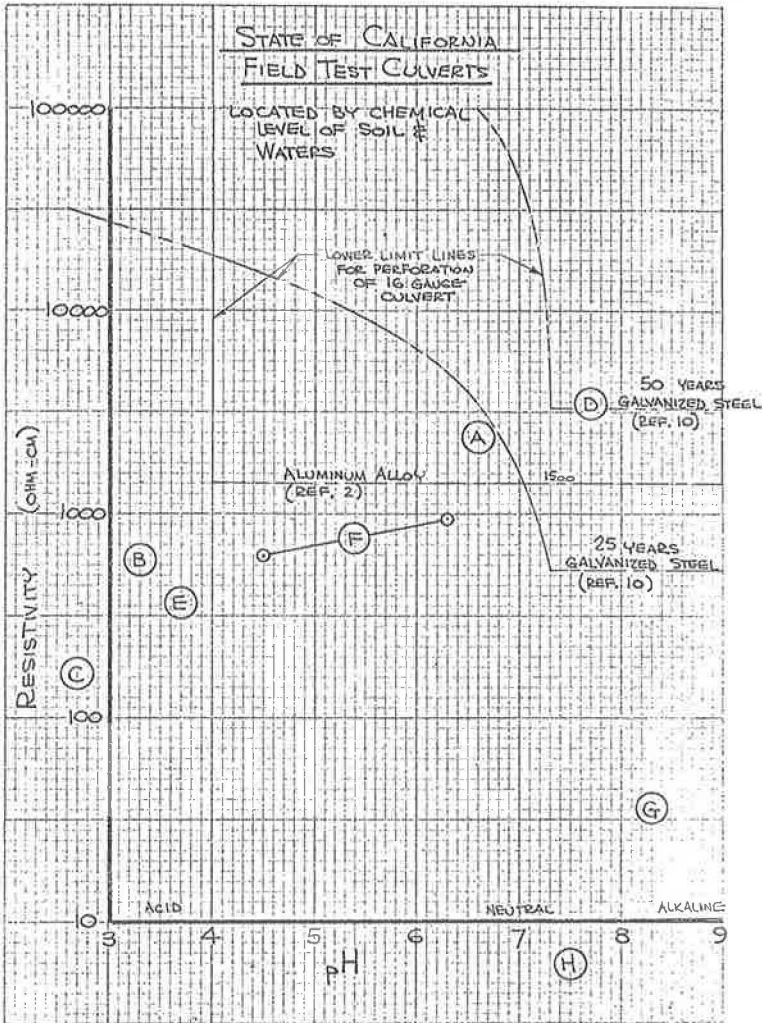


Figure 42.

lower limit recommendations for long life for aluminum alloy culverts as developed by the aluminum industry. Figure 42 and column 4 of Table 26 indicate clearly that all test sites represent extremes, thus offering possibilities for rapid acquisition of knowledge if each site is evaluated comparatively but separately from other non-similar sites. A general description of each site was not included in the paper. Therefore, column 3 of Table 26 is included for reference.

The preparation of the paper bases service predictions on application of statistical averaging. Earlier work was based upon as much as 7,000 sites (10) from which statistical averaging can be expected to produce well-supported results. From the previous data and restated in this paper, there is some trend of linearity of wastage in corrosion of galvanized steel which, of course, improves the accuracy of predictions of years-to-perforation of steel.

The same statistical averaging approach was used to analyze the corrosion performance of aluminum alloy culverts. However, in this case, this was done with but eight specimens with all but one (A) substantially outside of the recommended application range for either steel or aluminum, as shown in Figure 42.

Application of statistical analysis is only as good as its base data. It is readily apparent that when all sites are beyond the normal product working range and limited to

eight specimens general averaging, adopted by the authors, produces results of little value. As an example, consider the use of this approach on galvanized steel life. The prediction formula of the Division (10) shows the seven corrosion sites for steel to have an average years-to-perforation of 5.0 to 6.8 years. Discounting Sites B, C, and E in sulfuric acid with rated times of zero years, the remaining four corrosion sites average 8.7 to 11.7 years-to-perforation. On the basis of this data alone, using statistical averaging, steel culverts which are expected to resist perforation for more than 10 years would need bituminous coating. A blanket conclusion such as this is obviously invalid. It is well established that in many exposures steel will perform well for many times that period. However, this is the exact analogy and statistical base upon which the authors' conclusions on aluminum service life were derived and coating requirements established.

### Progression of Corrosion

The progression of corrosion of alclad aluminum alloys has been established by a number of investigators. The unique characteristics which resist or arrest corrosion are the basis upon which the wide use of aluminum in corrosive exposures may be considered. The need for enlightened understanding of the stages of corrosion of aluminum is mandatory if proper credence is to be placed in the uses of the material which have been proven by time. Where the exposure is noncorrosive or of a mildly corrosive nature, the surface may be observed to perform in several manners. It can appear stained, a result of differential light diffraction from oxide buildup of varying thicknesses. It may show a random nonprogressive pit with hard corrosion product buildup. Neither case represents corrosion which proceeds at a linear rate; in fact, the surface performance might be improved as a result of oxide buildup. In this first phase of exposure, the aluminum is structurally unaffected.

When the exposure becomes more corrosive to aluminum, the cladding proceeds to provide anodic protection of the base metal. Electrochemically, the protection may be likened to that of zinc on steel only to a limited extent. Cladding is anodic to the aluminum alloy core by a small potential difference and thus appears to be more active than zinc on steel in early stages. It cannot be effective unless it does suffer corrosion. However, in so acting, deposits of corrosion products inhibit further electrochemical current and the corrosion cell action becomes self-arresting. Zinc on steel reacts somewhat differently, more like a coating. Because of the high potential difference between zinc and iron, the removal of the zinc coating, once penetrated by corrosion, may well proceed at a higher unit rate than on alclad aluminum. Neither the zinc nor the iron have self-healing oxides and progressive corrosion may be expected. Thus in the second phase, the aluminum will show evidence of corrosion relatively quickly and just as quickly show evidence of the self-arrestment of surface corrosion. Galvanized steel will suffer uniform attack on the surface, sometimes becoming arrested if the surface buildup is completely contained by the environment, such as soil. A second type corrosion has been observed to occur in culvert most frequently in heavy or salt-laden soils which may be likened to concentration cell activity. Such soils are usually fine grained and dense with very poor oxygen circulation and are characterized as silts or mucks or soils of very low resistivity.

A third type of aluminum corrosion occurs when the chemical level is so high that the surface aluminum oxide can be chemically attacked and corrosion will proceed aggressively as fast as reaction rates allow. In the same exposures, zinc and iron are also readily attacked. The example of such progressive corrosion occurs in strong sulfuric acid exposures.

Each of the eight test sites falls within a category broadly defined by the types of corrosion above. Sites A and D are in the noncorrosive soils; Sites F, G, and H are in soils causing some, but not progressive-type, corrosion; and Sites B, C, and E are in aggressive environments.

The authors did not consider the step-wise characteristic behavior of aluminum alloys which does not lend itself to life predictions by linear projections except in aggressive corrosion exposures. The possibility of progressive corrosion behavior may be reasonably confirmed by making two or more inspections over a period of time. This paper

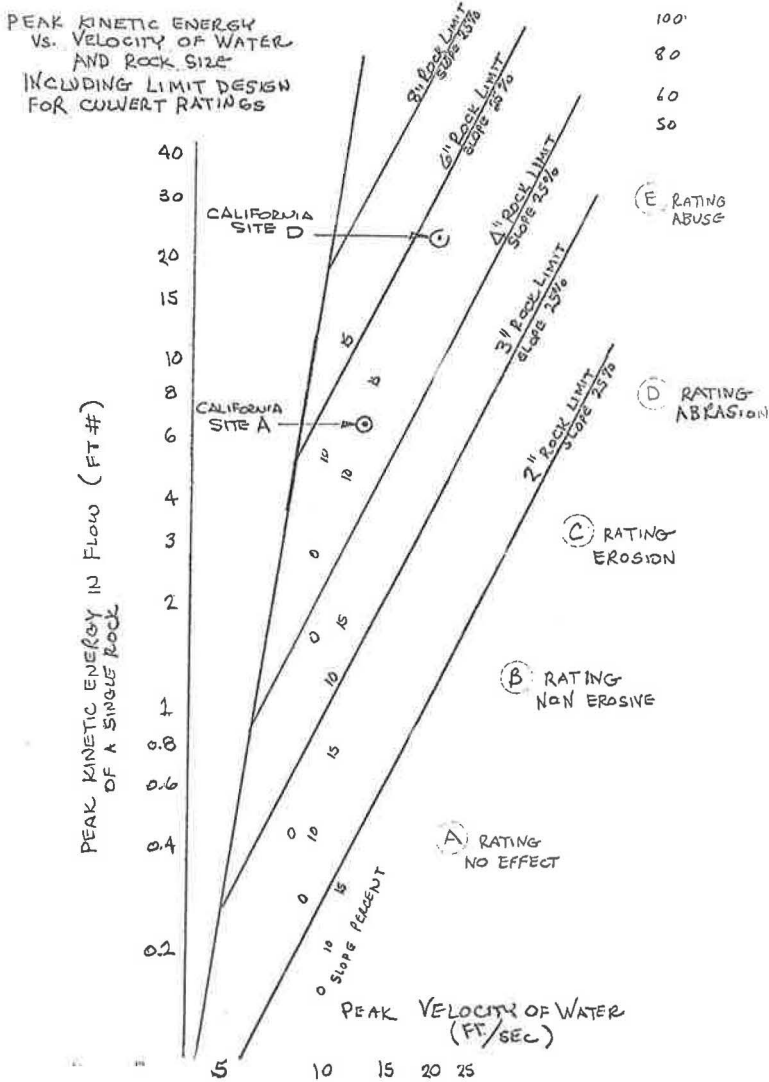


Figure 43.

does not check this very important point, even though over a year elapsed after the reported inspections and the completion of the paper.

When the function of the cladding is not fully considered and service life is reported by linear projection from corrosion depth measurements using a single observation the results are obvious. The standard thickness of cladding on aluminum culvert sheet is 5 percent of the total on each side and when performing its function may be corroded to this depth. Using the linear means of projection, based upon measured depth of corrosion by the years-to-perforation extension method, alclad aluminum alloys become rated at 10 or 20 years, such as Sites F, G, and H. Such an extrapolation is meaningless as it considers nothing other than that the cladding is functioning. A prediction of life can only be established from several inspections. However, these unrealistic extrapolations were made by the authors and have become prime base data for the previously described statistical averages. Thus, the years-to-perforation for Sites A, F,

G, and H have been reported as generally the same, 6.6 to 17 years, further reducing the questionable process of averaging.

### Erosion and Abrasion

The wastage of aluminum alloy or galvanized steel by combined action of water velocity and size of bed-load cannot be conveniently considered in the single category of "abrasion." The authors acknowledge this in comparing the performance of Sites A and D. In spite of this, however, the conclusions on service life are made on the basis of such a single broad category.

Contrary to the opinions stated by the authors, work has been done in studying the effects of abrasion on culvert. The method of establishing such a study has been to develop an expression of energy level exerted by a combination of rock size and velocity of flow and relate this level to the effect on culverts. Energy level of a single rock may be developed from equations of dynamics using approximations of surface friction. Using this approach as a comparison basis, Figure 43 was developed. In order to relate the effect of the energy level on culverts, a series of rating conditions have been established for aluminum culvert. The five rating conditions are as follows:

- A - No effect on the aluminum surface
- B - Slight roughening of crown of invert corrugation, but no significant metal removal as a result of flow
- C - Erosion; slight abrading of the corrugation surface at an estimated rate of 0.002 in. per year (25-year life)
- D - Abrasion; abrading of the corrugation surface at an estimated rate of 0.002 in. to 0.005 in. per year
- E - Abuse; rapid abrasion of the corrugation surface at an estimated rate exceeding 0.005 in. per year

A number of investigations have been made and the rating condition lines have been superimposed on the previously calculated energy level curves. The completed curves and rating lines for the first time allow a method of determining cause and effect so that the spectrum of abrasion may be properly described.

An energy rating system for culvert must, of necessity, be an approximation. Widely varying flow rates and velocities, maximum sizes, gradation of bedload, and shape of rocks during each period of exposure require that any system be used with judgment based upon experience. Nonetheless, it is felt that these tend to strike an average in their effect on the surface. In order to lend uniformity in ratings, flow velocities for this analysis are based upon the condition of a projection inlet culvert flowing two-thirds full at the entrance. This condition represents a flow which could occur frequently in the service period and if the culvert flows full or half full, the velocity in the culvert will not vary widely. Rock size is established by approximating a mean-peak size which can be expected to pass through the pipe during the higher flows, based upon observation of the site or prior knowledge of stream bed behavior. The rating system was established to consider fractured rocks rather than rounded rocks. The lesser area of contact for sharp rocks would, of course, concentrate more stress at the impact point and would be expected to abrade more. Limited observations appear to call for reduction of ratings for flows of rounded rocks one or two levels.

Using this rating system, results of the report's abrasion Sites A and D have been plotted on Figure 43 and may now be properly assessed as abrasion and abuse. The conclusions of the paper may then be amended to state that these conditions could be expected. The laboratory coupon tests with sand flow represent another condition of either rating B or C.

Wastage of metal in culvert inverts is a result of combined corrosion and erosion. When the mechanics of corrosion are superimposed upon an energy spectrum, it is then possible to evaluate the cause of early failure of metal culverts due to "abrasion." This process on galvanized steel usually takes the form of combined corrosion-erosion over a period of several years. On aluminum alloy culvert, the failure must normally be due to erosion or abrasion alone, as rarely does corrosion of aluminum appear in

abrasive flows. Once again, arbitrary statistical comparisons are meaningless without the exercising of judgment in analysis of the data which have been presented.

The laboratory corrosion-abrasion tests, when considered, offer ample evidence of the considerably different means to approach equivalent end results. The aluminum results showed generally low-corrosion wastage but some displacement of the cladding. The steel results showed the relatively rapid wastage of metal as a result of corrosion assisted by the scrubbing action of the sand to expose new metal. While the authors did not mention it, the zinc layer on the galvanized steel specimens in this test were rapidly abraded to expose bare steel so that, except for a starting lag, galvanized steel may be expected to perform similarly to the bare steel.

The principal conclusion one can draw from these tests is confirmation that, in normal culvert service, the corrosion-erosion wastage cycles must be considered as applicable with steel on the corrosion side and aluminum on the erosion side of the cycles. It is interesting to note that the calculations and observations for energy ratings indicate that, generally, bedloads with rocks up to 2 in. in size do not appear to be deleterious to aluminum as erosion culvert service but that smaller particles can propagate the corrosion-erosion cycle on galvanized steel. In this range, it does appear aluminum alloy is equal to, or superior to, galvanized steel as the laboratory tests confirm.

The Division of Highway's method for definition of abrasion flow design limits at  $Q_{10}^*$  of 5 or 7 ft/sec is an excellent one, particularly as it limits the probable rock sizes at the entrance of the culvert which may be carried into the pipe.

As the water velocity and rock sizes in the bedload increase, the impact effect begins to increase markedly, following a form approximated as up to  $V^6$ . At higher energy levels, the erosion in the erosion-corrosion cycle increases markedly and the aluminum may be expected to begin to be wasted by abrasion more rapidly than steel. Meanwhile, the corrosion rate on steel would remain relatively constant across most of the range. At some point, the cumulative wastage of aluminum and galvanized steel would be comparable and above this in highly abrasive or abusive flows, the galvanized steel will perform better, though the design life of both will be shortened.

The report's culvert test Sites A and D are performing within the projections of the abrasion hypothesis. Site A, rated as abrasive to aluminum, is confirmed. The principal wastage on steel is due to corrosion assisted by bedload scrubbing to remove zinc, and later, iron oxide, while aluminum was subjected to localized abrasion and no corrosion. Site D, rated as abusive to aluminum clearly demonstrated it. Galvanized steel was abraded considerably, but as the time was so short, the corrosion part of the cycle was virtually nonexistent. Site D contains a great deal of valuable information of use in design of inverts and invert protection, and it is unfortunate the authors did not discuss this.

Concluding the discussion on abrasion, it is important to indicate that the corrosion-erosion cycle must be considered in evaluation; that mathematical approximations based upon impact energy do exist from which levels of abrasive flow may be derived; that aluminum performs well in normal erosion flows but poorly in abusive flows. The conclusions of the authors upon which the report recommendations on abrasion for all conditions of flows are based were arrived at without placing the data into some evaluation form on severity of exposure.

## Conclusions

The report in question is just that. Data were obtained from eight culvert test sites subjected to aggressive exposures, each representing an extreme. This was superficially supported by limited laboratory abrasion, water immersion and fog tests. The data developed were noted in some detail, but did not include observations and measurement details which are necessary to complete understanding of performance. The conclusion and opinions of the authors were arrived at through a combination of statistical

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\* $Q_{10}$  is defined as the 10-yr storm flow which will develop. Entrance headwater depth equal to the height of the culvert, or the condition of flowing full at the entrance. The velocity at the entrance is obtained by dividing  $Q_{10}$  by the area at the entrance.

averaging with an inadequate data base and by not thoroughly understanding the observed performance.

Contrary to the opinions stated in the report, aluminum alloys are performing as well as, or better than, might be predicted from knowledge of the exposures—indicating it likewise will perform well in milder normal exposures.

E. F. NORDLIN and R. F. STRATFULL, Comments.—

Statement 1 (Koepf)

"The paper, 'A Preliminary Study of Aluminum as a Culvert Material,' has been prepared to describe data from a first inspection of eight culvert sites where aluminum alloy and galvanized steel culverts were exposed to aggressive environments."

Comments

Tables 2, 14, and 15 in the subject paper report the results of two inspections on some culverts.

Statement 2 (Koepf)

"The need for enlightened understanding of the stages of corrosion of aluminum is mandatory if proper credence is to be placed in the uses of the material which have been proven by time."

Comments

The maximum previously reported amount of time in which aluminum had been used as a culvert material was 3.6 years (2). This is believed to be an insufficient amount of time to definitely establish a long-term corrosion pattern of aluminum as a culvert material.

The results of other tests of the underground corrosion resistance of aluminum for up to 10 years are shown in Figures 37, 38, 39, and 40, which are included in our comments on Godard's discussion. These tests were all performed on comparatively small specimens that do not necessarily encompass corrosion variables that can occur as the result of larger dimensions and methods of fabrication such as found in culverts.

Statement 3 (Koepf)

"The recommended lower limits for galvanized steel for 25- and 50-yr time for perforation established by the Division of Highways (10) are shown along with the lower limit recommendations for long life for aluminum alloy culverts as developed by the aluminum industry."

Comments

No. 1. Reference is made to aluminum industry (2) recommendations, as shown in Figure 42 of Koepf's discussion, for a lower resistivity limit of 1,500 ohm-cm and an indicated pH range of 4 to 9. The aluminum industry (2) has not demonstrated by mathematical verification that these criteria are applicable to aluminum alloy culverts.

In Figure 42, "Resistivity (ohm-cm)" is not defined. The 25- and 50-yr curves for galvanized steel (10) represent the minimum resistivity of a soil sample removed from the culvert channel or the resistivity of the culvert flow and are not an average in-place soil resistivity measurement.

No. 2. The aluminum industry (2) did not define how many years is considered to be "long life" for aluminum alloy culverts.



Statement 4 (Koepf)

"The authors did not consider the step-wise characteristic behavior of aluminum alloys which does not lend itself to life prediction by linear projections except in aggressive corrosion exposures."

Comments

No. 1. Reference is made to our Figures 37 through 40. These figures indicate two general behavior patterns for aluminum alloys. For the reported periods of testing, the indicated patterns of underground corrosion behavior as shown in Figures 38 and 40 are: (1) aluminum has a weight loss of 0.1 percent and 0.2 percent, or (2) the results of testing indicate a log-normal distribution of greater amounts of weight losses. In Figures 37 and 39, the indicated underground corrosion behavior patterns are: (1) zero mils of pitting, or (2) a normal distribution of increasing amounts of pit depths.

None of these Figures (37 through 40) demonstrate that when aluminum is randomly placed in all types of soils, there is a corrosion characteristic which will prevent the significant deterioration of all culverts of 0.060-in. wall thickness by the defined corrosion criteria of weight loss or pit depth.

No. 2. "Aluminum alloys are quite resistant to sea water. A corrosion rate of about 0.4 mpy or one-tenth the rate for steel was found for Alcan 57S (US 5052) at Harbor Island, N. C." (48).

This corrosion rate is a linear 0.0004 in. per year and thus one might assume that sea water is not an aggressive environment to aluminum.

No. 3. McKee and Brown (9) state: "In solutions such as acetic acid and sodium hydroxide (see Figures 1 and 2) the weight loss of aluminum varies linearly with time." . . . "Therefore, weight losses in ammonium hydroxide solutions were determined after two days and after seven days, and the calculated penetration rate was based on the difference between the two-day and the seven-day weight losses." Since they conclude in their report that aluminum is resistant to corrosion in ammonium hydroxide and acetic acid solutions one can assume that these are environments which are not aggressive to aluminum.

McKee and Brown (9) reported most of their test results in the linear units of mg/sq cm/day and penetration-mils/year. These are linear descriptions of the rates of corrosion of aluminum.

Some of the data shown in our paper may be converted to the terms of mg/sq cm/day by dividing the weight per unit area (sq cm) of 16-gage aluminum or steel by the reported years (times 365 days) to 100 percent weight loss.

Statement 5 (Koepf)

"The possibility of progressive corrosion behavior may be reasonably confirmed by making two or more inspections over a period of time."

Comments

Sometimes it is extremely difficult to establish and reasonably confirm the pattern of progressive corrosion on the basis of two or more samples randomly selected at different times. For example, in the paper by Lowe and Koepf (2), the microsections of aluminum shown in their Figures 3 and 4 after 1.0 years of exposure appear to be more corroded than those shown in Figures 6 and 7 after 3.1 years at Royal City, Washington. This is indicated by comparing Figure 3 to Figure 6 and Figure 4 to Figure 7. Thus, one might question the validity of any one sample as reasonably confirming a minimum, average or maximum amount of corrosion of the culvert. This factor is also demonstrated on Table 19, which was submitted as a part of this discussion by H. P. Godard, wherein 2 out of 4 samples had less depths of pitting after 7 to 8 years than at 4 years.

Statement 6 (Koepf)

"Contrary to the opinions stated by the authors, work has been done in studying the effects of abrasion on culverts."

## Comments

It is not clear as to what is meant by Koepf's statement as this was not stated or implied in our paper. For example, abrasion tests were performed as a part of this investigation under discussion.

We wish to compliment Koepf for his approach to the effects of abrasion on culverts. His chart, "Peak Kinetic Energy vs. Velocity of Water and Rock Size Including Limit Design of Culvert Ratings," seems to be a reasonable approach to the evaluation of the effects of abrasion. However, we do not have information or a reference where this hypothesis with regard to culverts has been documented or confirmed by a previous publication in a technical journal.

Koepf's abrasion hypothesis would be enhanced if the 22 categories of abrasion and rock size were verified by more than the two observations which he shows on the chart.

JOHN R. DAESSEN, Director, The Galvanizing Institute.—A test sponsored by Bureau of Public Roads, which results in recommendations for use of aluminum culverts for an estimated life of 25 years, should state clearly and briefly in its summary, conclusions and recommendations the limitations discovered, namely:

Uncoated aluminum culverts are not recommended for use in soils of average pH below 6 or over 8, or with soil resistivities below 2,000 ohms-cm, or with abrasive flow over 7 fps; and should not be used, bare or coated, when the flow contains heavy metals unless the invert is paved.

The following comparative relationships, developed by the test, between galvanized steel and aluminum should be clearly indicated.

From Tables 3 and 4, in 7 field test sites, most of them highly aggressive, with pH ranging from 2.7 to 8.3, the life of aluminum was estimated to average 9 or 48 percent that of galvanized steel, based on abrasion and corrosion, respectively. In 5 test sites with pH between 4.5 and 8.3 the ratio of life was as above, but the average life for both materials was 38 percent longer for both materials than in the broader pH range.

From Table 8, in laboratory corrosion-abrasion tests, bare steel was estimated to have a life (to perforation in 16 gage) of 51 to 76 percent of that of aluminum. Galvanized steel, in pilot tests, showed far greater resistance than either bare steel or aluminum ("each test would probably require more than two weeks"). The test results of bare steel against aluminum in this exposure are therefore without value in predicting comparative life.

From Table 11, in continuous submersion tests at pH 4.3 to 9.0, aluminum had an estimated life of 2.9 to 3.7 years (to perforation in 16 gage) while galvanized steel was unaffected (70-day test).

From Table 12, in laboratory fog room tests, aluminum had an estimated life of 3.2 years to perforation (16 gage) while galvanized steel was unaffected (one year test of galvanized steel).

As the connection between the reported results and the estimate of a 25-yr life for aluminum culverts where recommended is not indicated, it can not be presumed that this test supports a recommended use for a life of 25 years.

E. F. NORDLIN and R. F. STRATFULL, Comments.—J. R. Daesen is entirely correct in that we were unable to directly correlate our test results with a 25-yr service life of aluminum culverts. However, as we pointed out, we exercised judgment in relating our test results to a numerical service life. This judgment was based upon pH and resistivity levels which indicated a minimum corrosion rate for aluminum.



ERNEST W. HORVICK, Director of Technical Services, American Zinc Institute.—The tests carried out by the California Highway Division were certainly technically conducted, neutral, objective and unbiased. We agree with the discussion of findings under the heading "Remarks."

It was emphasized that since the paper related to accelerated investigations, actual service experience would be carefully noted to ascertain the verity of the accelerated tests.

A culvert in performance represents a dynamic situation in which the material is exposed to soil, running water and that which is entrained in it. This represents true performance.

The aluminum soil test data offered in rebuttal only related to test pieces embedded in soil and represent a static condition in which all of the variables encountered in culvert performance are not met.

E. F. NORDLIN and R. F. STRATFULL, Comments.—We agree with E. W. Horvick that test results of small samples placed in the soil can only be indicative of a particular parameter of the corrosion phenomenon on the soil side or beneath silt in a culvert. It is reasonable to assume that even these underground test results would have been different if the dimensions of the samples were drastically altered.

S. K. COBURN, Applied Research Laboratory, U. S. Steel Corporation, Monroeville, Pennsylvania.—The following comments are offered to supplement the references given in the paper with respect to the effect of heavy metals, principally copper, on the pitting tendency of quiescent natural waters in contact with aluminum. Porter and Hadden, The British Nonferrous Metals Research Association, reported on their studies concerning the performance of several aluminum alloys in the waters of eight cities (64). They found that copper concentrations of 0.02 ppm and greater in stagnant water would seriously influence the behavior of aluminum alloys. They also found that the solution in the pits was strongly acid and contained chlorides concentrated some tenfold over those found in the flowing water.

Sawyer and Brown (65), Aluminum Company of America, indicated that very small amounts of heavy metals may stimulate corrosion of aluminumbase alloys. The attack is usually of the pitting type and is accelerated by the presence of chlorides. They described the pitting that occurred in aluminum utensils used in Altoona, Pennsylvania, where the water was found to contain, among other elements, 0.09 ppm of copper and 0.08 ppm of cobalt, together with chlorides, sulfates, silicates, and bicarbonates.

Rowe and Walker (66), General Motors Corporation, commented on the harmful effects on aluminum of copper found in tap water in various parts of the United States. Presumably they were concerned with the possibility of corrosion of aluminum engine blocks and/or radiators. They believe that the pickup of copper in domestic water systems employing copper tubing, together with the bicarbonates and chlorides that are present, would require the use of corrosion inhibitors to reduce the pitting tendency of the circulating cooling water.

One investigator (67), commenting on the Rowe and Walker paper, indicated that in the analysis of 100 natural waters, a range of copper contents was found from less than 0.001 ppm to 0.30 ppm with most containing less than 0.010 ppm (67).

These reports make it clear that the composition of natural waters can have a pronounced effect on the pitting of aluminum culverts. The most important factor in the occurrence of pitting is the presence of heavy metals in natural waters under stagnant conditions.

## References

64. Porter, F. C., and Hadden, S. E. Corrosion of Aluminum in Supply Waters. *Jour. of Appl. Chem.*, Vol. 3, pp. 385-409, 1953.
65. Sawyer, D. W., and Brown, R. H. Resistance of Aluminum Alloys to Fresh Waters. *Corrosion*, Vol. 3, pp. 443-457, 1947.
66. Rowe, L. C., and Walker, M. S. Effect of Mineral Impurities in Water on the Corrosion of Aluminum and Steel. *Corrosion*, Vol. 17, pp. 353t-356t, 1961.
67. Comments on paper by Rowe and Walker. *Corrosion*, Vol. 17, pp. 597t, 1961.

E. F. NORDLIN and R. F. STRATFULL, Comments.—As S. K. Coburn points out, the influence of relatively small trace amounts of copper in a natural water can have a significant influence on the corrosion of aluminum.

This point is of further concern because these fractional quantities of impurities can only be determined by a costly laboratory analysis. The cost of this analysis would be far and above that currently used by the California Division of Highways when considering the use of other culvert materials. Furthermore, even with the results of a laboratory analysis, we are not cognizant of any information which would enable us to definitely predict a corrosion rate of aluminum.

ALBERT R. COOK, International Lead Zinc Research Organization.—The authors and the California Division of Highways are to be congratulated on a very objective study. They must necessarily deal with the difficult program of deciding what long-term experience can be predicted on the basis of short-term tests. In corrosion work, this is always a difficult and hazardous undertaking. Clearly the authors are justified in their concern about pitting attack. Since the time to perforation is of vital importance, general weight loss measurements as opposed to pit depth measurements have very little relevance to a true evaluation of aluminum as a culvert material.

The mechanism and extent of corrosion in flowing water will be quite different from that experienced under static water conditions. The pitting characteristics of aluminum under static water conditions are well known; they can be catastrophic in the presence of copper ions. Under flowing water conditions perhaps one should be more concerned about abrasion resistance; abrasion is a hazard with most culvert materials but perhaps this paper shows it to be a serious hazard for aluminum culverts.

Since aluminum is used for sacrificial anodes one must clearly be concerned about bimetallic corrosion and possibly stray current corrosion. It would be well for users to bear in mind that where you have a small area of anode (e.g., aluminum) and large area of cathode (e.g., steel) such corrosion due to the bimetallic couple can be catastrophic in its intensity. I agree with the authors that where the steel is galvanized, the zinc coating on the steel will give some measure of protection to the aluminum and may still confer some continued protection to the steel since zinc corrosion products are often inhibiting when kept in contact with steel.

Where corrosion on the soil side may be a hazard, attention should be drawn to the National Bureau of Standards, Circular 579, *Underground Corrosion*—M. Romanoff. Here the data show that after being buried for 10 years in a number of corrosive soils none of the aluminum alloys tested including commercial aluminum and aluminum manganese alloys were satisfactory for use unprotected. One could speculate that some newer aluminum alloys may show improvement here, and there would be soils where satisfactory experience might be expected.

In one test reported on galvanized steel specimens with 3.08-oz zinc coatings, in 8 out of 10 inorganic soils the zinc coating remained virtually intact after 13 years, while

in two highly reducing inorganic soils the zinc coating was almost completely removed during the first few years yet the subsequent attack on the steel was relatively slow as compared with the controls. A careful study of this excellent report is recommended. On the basis of relatively long-term evaluations, the value of galvanizing for buried steel is clearly brought out. It also indicates the need to consider attack on the basis steel as a criterion of performance rather than corrosion of the zinc coating. As the authors have pointed out care is necessary in specifying uncoated galvanized steel for service in specific aggressive environments.

In general, one always feels safer when a proposed application can be related to a similar one where long experience has given assurance of good results. Fortunately, there are excellent case histories to support the use of galvanized steel under a wide variety of conditions and for periods of the order of 30 years.

E. F. NORDLIN and R. F. STRATFULL, Comments.—The authors agree that in corrosion work any predictions of a rate of corrosion is a difficult and hazardous undertaking.

The highway engineer must be concerned with the durability of a material in its anticipated environments because disregard of this factor can lead to abnormal costs for maintenance. He can no longer accept a material on the basis of recommendations given in the terms of "maybe," "better," "looks good," etc. As a result, in the California Division of Highways, culverts are now judged and economically evaluated on the basis of expected years of service, which can always lead to a difference of opinion.

E. F. NORDLIN and R. F. STRATFULL, Closure.—We thank all of the contributors to this discussion. Their comments give the readers a broader picture of the use of aluminum than that given in the paper, alone.

We especially wish to thank Dr. Hugh P. Godard for submitting the previously unpublished data. This information will be of value to many engineers.

We are pleased that there was open discussion and hope that it will result in a diligent effort to accumulate further engineering data which could clarify and resolve the use of aluminum as a culvert.

The authors wish to take this opportunity to correct an oversight in their paper wherein the thickness of metal for the steel and aluminum field test culverts was not mentioned.

With reference to Tables 3 and 14 of our paper, culverts placed at IV-SCI-5-C were 10 gage, at I-Hum-35-C were 12 gage, while the remainder of the culverts were 14 gage. All laboratory test samples were 16 gage.