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Foreword

"A Preliminary Study of Aluminum as a Culvert Material" by Nordlin and Stratfull should be of interest and value to highway drainage structure engineers, as well as those making research studies of the suitability of aluminum and galvanized steel for culvert materials under various service conditions and environments. The paper, together with the discussions, constitutes a good summary of the information that is available to the designer of drainage structures, as derived from laboratory studies and experience, for choosing flexible culvert materials. Likewise, they provide a good review of the literature on this subject for the benefit of the researcher who is interested in carrying forward the much needed further research in this field. The information presented provides a basis for further research to improve the mechanical and chemical properties of materials and combinations of materials for flexible culverts. The bibliography of the original paper is strongly supplemented by the bibliographies of the discussions.

As might be expected in the light of conflicting opinions as well as commercial interests, this paper and the discussions given at the technical session where it was presented have been the subject of much controversy.

The original paper has been criticized by some as appearing to draw some unwarranted conclusions. This criticism is based on the comparative severity of service conditions at the test site chosen, the limited extent of observations of behavior, and some question as to whether the procedure used in the laboratory was representative of actual conditions.

Those charged with making recommendations and decisions as to publication sought advice from disinterested parties. Consensus was that the paper and the discussions provide a good deal of valuable information. Even though there was not always agreement that all of the data presented verified the accompanying contentions, the data were considered to be useful and in at least some important way relevant to the general problem of choosing culvert materials.

Taken all together, the information of the paper and the discussions seem to provide quite a comprehensive statement of the problem, and to emphasize most, if not all, of its important aspects. These aspects including the influence of chemistry and mineral content of soil and water of the environment, as well as quiescence, erosion, abrasion and other mechanical factors.

Accordingly, the complete paper and all the discussions have been published. As the authors note, the paper should be considered as only a progress report. The results of further studies and longer experience must be available before definite criteria can be established for choosing the most suitable culvert materials for the various environments that may be encountered for highway drainage structures.

The investigation described in "Nondestructive Tests for Detecting Discontinuties in Aluminum Alloy Arc Welds," by Panian, Patsey and Sager, was intended to evaluate radiographic and ultrasonic procedures for detecting 14 different types of discontinuities in TIG (gas tungsten-arc welding) and MIG (gas metal-arc welding) welds in aluminum alloy plating and to determine the effects of these discontinuities on the static strength of the welded joints. The test specimens were made of ½-in. and 1-in. thick material.

Highway engineers engaged in the design, construction, or inspection of either steel or aluminum structures should find something of value and interest to them in this paper. Although the work was done on welded aluminum alloy plates, most of the information developed on the comparison of the radiographic and ultrasonic test methods and on the effectiveness of each method under various circumstances would apply equally well to either steel or aluminum structures with welded joints made by almost any arc welding process.

Because of the recent rapid growth of the use of welding for the construction of bridges and large overhead structures for directional signs, highway engineers have become greatly interested in nondestructive tests for welds and the advantages and disadvantages of the various test methods.

One of the most controversial subjects related to structural welding is the choosing of acceptance standards for use with nondestructive testing and inspection methods, which will assure adequate strength without being needlessly severe and costly. Therefore, the information developed in this investigation on the effect of defects and discontinuities of various kinds upon the strength of welded aluminum joints should be of interest to almost anyone engaged in design for welding. However, one might hesitate to apply to steel structures such information regarding effects of various defects upon the strength of aluminum welds, without some verification of the applicability to steel.

The paper points out certain kinds of defects which are difficult or impossible to detect radiographically. Some of these can be detected by ultrasonic testing. Some of them are surface defects which can be detected easily by visual inspection.

Some of those who have reviewed the paper feel that the investigation should be considered as only a beginning, and the work has not been carried far enough to warrant conclusions. Probably the greatest value of the paper is that it focuses attention upon the various facets which need deeper investigation. For example, in determining the effects of weld defects upon strength, the investigators in some cases used specimens containing grossly defective welds. This work should be carried further to determine critical sizes or extents of weld defects such as porosity and slag inclusions.

In all of the work, the size and extent of weld defects were determined by metallographic examination and examination of fracture surfaces of tensile test specimens as a basis for evaluating the effectiveness of radiographic and ultrasonic testing.

The authors point out advantages and shortcomings for both of these nondestructive test methods. They conclude that they are both valuable and effective procedures for determining the structural integrity of welds. They feel that radiography provides a more definite picture of the actual weld condition. Although they consider it advisable to take time to grind weld surfaces flush when using the ultrasonic method, to avoid false extraneous indications from surface geometry, they think it probable that ultrasonic examination will gradually replace radiography for the inspection of long lengths of weld because the ultrasonic method is faster and more readily automated.

Contents

A Preliminary Study of Aluminum as a Culvert Material

ERIC F. NORDLIN and R. F. STRATFULL
Respectively, Assistant Materials and Research Engineer—Structures; and Corrosion Engineer, Materials and Research Department, California Division of Highways

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

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Paper sponsored by Committee on Metals in Highway Structures.

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 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[1]	pH Range	Flow Conditions[2]						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 drain	None	6-8	X	X	X	X	No	X	X	2,000
	Bituminous	5-9	X	X	X	X	No	X	X	1,500
Under drain	None	6-8	X	X	X	X	No	X	X	2,000
	Bituminous	5-9	X	X	X	X	No	X	X	1,500
Side drain	None	6-8	X	X	X	X	No	X	X	2,000
	Bituminous	5-9	X	X	X	X	No	X	X	1,500
Cross drain	Bituminous	6-8	X	X	No[3]	X	No	X	No	2,000
	Bituminous plus paved invert	5-9	X	X	X	X	No[3]	X	X	None

[1] When pipe is bituminously coated, backfill to have pH of not less than 5.0 and no resistivity limitation.
[2] "X" in column denotes recommended use.
[3] 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 (hydragillite, $Al_2O_3 \cdot H_2O$) 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):

$$\text{Total dissolved solids} = \frac{900,000}{R} \tag{1}$$

$$\text{Sum of sulfates and chlorides } (SO_4 + Cl) = \frac{784,000}{R^{1.15}} \tag{2}$$

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[1]	0.83[2]	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_3, ppm	–	Nil	Nil	Nil	Nil	Nil	Nil	Nil
HCO_3, ppm	–	Nil	Nil	204	–	9	170	180
Cl, ppm	–	Nil	50	516	26	144	14,920	41,520
SO_4, ppm	–	996	13,800	132	2,246	356	2,220	7,920

[1] This installation was removed during the last inspection. [2] Steel CMP was in place approximately 1 year prior to installation of aluminum test pipe.

TABLE 3

CULVERT SITE TEST RESULTS[1]

Location	Metal	Time in Test (yr)	pH	Minimum Resistivity (ohm-cm)	Estimated Years to Perforation Based on Metal Loss at:[2] Minimum Cross-Section Loss	Upstream Surface of Corrugation: Abrasion	Upstream Surface of Corrugation: Pitting	Downstream Surface or Valley of Corrugation (corrosion surface)
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	No test culvert			
	Aluminum				0.83	–	–	0.83
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[3]	Steel	2.4	4.5 to 6.3	620 to 973	49	–	–	49
	Aluminum				12	–	–	12
XI-Imp-187-F[3]	Steel	1.7	7.5	6.5	6.7	–	–	6.7
	Aluminum				12	–	–	17
XI-SD-2-Nat. Cty[3]	Steel	1.7	8.3	39	25	–	–	33
	Aluminum				4.8	–	–	6.6

[1] All test results are based upon metallographic analysis of culvert samples.
[2] Estimated years to perforation for all samples were calculated on the basis of a 16-gage metal thickness.
[3] 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[1] for Five Test Sites with pH Between 4.5 and 8.3			
Galvanized steel	18	21	27
Aluminum	6.5	1.9	13

[1] Test site with pH of 4.5 has a pH range of 4.5 to 6.3.

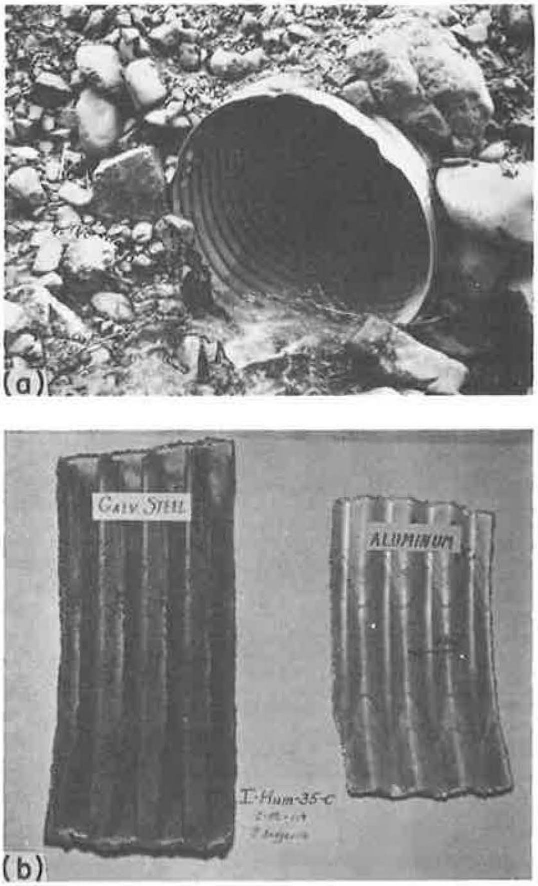

Figure 1. Field test site, I-Hum-35-C, mile 1.19: (a) inlet of test pipe—aluminum section; (b) samples removed from invert after 2-yr exposure.

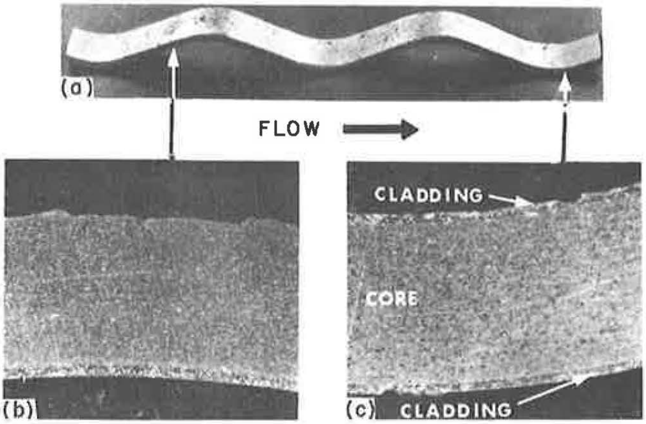

Figure 2. Field test site—aluminum, I-Hum-35-C, mile 1.19: (a) sample from invert of aluminum culvert; (b) typical loss of cladding at abrasion surface—2 yr; (c) cladding intact—2 yr.

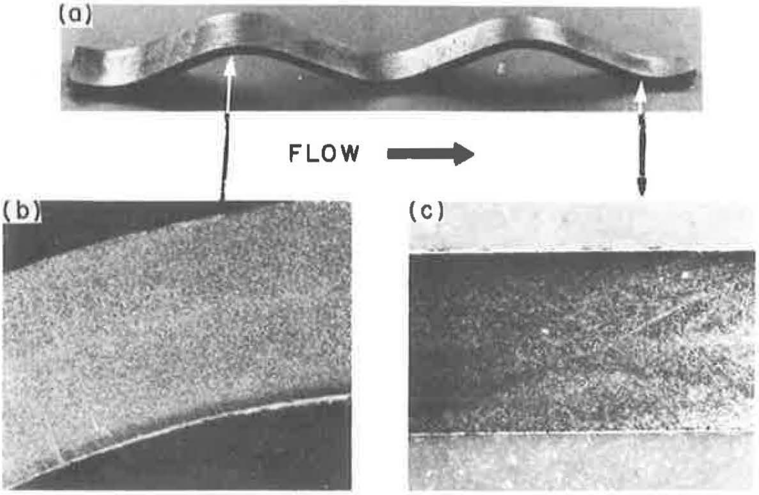

Figure 3. Field test site—steel, I-Hum-35-C, mile 1.19: (a) sample from invert of galvanized steel culvert; (b) note loss of zinc and minor loss of steel at abrasion surface—2 yr; (c) zinc abraded but intact—2 yr.

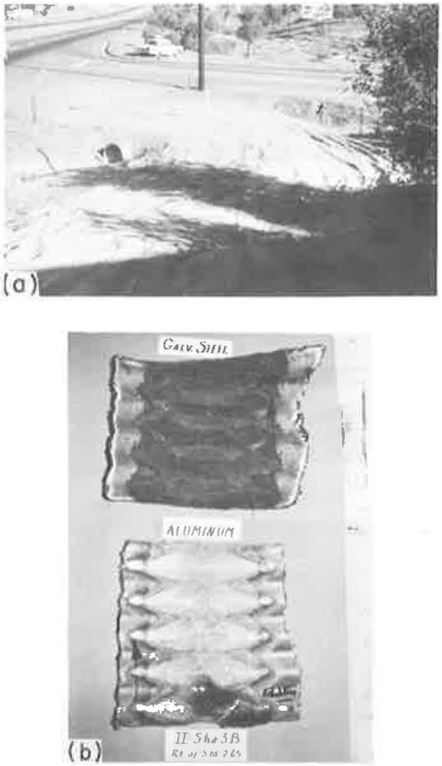

Figure 4. II-Sha-3-B, right of Sta. 265±: (a) field test site; (b) typical invert samples removed after approximately 1.5 yr of test.

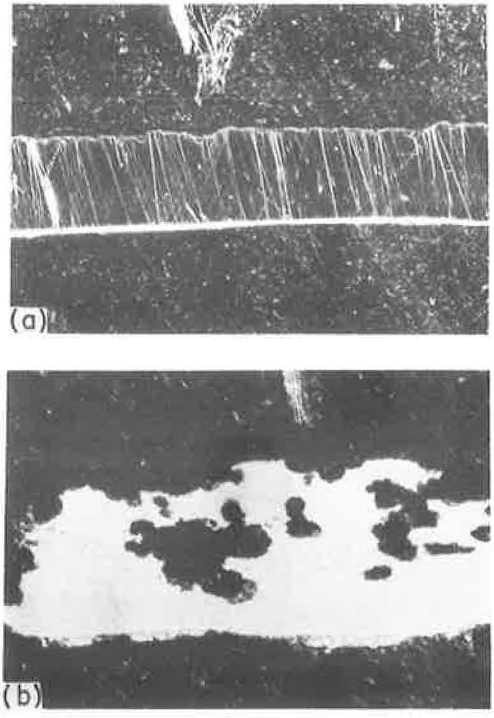

Figure 5. II-Sha-3-B, right of Sta. 265±: (a) cross-section of steel after 1.5 yr of test; (b) cross-section of aluminum.

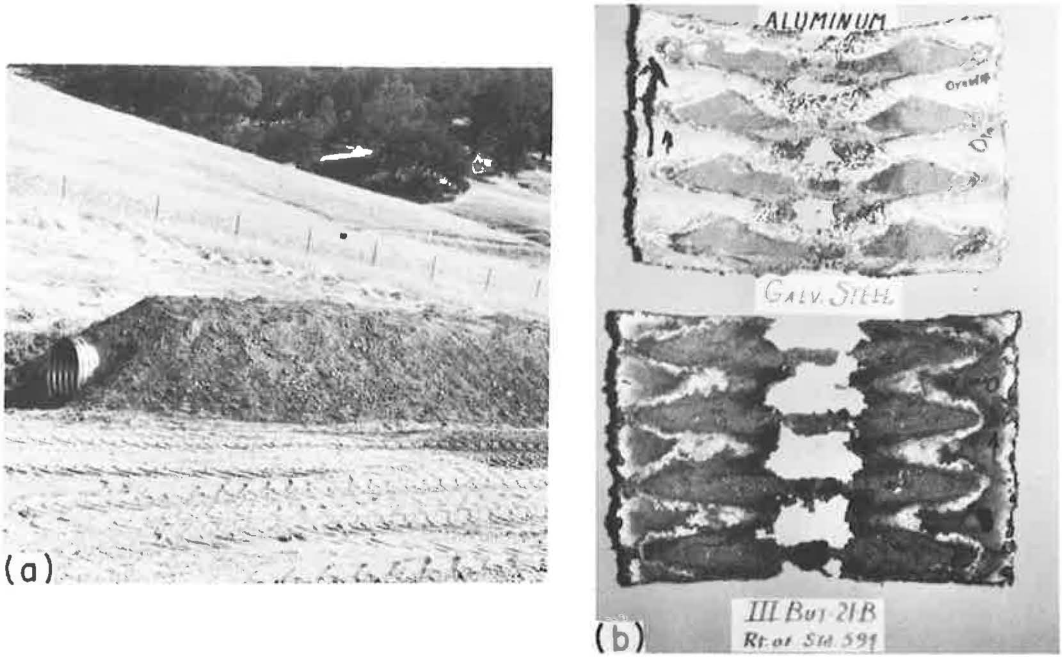

Figure 6. III-But-21-B, right of Sta. 594±: (a) field test site; (b) invert samples removed after approximately 1.7 yr of test (highly corrosive exposure).

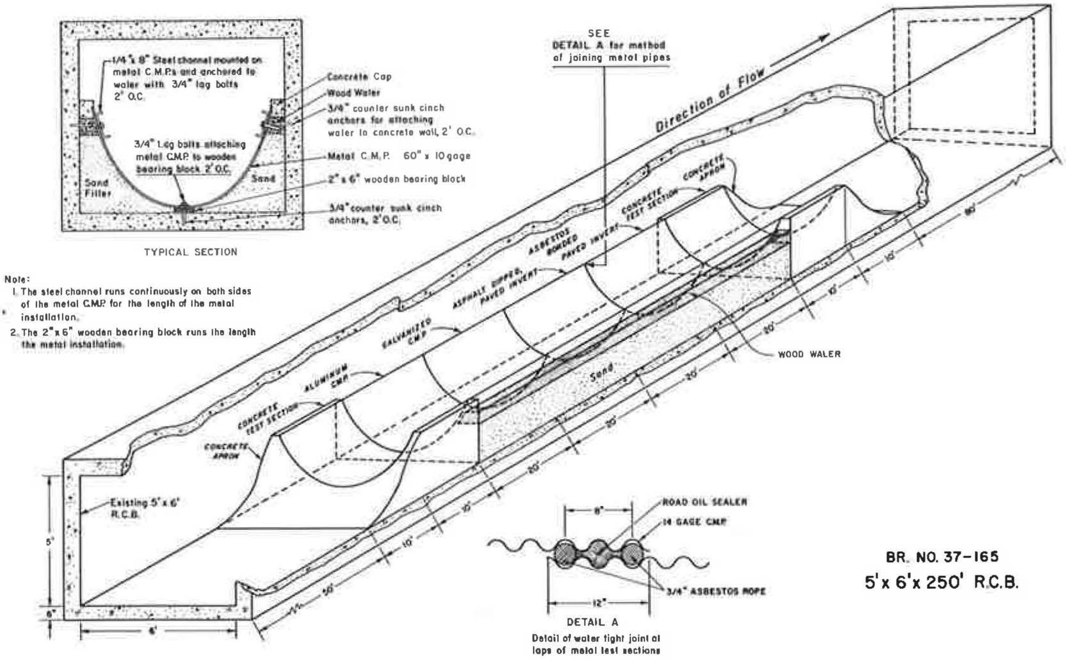

Figure 7. Abrasion test site, IV-SCI-5-C, Trout Creek.

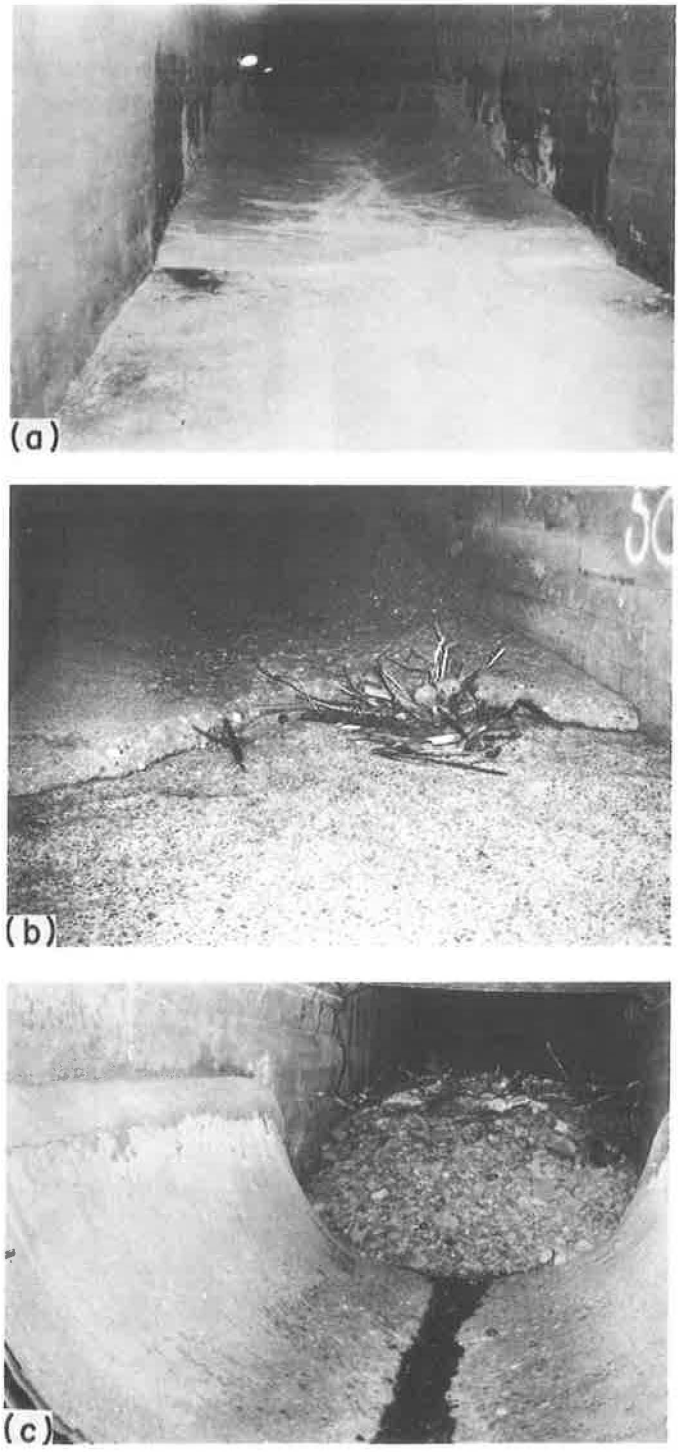

Figure 8. Abrasion test site, IV-SC1-5-C, Sta. 250+25, Bridge No. 37-165: (a) "as built" concrete test section at inlet section of test culvert; (b) appearance of concrete test section after 1.4 yr of service showing severe abrasion; (c) view showing loss of approximately $\frac{1}{2}$ in. of concrete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

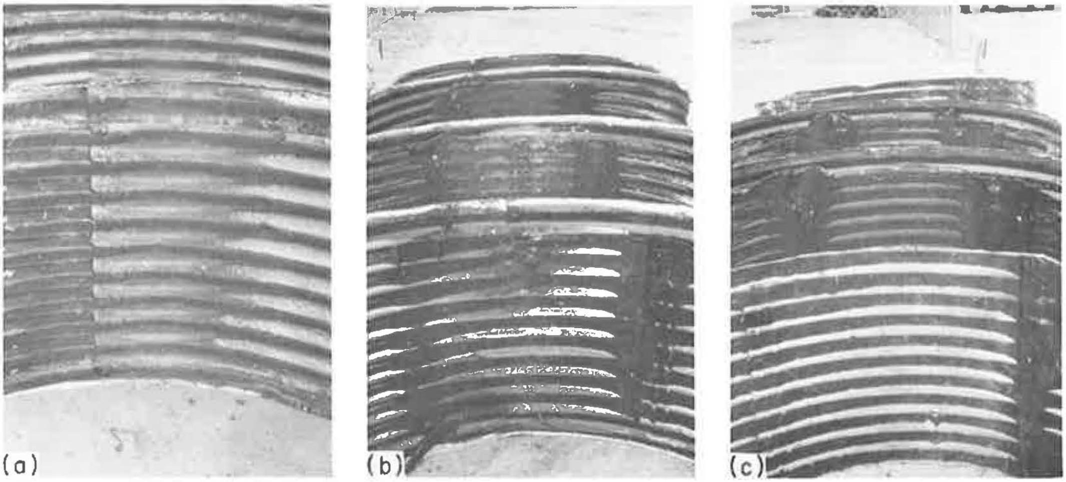

Figure 9. Abrasion test site, IV-SC1-5-C, Sta. 250+25, Bridge No. 37-165. Samples of the invert from: (a) galvanized steel section (note wear of rivet heads); (b) A.D.P.I. section (note loss of rivets at joint); (c) A.B.A.D.P.I. section.

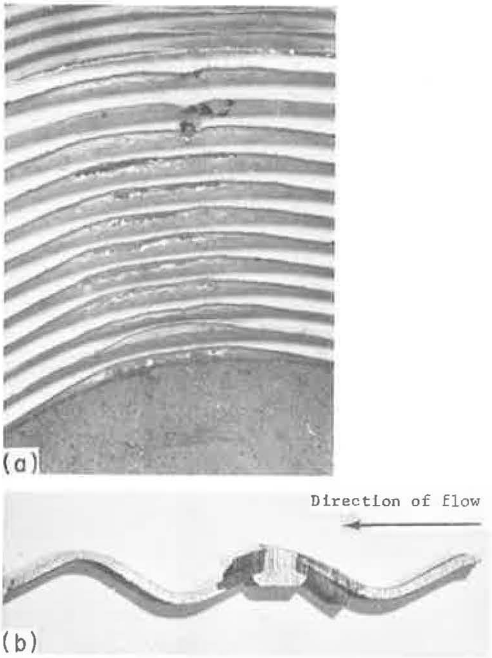

Figure 10. Abrasion test site, IV-SC1-5-C, Sta. 250+25, Bridge No. 37-165: (a) severe abrasion of aluminum after 1.4 yr of service; (b) severe abrasion of galvanized steel after 1.4 yr of service (note loss of head of rivet).

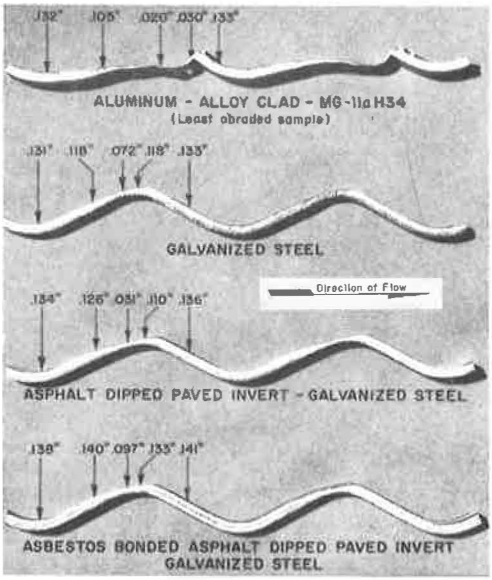

Figure 11. Results of abrasion tests, IV-SC1-5-C, Sta. 250+25, Bridge No. 37-165. Typical cross-sections of pipe invert after test exposure. (Note: All C.M.P. samples were 10 gage (0.140±). Steel samples are typical of the most abraded pipe sections.)

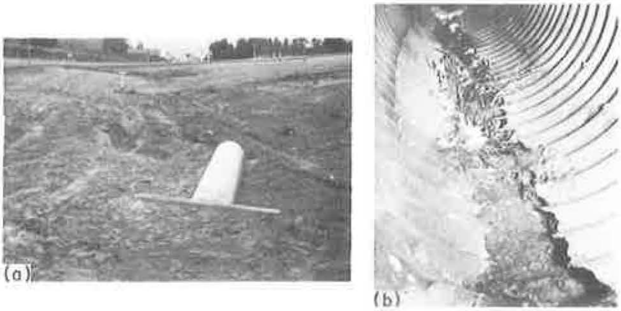

Figure 12. Field test site, IV-SCr-5-A, right of Sta. 530±: (a) aluminum culvert, field test site (exposed pipe subsequently backfilled); (b) existing galvanized C.M.P., approximately 2 yr of service (not placed as part of test program).

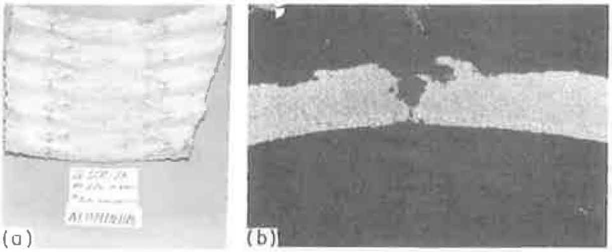

Figure 13. Field test site, IV-SCr-5-A, right of Sta. 530±: (a) aluminum invert sample approximately 0.8 yr of test; (b) cross-section of aluminum, nonperforated section.

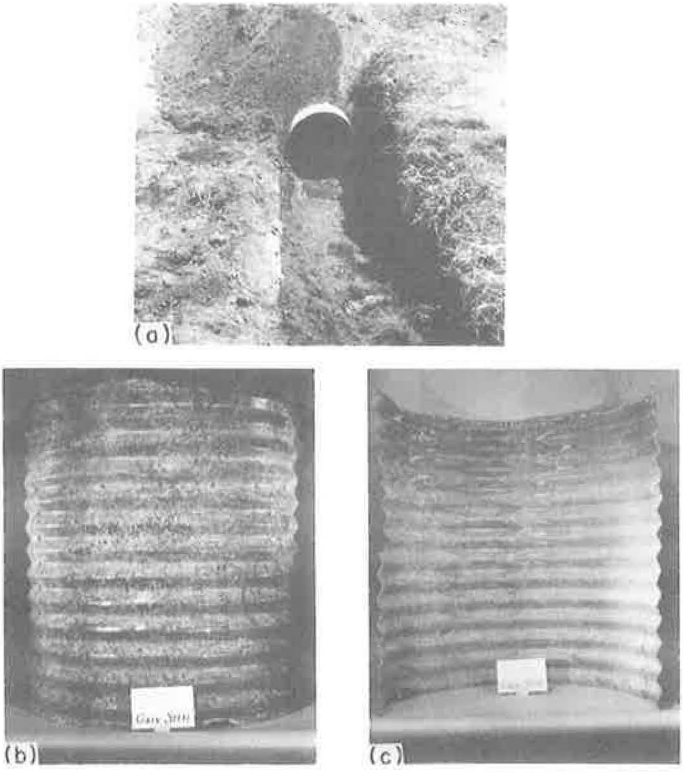

Figure 14. Field test site, X-SJ-53-C, right of Sta. 6±: (a) field test site: (b) backfill side: (c) inside (invert). Appearance of cleaned galvanized steel samples after 2.4 yr of test.

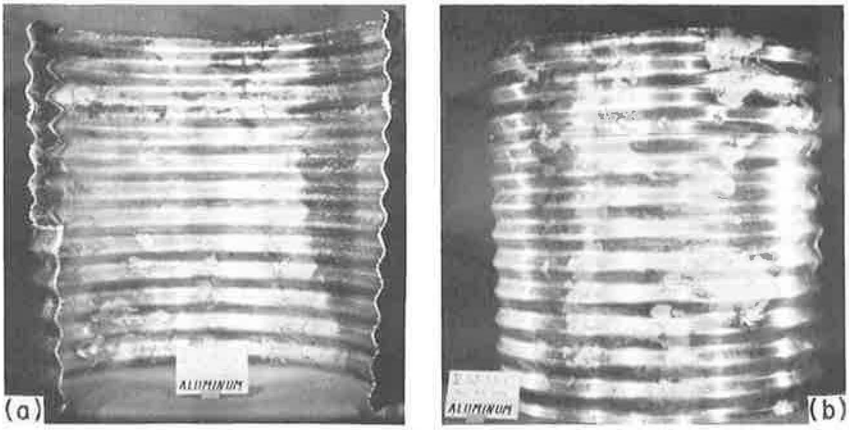

Figure 15. Field test site, X-SJ-53-C, right of Sta. 6±: (a) appearance of inside of aluminum sample after cleaning (invert); (b) appearance of soil side of aluminum sample after cleaning.

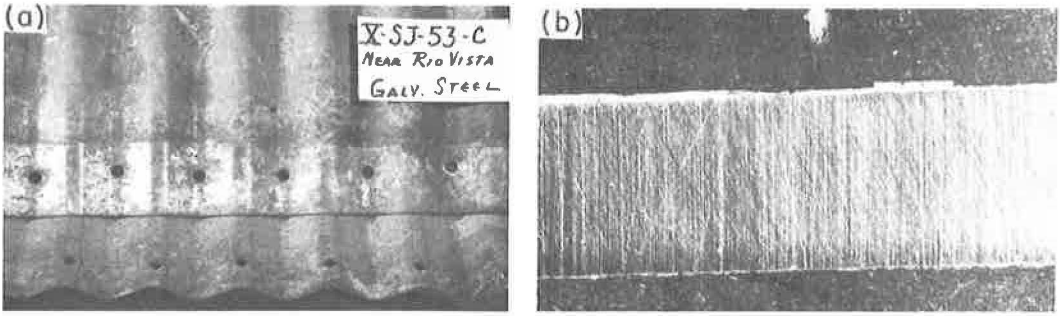

Figure 16. Field test site, X-SJ-53-C, right of Sta. 6±: (a) appearance of galvanized steel joint after cleaning; (b) cross-section of steel (note partial loss of galvanizing on both sides).

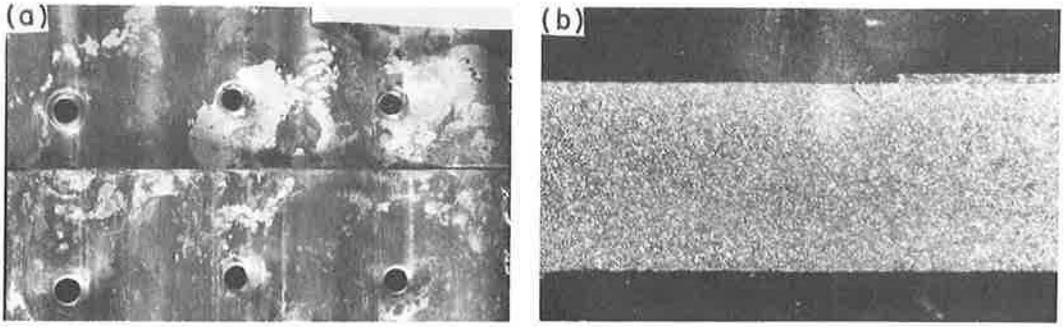

Figure 17. Field test site, X-SJ-53-C, right of Sta. 6±: (a) appearance of aluminum joint after cleaning—light-colored areas are corroded sections of pipe; (b) cross-section of aluminum (note loss of cladding on both surfaces).

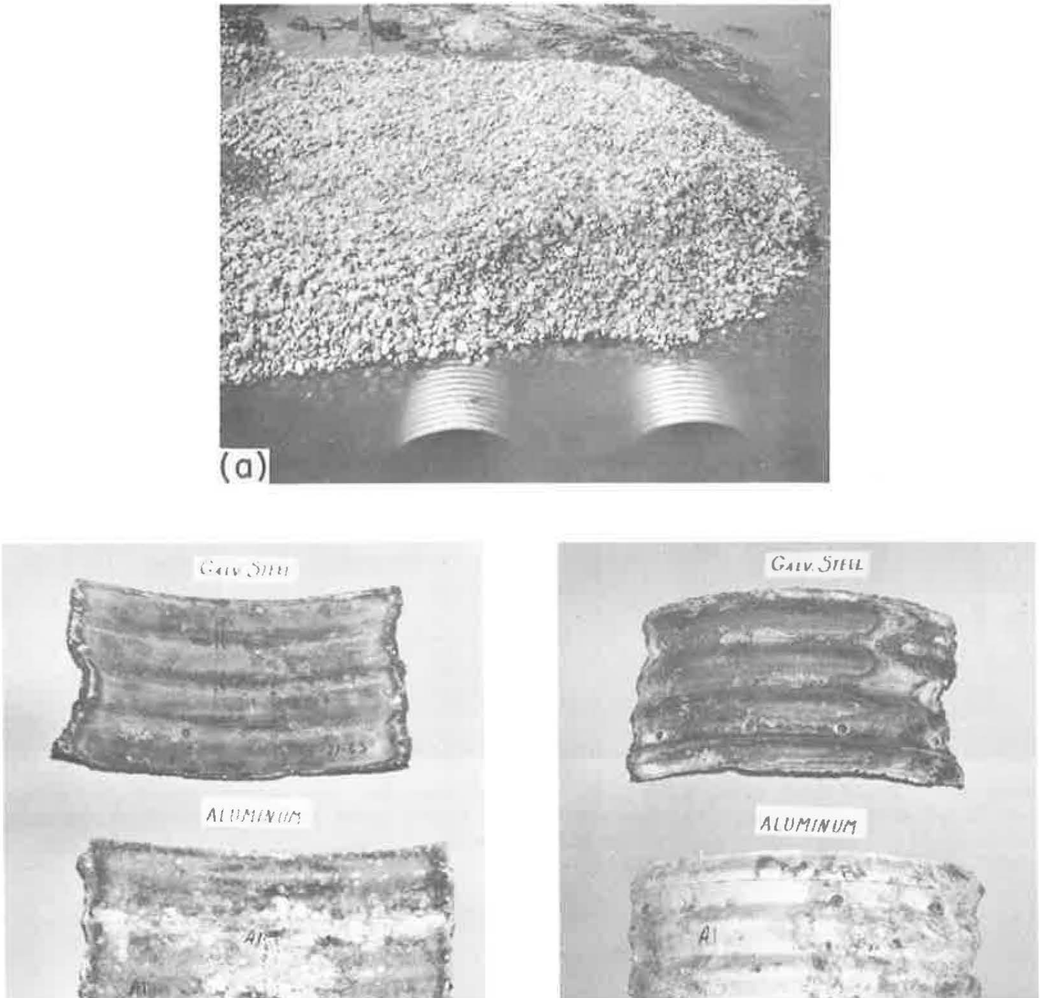

Figure 18. Field test site, XI-SD-2-Nat.Cty at Sweetwater Creek: (a) field test site at high tide; (b) sample removed from culvert inverts after approximately 1.6 yr of test; (c) backfill side of same culvert samples.

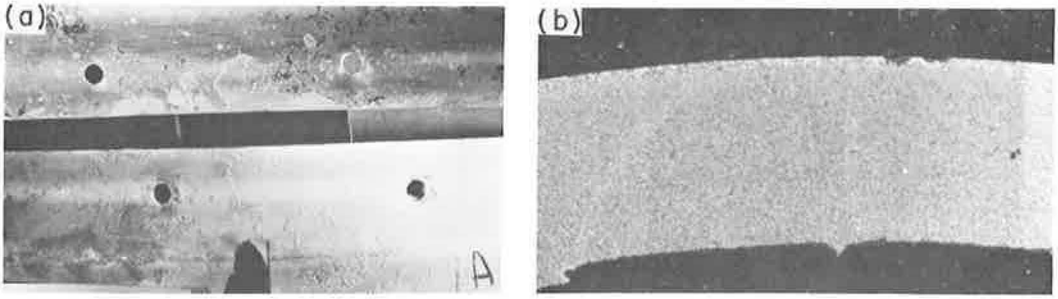

Figure 19. Field test site, XI-SD-2-Nat.Cty at Sweetwater Creek: (a) appearance of aluminum after cleaning—1.6 yr of test; (b) cross-section of aluminum (note loss of cladding and penetration into base metal on backfill side of pipe at bottom of photo).

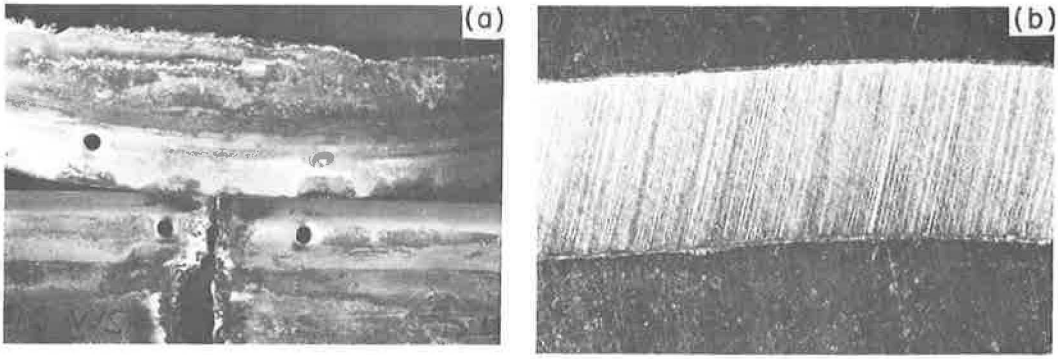

Figure 20. Field test site, XI-SD-2-Nat.Cty at Sweetwater Creek: (a) appearance of galvanized steel after cleaning—1.6 yr of test; (b) galvanizing penetrated at localized spots (top surface of photo).

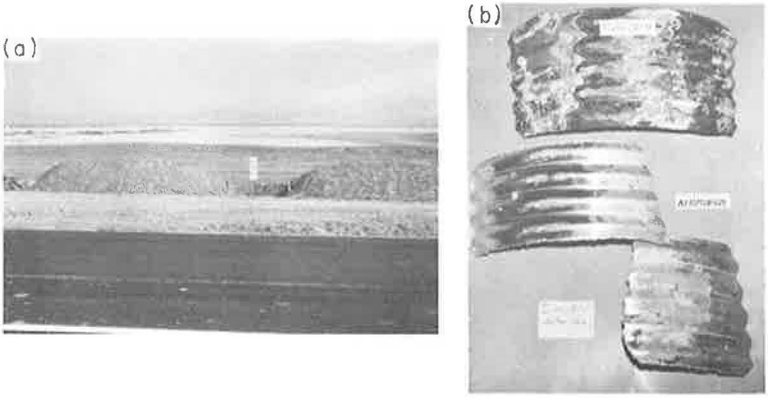

Figure 21. Field test site, XI-Imp-187-F, left of Sta. 498±: (a) field test site: (b) backfill side of culvert samples—approximately 1.7 yr of exposure. (Dark areas on steel and light areas on aluminum are locations of corrosion.)

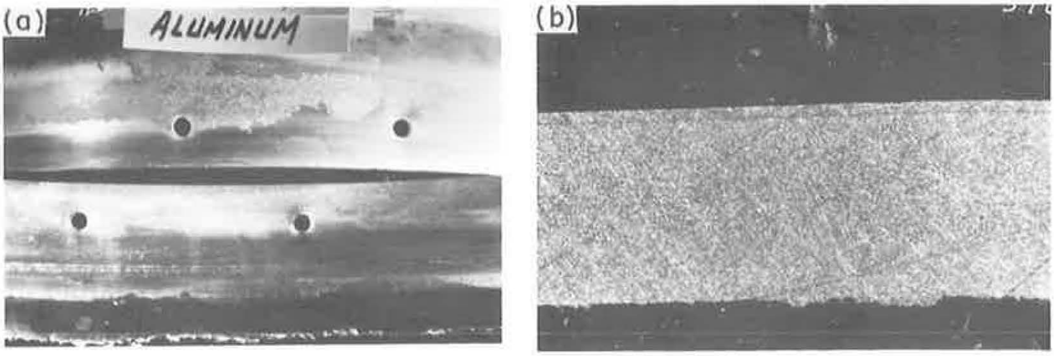

Figure 22. Field test site, XI-Imp-187-F, left of Sta. 498±: (a) appearance of aluminum joint after cleaning; (b) section through aluminum (note loss of cladding and penetration of base metal on soil side of aluminum culvert at bottom of photo).

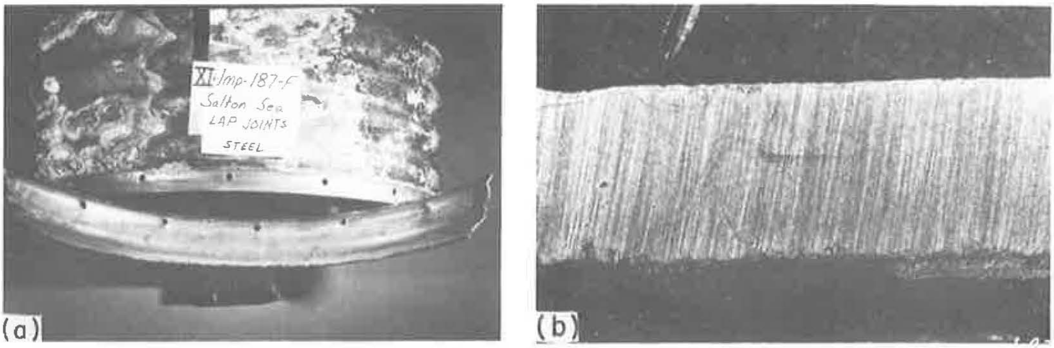

Figure 23. Field test site, XI-Imp-187-F, left of Sta. 498±: (a) appearance of galvanized steel joint after cleaning—dark areas are rust; (b) section through steel (note loss of galvanizing and penetration at localized areas).

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-SCl-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 witha 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[1] 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_2CO_3	40
							NaCl	25
4	Aluminum	8.8	8.6-9.6	100	4,000	4,000	$CaCO_3$	4
							NaCl	25
5	Aluminum	8.7	8.7-9.5	100	4,000	4,000	$CaCO_3$	20
							NaCl	25
6	Aluminum	10.5	10.3-10.7	100	4,000	4,000	Na_2CO_3	60
							NaCl	25
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_3COOH	845
							NaCl	25
9	Aluminum	3.6	3.5-3.9	100	4,000	4,000	$C_{76}H_{52}O_{46}$	32
							NaCl	25
10	Aluminum	6.3	6.2-6.4	100	4,000	4,000	NaOH	1.6
							KH_2PO_4	4.9
							NaCl	25
11	Aluminum	5.0	4.2-6.7	100	4,000	4,000	NaOH	7.47
							$K_3C_6H_5O_7H_2O$	46.04
							NaCl	25
							HCl	30
12	Steel + zinc	9.2	7.9-9.8	100	4,000	4,000	$Na_2B_4O_7 \cdot 10\,H_2O$	40
							NaCl	25
13	Steel + zinc	6.3	6.2-6.4	100	4,000	4,000	NaOH	1.6
							KH_2PO_4	49
							NaCl	25
14	Steel	6.3	6.2-6.5	100	4,000	4,000	NaOH	1.6
							KH_2PO_4	49
							NaCl	25
15	Steel	8.8	8.6-9.3	100	4,000	4,000	$CaCO_3$	20
							NaCl	25
16	Steel	7.5	7.0-8.8	100	4,000	4,000	NaCl	25
17	Steel	4.5	3.4-4.9	100	4,000	4,000	$C_{76}H_{52}O_{46}$	32
							NaCl	25
18	Steel	5.2	5.1-5.6	100	4,000	4,000	KH_2PO_4	60
							NaOH	0.5
							NaCl	25
19	Steel	6.7	5.5-9.9	1,000	4,000	4,000	NaOH	0.042
							KH_2PO_4	5.0
20	Steel	7.5	7.2-7.9	1,000	4,000	4,000	NaCl	2.2
21	Steel	9.1	8.9-9.6	1,000	4,000	4,000	$CaCO_3$	20
							NaCl	2.1
22	Steel	4.4	4.1-6.3	1,000	10,000	4,000	$KHC_8H_4O_4$	20
23	Aluminum	4.8	4.1-5.5	1,000	10,000	4,000	$KHC_8H_4O_4$	20
24	Aluminum	9.1	8.8-9.4	1,000	4,000	4,000	$CaCO_3$	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	$CaCO_3$	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
							$CaCO_3$	40
32	Aluminum	7.5	6.8-8.5	1,000	10,000	4,000	NaCl	4.1

[1] 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 forementioned 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[a]	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[a]	0.45	1.72
Aluminum	0.40	0.43	0.99	2.12

[a] Generally corrosion pits and not metal loss from simple abrasion.

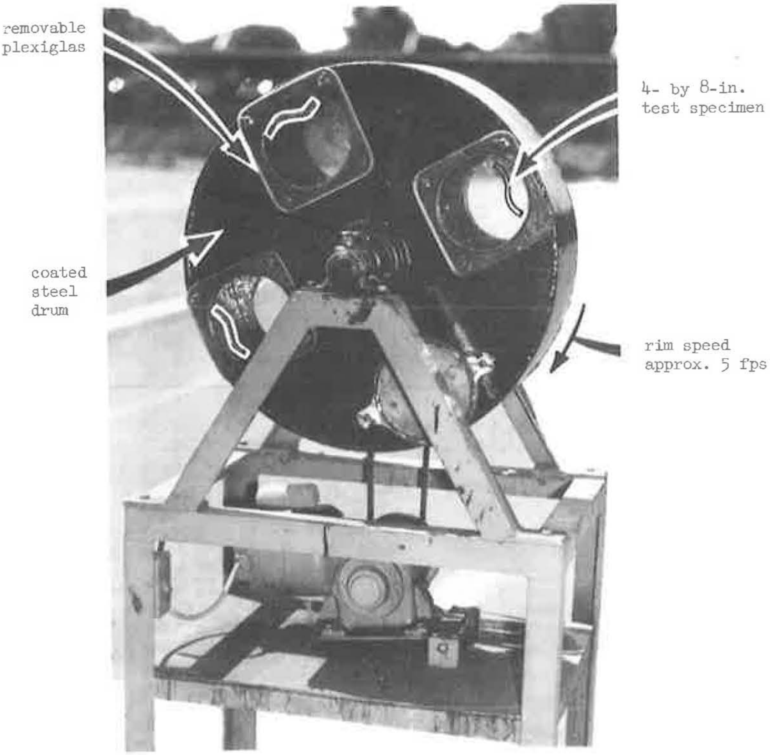

Figure 24. Corrosion-abrasion testing machine (steel drum 24 in. in diameter, 8 in. deep).

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

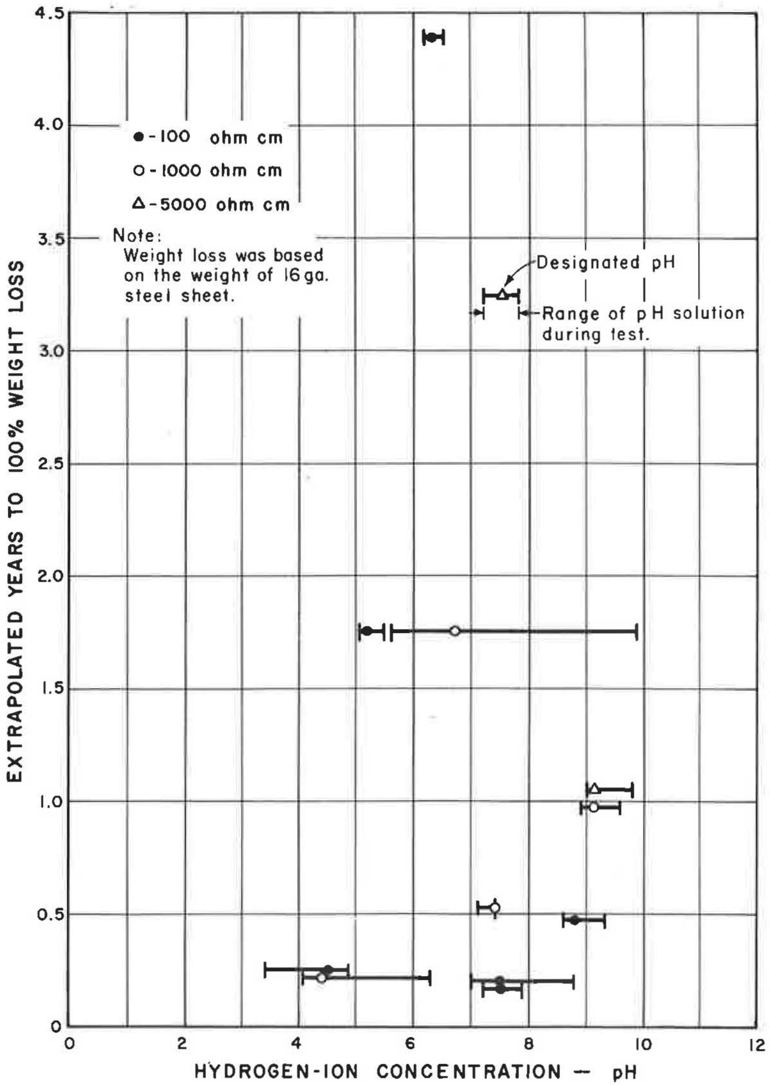

Figure 25. Laboratory corrosion-abrasion test of steel, extrapolated years to 100% weight loss vs pH.

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.

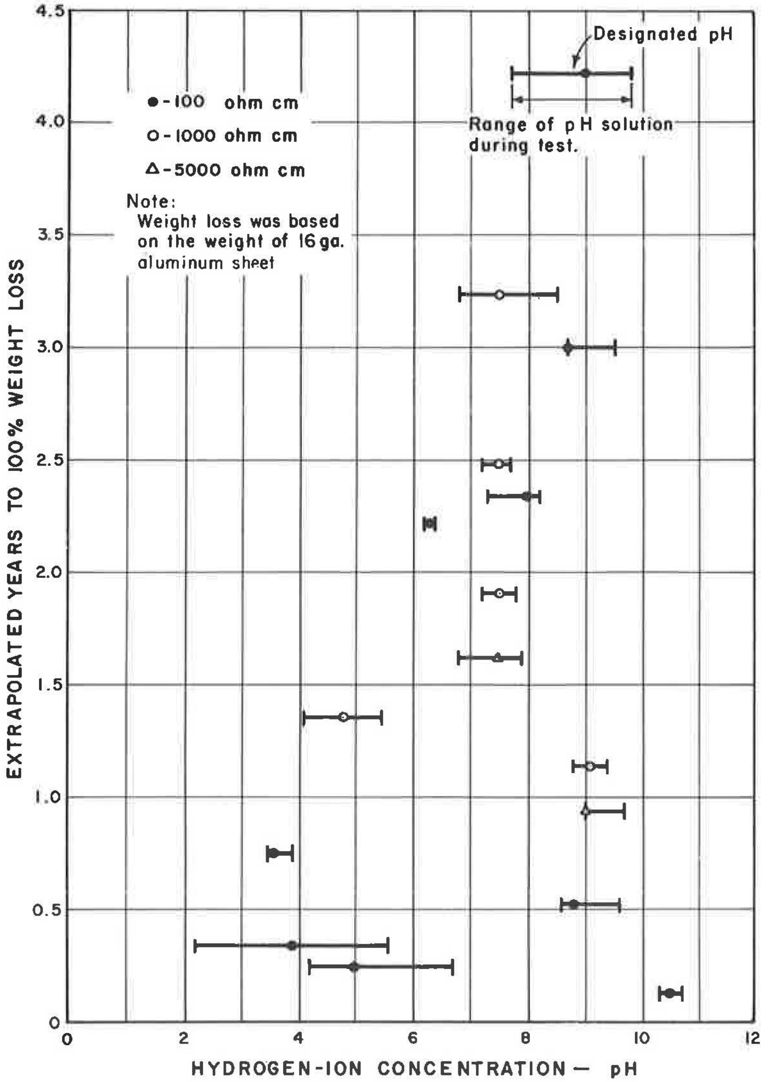

Figure 26. Laboratory corrosion-abrasion test of aluminum, extrapolated years to 100% weight loss vs pH.

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

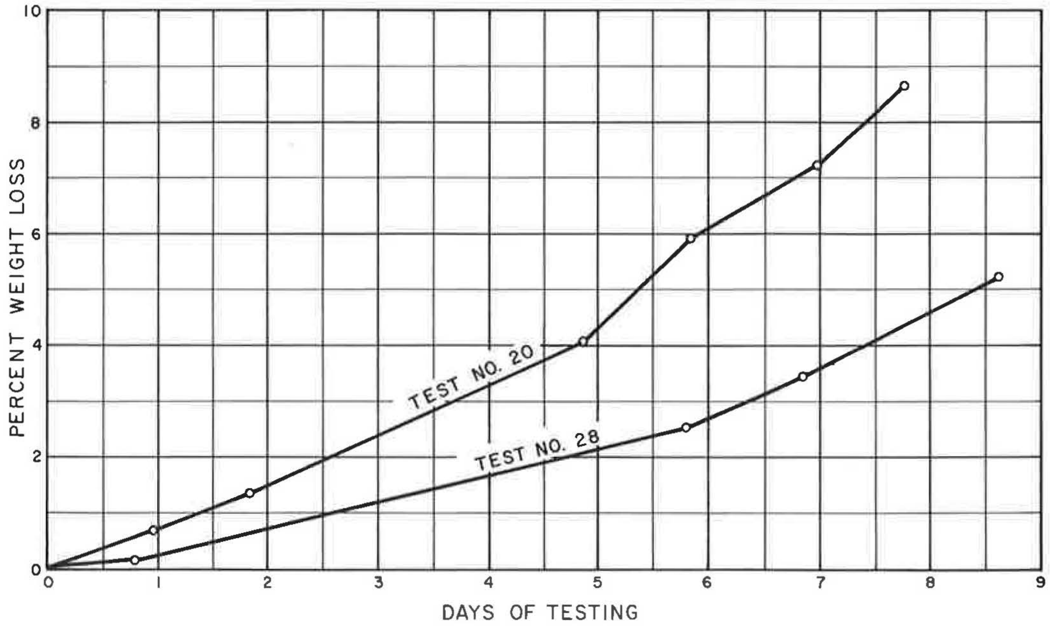

Figure 27. Laboratory corrosion-abrasion test, reproducibility of plain steel.

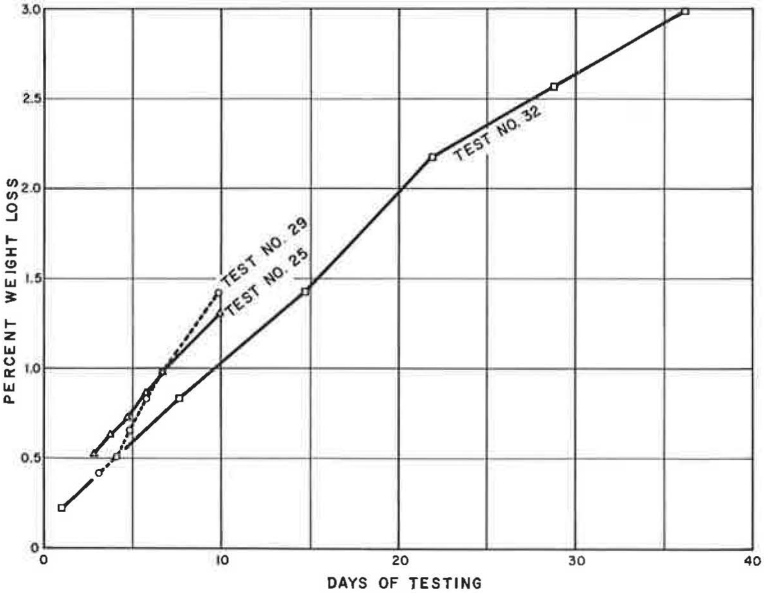

Figure 28. Laboratory corrosion-abrasion test, reproducibility of aluminum.

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 ± 20 percent.

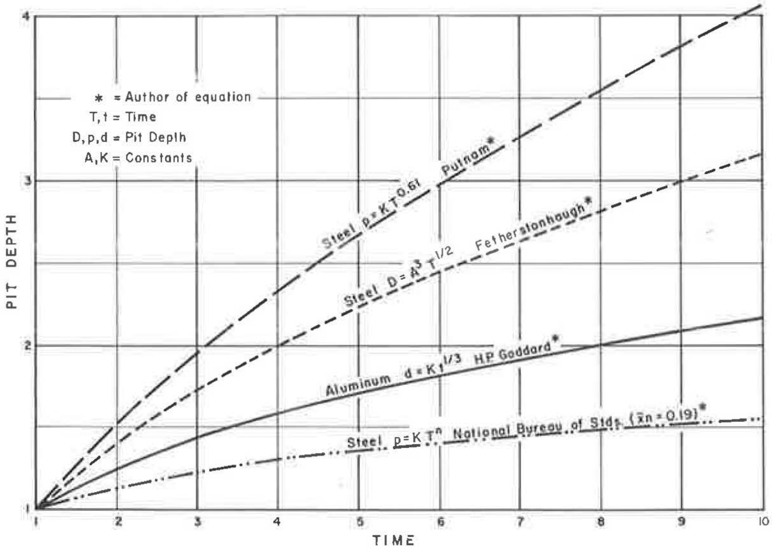

Figure 29. Time vs depth of pitting.

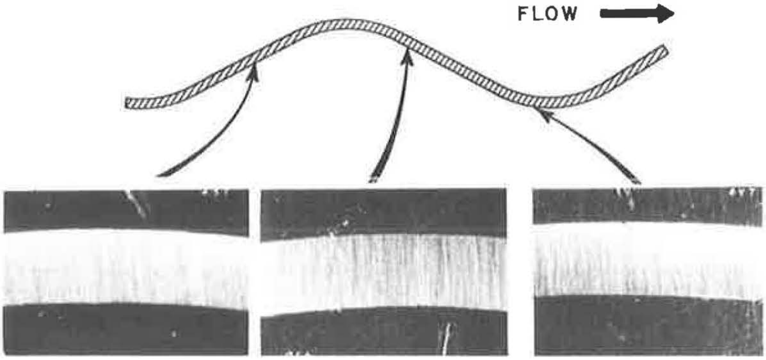

Figure 30. Laboratory corrosion-abrasion test, steel. Cross-sections of plain steel test sample after approximately 8 days of testing. Note minor abrasion loss of metal (left photo) which was caused by Ottawa sand and a specimen velocity of approximately 5 fps. Note lack of corrosion in this test.

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.

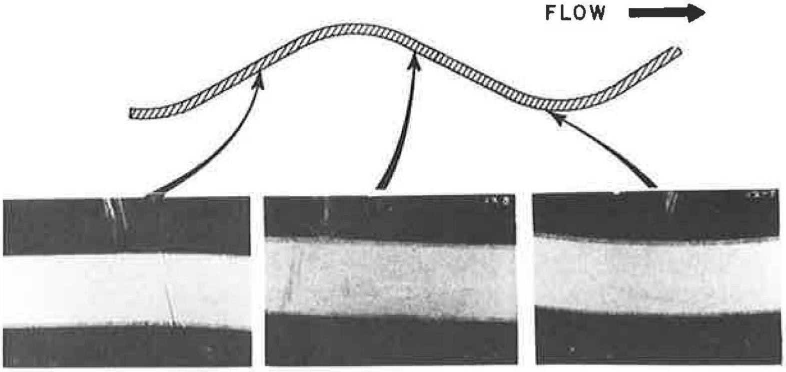

Figure 31. Laboratory corrosion-abrasion test, aluminum. Cross-sections of aluminum test sample after approximately 8 days of testing. Note typical loss of cladding (left photo) which was caused by Ottawa sand and a specimen velocity of approximately 5 fps. Note lack of corrosion in this test.

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	$KHC_8H_4O_4$	22
2	7.5	1,000	10,000	NaCl	5.2
3	9.0	1,000	10,000	$CaCO_3$ NaCl	10 5.0

TABLE 10

CHEMICAL ANALYSIS OF SACRAMENTO CITY TAP WATER

Total Solids	Hardness	Alk.	Cl	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[a]
(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

[a] Test solutions had a resistivity of 1,000 ohm-cm and test period was 70 days.

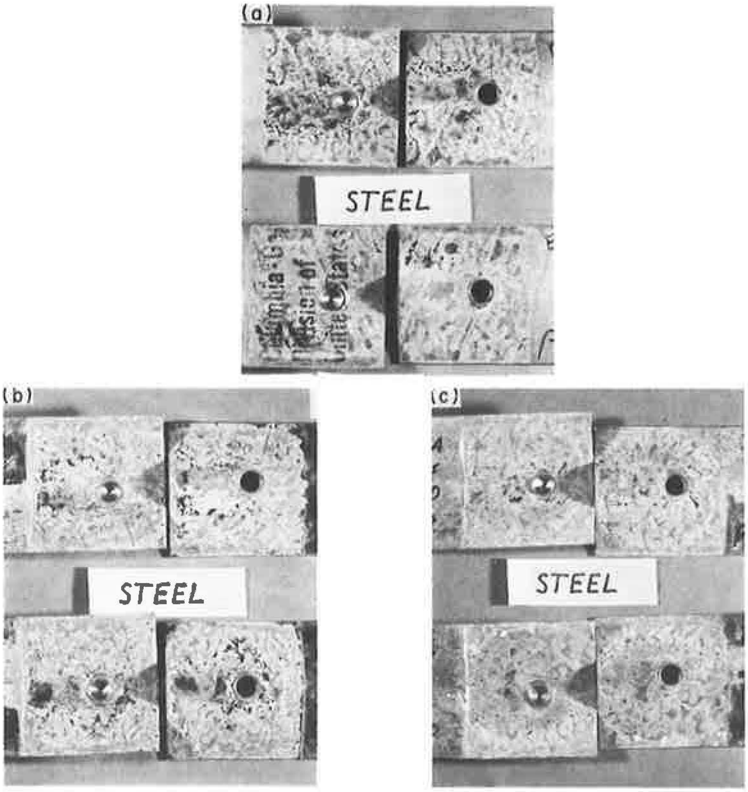

Figure 32. 70-day laboratory test of continuous submersion of galvanized steel: (a) pH = 4.3, resistivity = 1,000 ohm-cm, galvanizing intact, no corrosion of steel; (b) pH = 7.5, resistivity = 1,000 ohm-cm, galvanizing intact, no corrosion of steel; (c) pH = 9.0, resistivity = 1,000 ohm-cm, galvanizing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

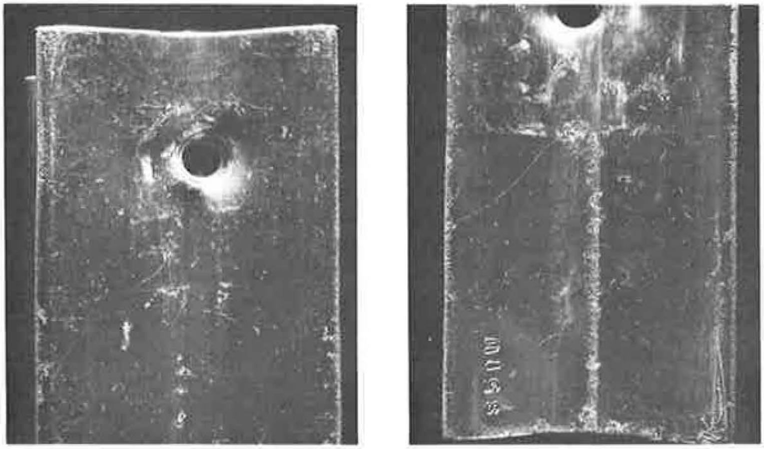

Figure 33. 70-day laboratory test of continuous submersion of aluminum—solution pH = 4.3, resistivity = 1,000 ohm-cm. Note corrosion at edges near rivet hole, role marks and where the two pieces of aluminum overlapped (right photo).

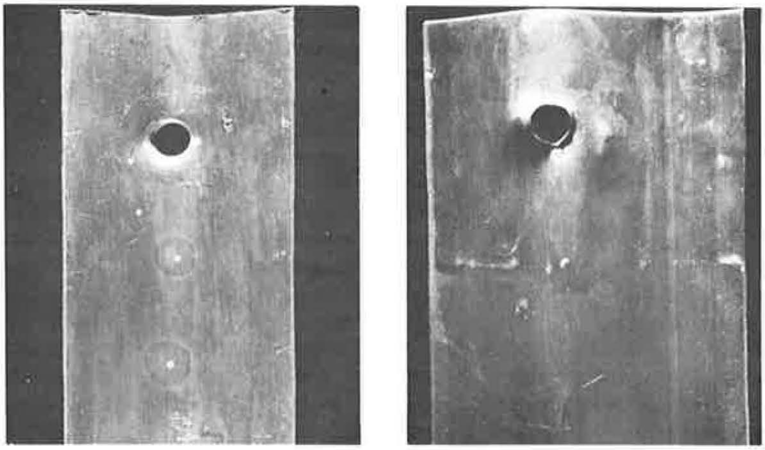

Figure 34. 70-day laboratory test of continuous submersion of aluminum—solution pH = 17.5 resistivity = 1,000 ohm-cm. Note corrosion at edges near rivet hole and where the two pieces of aluminum overlapped (right photo).

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 (HNO_3) and amyl alcohol ($C_5H_{11}OH$). The aluminum specimens were etched for approximately 10 minutes with concentrated sodium hydroxide (NaOH) solution.

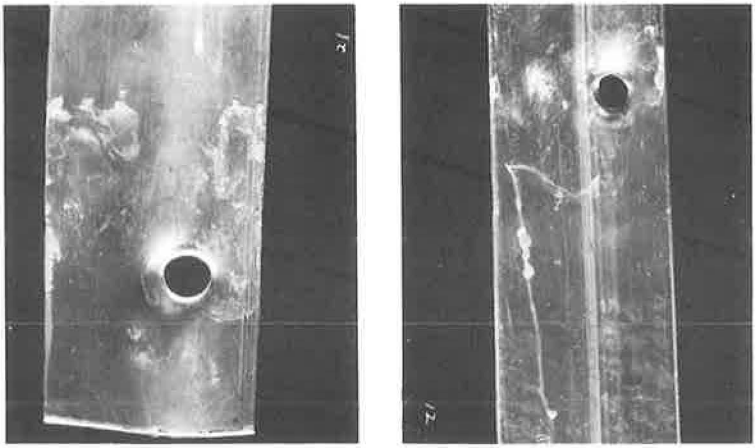

Figure 35. 70-day laboratory test of continuous submersion of aluminum—solution pH = 9.0, resistivity = 1,000 ohm-cm. Note corrosion at edges near rivet holes where the two pieces of aluminum overlapped (left photo), and corrosion in the long scratch (right photo).

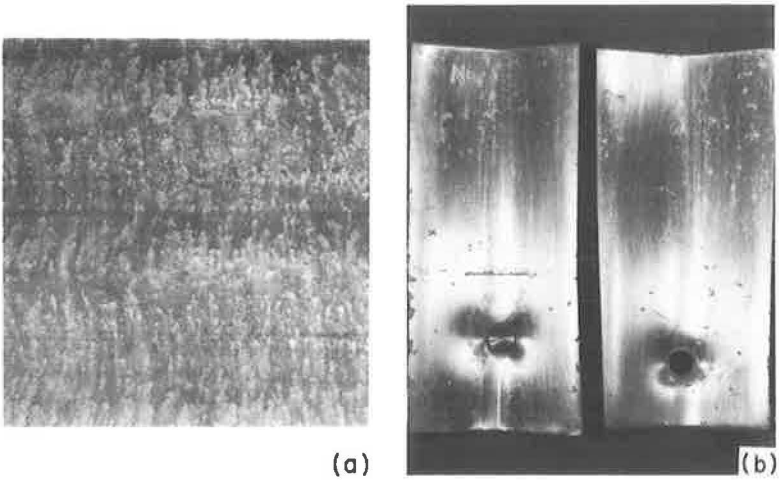

Figure 36. Laboratory test in fog room: (a) approximately 1 yr of exposure of galvanized steel and no corrosion of steel; (b) 117 days of exposure of aluminum (note corrosion at edges near rivet holes and at the line where the two pieces of aluminum overlapped).

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[a]
Aluminum	1	94	3.2
	2	94	3.2
	3	94	3.2

[a] 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[1] Resistivity (ohm-cm)	Estimated[2] Rate of Corrosion	Average Acid pH	Average Alkaline pH	Mean[1] 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				

[1] Geometric Mean.

[2] 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[1]
(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:[2]			
					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[3]	Steel	1.5	3.3	650	2.3	—	—	2.3
	Aluminum				0.33	—	—	0.33
III-But-21-B[4]	Steel	1.7	2.7	165	0.56	—	—	0.56
	Aluminum				0.56	—	—	0.56
IV-SCr-5-A[3]	Steel	0.83	3.7	330		No test culvert		
	Aluminum				0.83	—	—	0.83
IV-SCl-5-C[3]	Steel	1.4	7.7	3,500	1.3	1.3	—	—
	Aluminum				0.14	0.14	—	—
X-SJ-53-C[5]	Steel	2.4	4.5 to 6.3	620 to 973	49	—	—	49
	Aluminum				12	—	—	12
XI-Imp-187-F[5]	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

[1] All test results are based upon metallographic analysis of culvert samples.

[2] Estimated years to perforation for all samples were calculated on the basis of a 16-gage metal thickness.

[3] Aluminum only perforated within test time.

[4] Aluminum and galvanized steel perforated within test time.

[5] 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[1] for Five Test Sites with pH Between 4.5 and 8.3			
Galvanized steel	18	21	25
Aluminum	12	1.9	17

[1] 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

$$\text{Geometric mean} = \sqrt[n]{X_1X_2\ .\ .\ .\ X_n} \qquad (1)$$

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

This investigation of the corrosion of metal culverts was conducted as one of the activities of the Materials and Research Department of the California Division of Highways, in cooperation with the Bureau of Public Roads.

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.

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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 ⅛ 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[a]
42	62+	5.0	14	2.8
43	6	2.6	13	3.2
45	46+	6.8	20	4.6

[a] Second sample destroyed.

TABLE 17

BRITISH IRON AND STEEL RESEARCH ASSOCIATION—ALUMINUM BURIED IN FIVE SOILS[a]

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[b]	125+	—	6.4	—

[a] 1100 Alloy: 10- × 15- 0.125-in. sheet; 1-in. diam., 15 in. long, 0.062-in. wall pipe.

[b] Cinder embankment.

TABLE 18

BRITISH NON-FERROUS METALS RESEARCH ASSOCIATION TEN-YEAR TEST—ALUMINUM BURIED IN SIX SOILS[a]

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

[a] 4- × 8- × 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[a]

[a] 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.

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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 Nordlin 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 (%)[a, b] (20 yr)		Calculated Loss in Tensile Strength (%)[b, c] (20 yr)		Max. Pit Depth Mils, Microscopic Exam.[d] (20 yr)		Loss in Elongation (%)[e]			
							Pre-Machined Tension Spec. (1 yr)		Panels (20 yr)	
	New York	La Jolla	New York	La Jolla	New York	La Jolla	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						

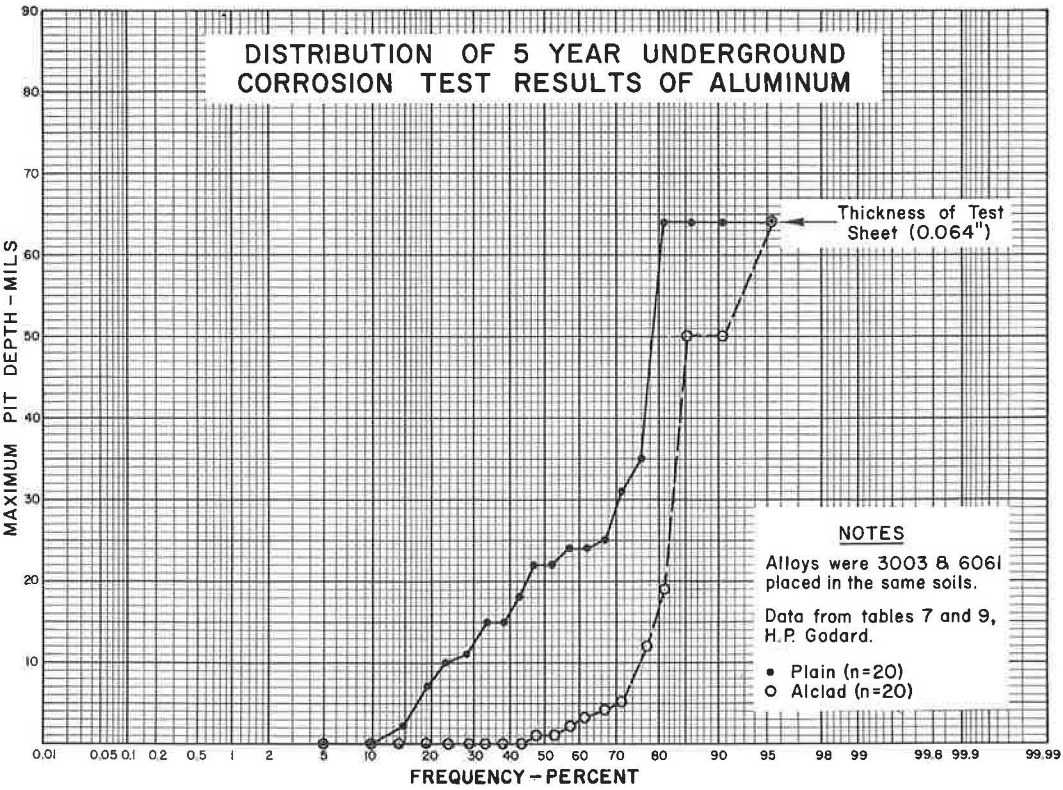
[a] Actual loss in tensile strength was measured on tension specimens machined from panels.

[b] From Table IV (50).

[c] Calculated from weight loss data, assuming corrosion to be perfectly uniform.

[d] From Table D (50).

[e] From Table C (50).



DISTRIBUTION OF 5 YEAR UNDERGROUND CORROSION TEST RESULTS OF ALUMINUM

Thickness of Test Sheet (0.064")

NOTES

Alloys were 3003 & 6061 placed in the same soils.

Data from tables 7 and 9, H.P. Godard.

- ● Plain (n=20)
- ○ Alclad (n=20)

Figure 37.

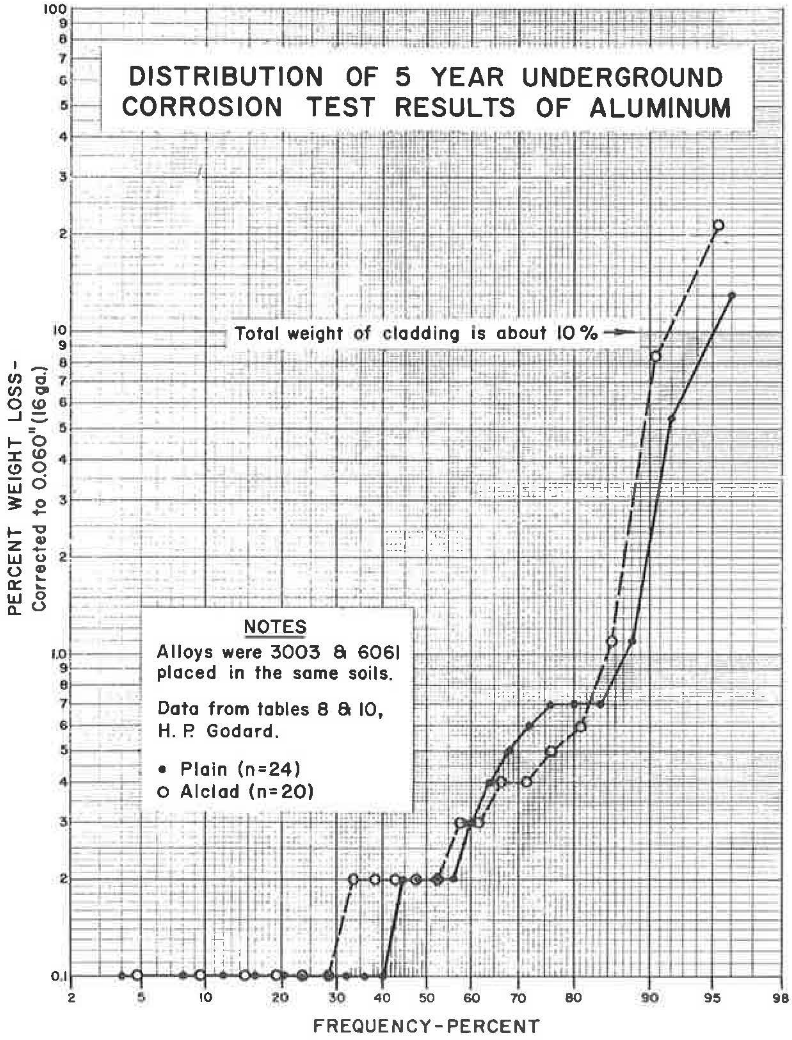

DISTRIBUTION OF 5 YEAR UNDERGROUND CORROSION TEST RESULTS OF ALUMINUM
Total weight of cladding is about 10 %
NOTES
Alloys were 3003 & 6061 placed in the same soils.
Data from tables 8 & 10, H. P. Godard.
● Plain (n=24)
○ Alclad (n=20)
PERCENT WEIGHT LOSS-
Corrected to 0.060" (16 ga.)
FREQUENCY-PERCENT
100
9
8
7
6
5
4
3
2
10
1.0
0.1
2
5
10
20
30
40
50
60
70
80
90
95
98

Figure 38.

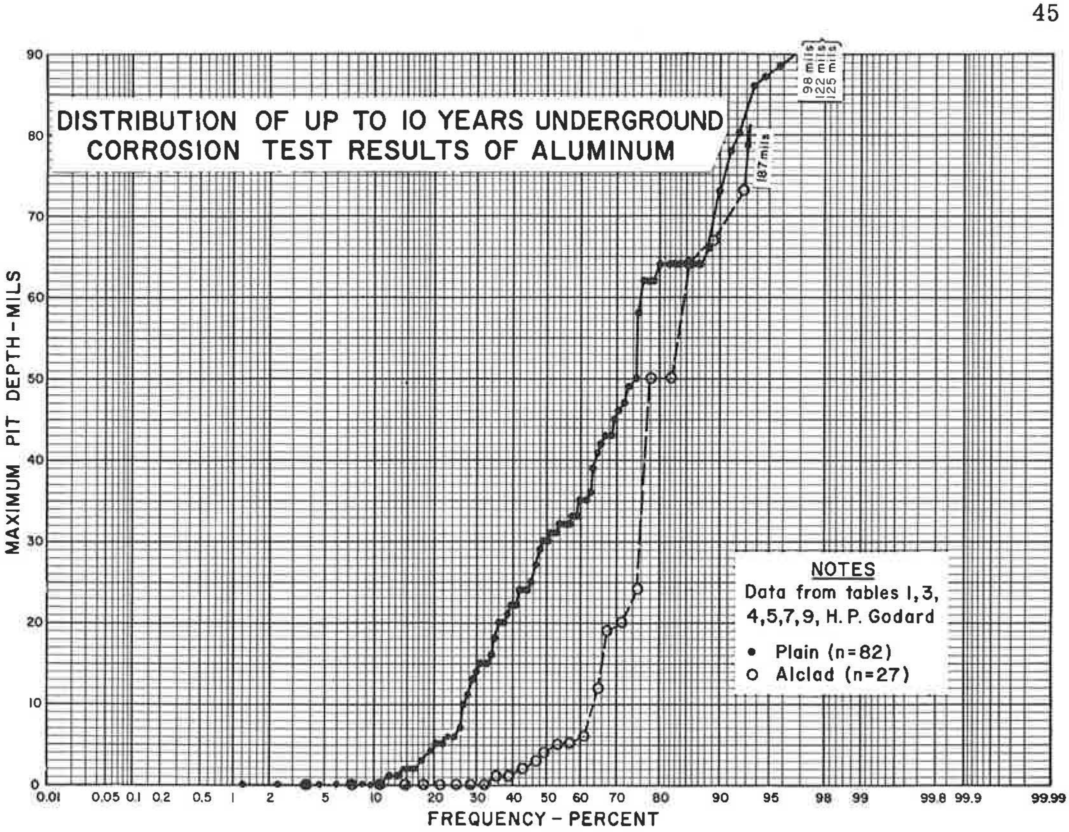


Figure 39.

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-

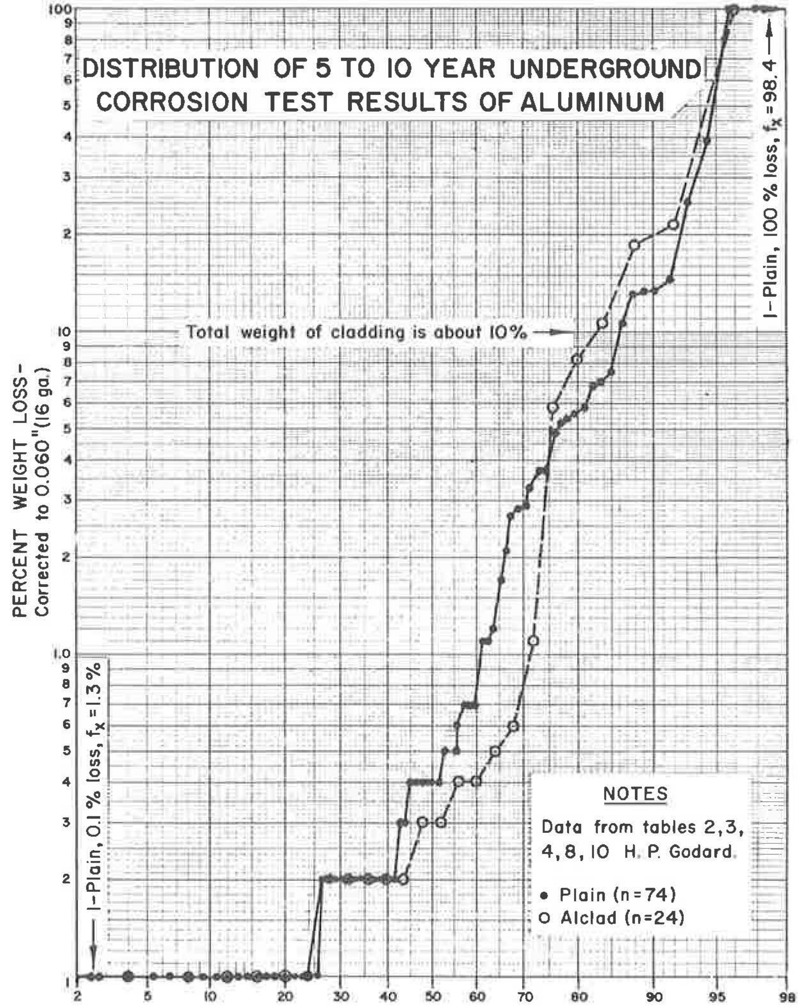

DISTRIBUTION OF 5 TO 10 YEAR UNDERGROUND CORROSION TEST RESULTS OF ALUMINUM
Total weight of cladding is about 10%
1-Plain, 100 % loss, f_x = 98.4
1-Plain, 0.1 % loss, f_x = 1.3 %
NOTES
Data from tables 2,3, 4,8,10 H. P. Godard.
● Plain (n=74)
○ Alclad (n=24)
PERCENT WEIGHT LOSS- Corrected to 0.060"(16 ga.)
FREQUENCY-PERCENT
100
10
1.0
.1
2
5
10
20
30
40
50
60
70
80
90
95
98

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.

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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, $Al_2O_3 \cdot 3\,H_2O$, (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 Al^{+++} and AlO_2^- species and in terms of the solid Al^0 and $Al_2O_3 \cdot 3\,H_2O$. 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 $Al(OH)_3$ 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.

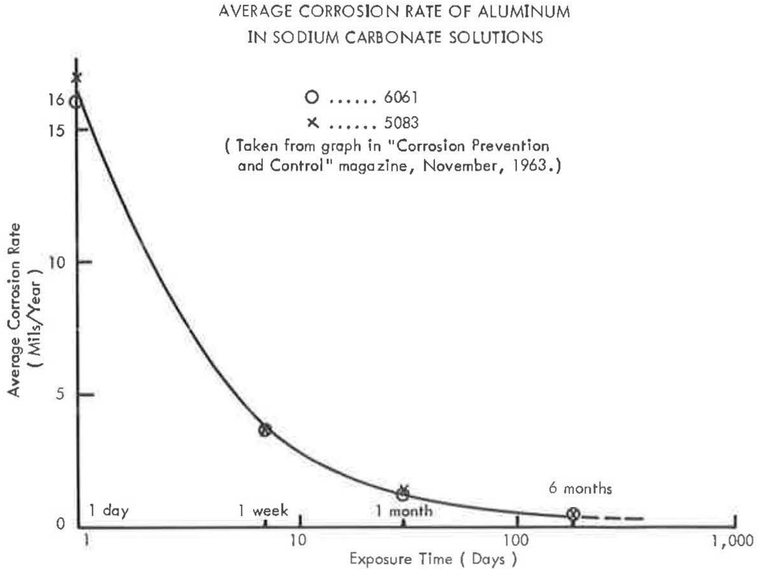

Figure 41. Rapid decrease in corrosion rate with increasing exposure, of aluminum alloys 6061 and 5083 to 10 percent (by wt) and to saturated sodium carbonate solutions at room temperature.

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 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.

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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 $Al(OH)_3$ 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 $Al(OH)_3$ 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 $Al_2O_3 \cdot 3H_2O$, of which Fricke and Jucaitis have calculated the solubility product $(AlO_2^-)(H^+) = 2.5 \times 10^{-15}$ 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 $Al(OH)_3$ 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 9(10)."

(b) Statement by C. J. Walton, F. L. McGeary, and E. T. Englehart (53): "It has been indicated by McKee and Brown[4] 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' terminology 'corrosion inhibiting clading.' 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 resistivites 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 Nordlin 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

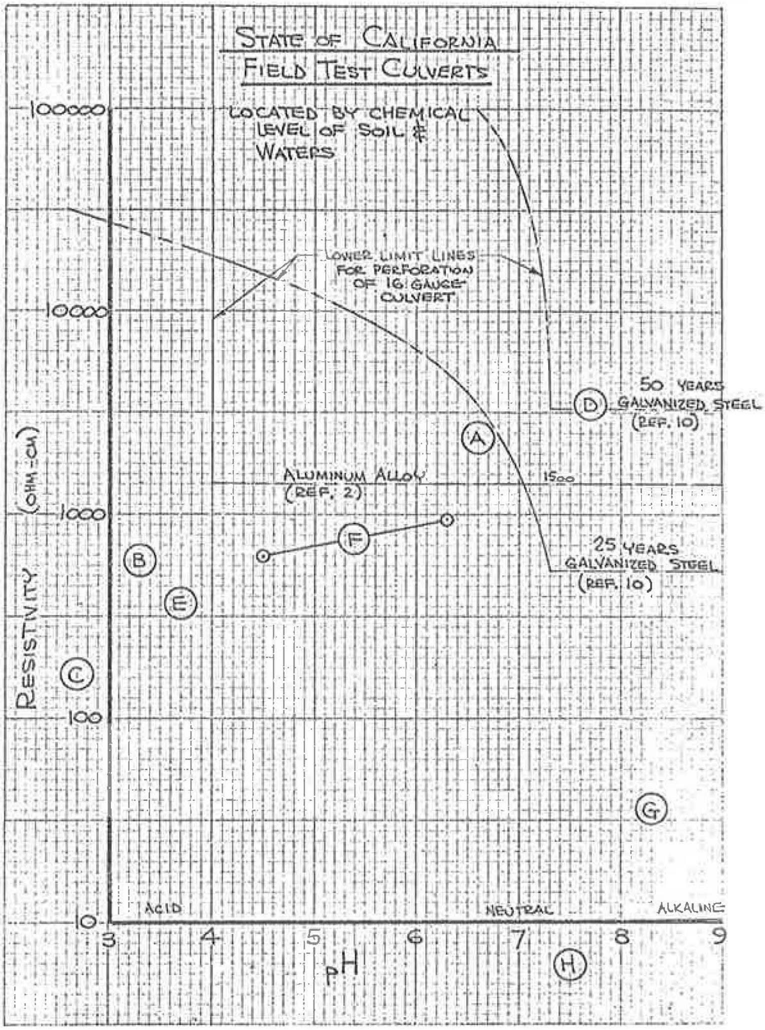

Figure 42.

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 with 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

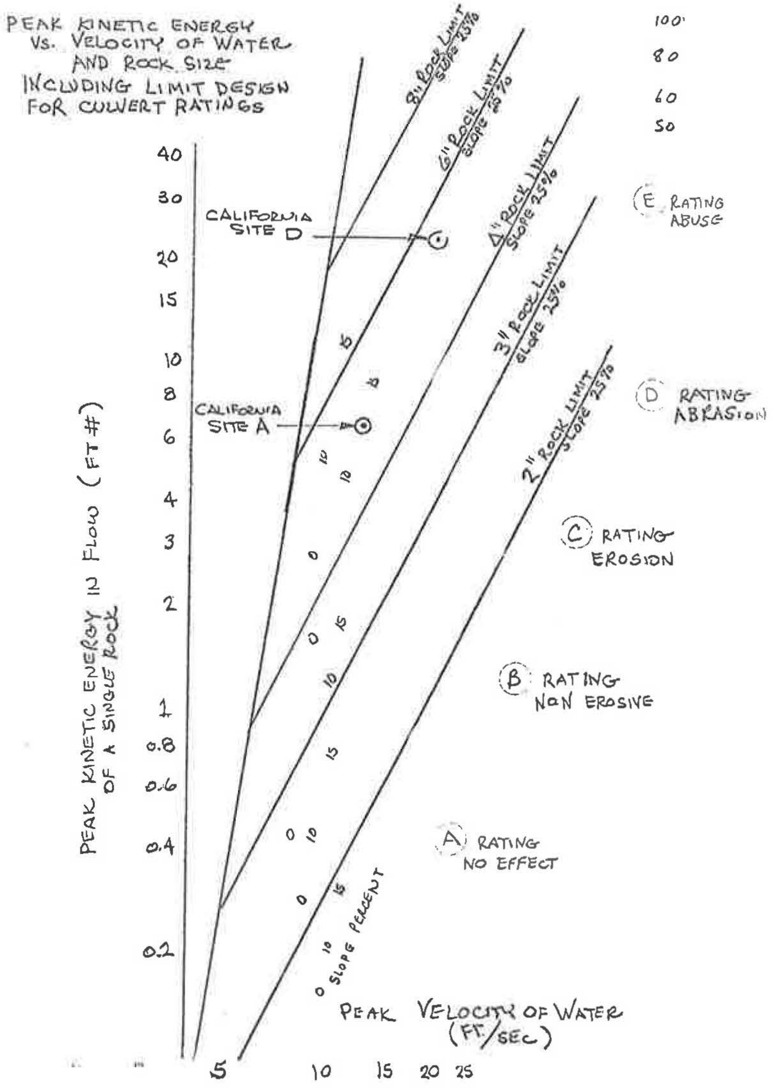

Figure 43.

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 clading 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. DAESEN, 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-SCl-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.

Nondestructive Tests for Detecting Discontinuities In Aluminum Alloy Arc Welds

F. C. PANIAN, J. A. PATSEY and G. F. SAGER, Aluminum Company of America, Alcoa Research Laboratories, New Kensington, Pa.

This paper describes an investigation conducted to evaluate radiographic and ultrasonic procedures for detecting 14 types of discontinuity in TIG or MIG arc welds in 2219-T87 aluminum alloy plate, and to determine the effects of these discontinuities on the static strength of the welded joints. The discontinuities studied were microporosity, linear porosity, scattered porosity, oxide inclusions, tungsten inclusions, lack of interpass fusion, lack of root fusion, lack of side fusion, incomplete root penetration, crater cracks, longitudinal cracks, craters, underbead folds and weld bead overlaps. The welds were examined metallographically to aid in establishing or confirming the types of discontinuity present.

Although the above work was done on 2219-T87 aluminum alloy plate, the nondestructive tests employed could also be applied to other aluminum alloys.

This investigation represents a portion of the work done on NASA Research Contract No. NAS 8-5132 on the Arc Welding of 2219 Alloy.

•WELDS of high structural integrity have been made in aluminum alloys for many years, but as in any other metal, the consistent production of such welds depends upon the use of suitable equipment and the skill and care of the welder. For these reasons, appropriate nondestructive testing procedures are necessary for determining the quality of welds in structures.

While there has been wide experience in welding and inspecting aluminum alloy weldments, there have been few data on the size and distribution of discontinuities in welds coupled with the effect on the static strength. Another area where there has been little reported work concerns the relative accuracy of radiography and ultrasonic techniques in examining aluminum alloy weld structures.

Although some data indicating relative capabilities of these nondestructive tests were obtained, no attempts were made to establish inspection standards or to develop specifications. These data should be helpful in this connection, but additional research and development is necessary before realistic inspection standards and specifications can be established.

Aluminum alloy 2219 is used extensively in welded missile structures because it exhibits good welding characteristics, uniformity of weld strength, resistance to stress corrosion cracking, and high strength at ordinary, elevated, and cryogenic temperatures. This investigation was undertaken in conjunction with a NASA research contract on the arc welding of 2219 alloy to obtain data that would be of use in establishing nondestructive testing procedures for welded joints in 2219 alloy plate. Although the radiographic and ultrasonic testing procedures discussed were employed to evaluate welds in 2219 alloy plate, the same procedures also can be applied to other aluminum alloys that might be used in highway applications.

Fourteen different types of discontinuities were deliberately introduced into a group of welded plate samples, which also included relatively sound welds (for controls).

Paper sponsored by Committee on Metals in Highway Structures.

TABLE 1

WELD CONDITIONS CONSIDERED IN INVESTIGATION

General Type	Specific Condition
Relatively Sound	Relatively Sound
Porosity	Microporosity
	Linear Porosity
	Scattered Porosity
Inclusions	Oxide Inclusions
	Tungsten Inclusions
Lack of Fusion or Penetration	Lack of Interpass Fusion
	Lack of Root Fusion
	Lack of Side Fusion
	Incomplete Root Penetration
Cracks	Crater Cracks
	Transverse Cracks*
	Longitudinal Cracks†
Miscellaneous	Craters
	Underbead Fold
	Weld Bead Overlap

* *Transverse cracks were eliminated from the investigation after a number of attempts to produce such cracks failed.*

† *Investigated to only a very limited extent because of difficulty in producing such cracks.*

TABLE 2

TENSILE PROPERTIES OF 2219-T87 PLATE USED FOR WELDED PANELS*

Designation	Plate Thickness	T.S. psi	Y.S. psi	Red. of Area-%	Elong. %
Lot A	1/2"	71100	59400	20	10†
Lot B	1/2"	67750	55200	22	10†
Lot C	1"	68850	56800	20	9**

* *Properties are averages for two tests. Specimens from 1/2" plate had nominal diameter of 1/4"; those from 1" plate had nominal diameter of 1/2". All specimens were taken in the transverse direction.*

† *Elongation in 1" gage length.*

***Elongation in 2" gage length.*

The weld in each sample was subjected to radiographic examinations and ultrasonic tests employing conventional and some experimental procedures. The two series of tests were performed to determine which of the test methods is the more suitable in each instance. Reduced section tensile and guided bend tests on specimens containing portions of the various welds finally were conducted to determine the effect of the weld conditions on joint strength and ductility. Auxiliary phases of the work included metallographic studies to verify the types of discontinuity or to explain their effects on the properties of the joints, and fracture studies for the same purposes.

The weld conditions considered in the investigation are given in Table 1.

PREPARATION OF WELDED PANELS

Plate of 2219 alloy and filler wire of 2319 alloy were used for the welded panels prepared for this investigation. The tensile properties of the unwelded plate are given in Table 2. One series of panels was fabricated from ½-in. plate and a second from 1-in. plate. The panels were 18 × 24 in. and were made by joining two 12 × 18 in. pieces of plate by a weld running along an 18-in. edge. In general, single-V butt joints were used in the ½-in. panels and double-V butt joints in the 1-in. panels. However, additional ½- × 18- × 24-in. panels were prepared with square butt joints welded in two passes (one on each side) with various degrees of weld penetration.

All welds were made by tungsten or consumable electrode inert-gas shielded arc welding (TIG or MIG). These procedures eliminate the need for flux and are used extensively for the welding of aluminum alloys. Joint preparation and welding procedures were varied to achieve the desired weld conditions. For example, the degree of penetration was controlled by varying such factors as root spacing, welding current and welding speed. Lack of fusion was achieved by the use of relatively cold passes at appropriate stages in the welding operation. Oxide inclusions were introduced by reducing the flow of inert gas to the point where shielding was no longer sufficient to prevent oxidation. An oiled liner in the electrode hose was used in some instances to produce porous welds. Tungsten inclusions were produced with the TIG procedure by jogging the arc on and off. Craters and crater cracks were produced by a backstepping procedure that interrupted the continuity of the welding operation.

In several instances it was necessary to produce "synthetic" defects by procedures that would not be encountered in ordinary welding operations. For example, longitudinal porosity was simulated in one instance by drilling small holes in the root pass and then covering them with a cold pass. These simulated defects were useful for checking the capabilities of the nondestructive testing procedures but such defects were not included in the mechanical property tests because the results would be misleading.

TABLE 3

IDENTIFICATION OF PANELS EXEMPLIFYING VARIOUS WELD CONDITIONS

Nominal Weld Condition	Plate Thickness	Type of Joint	Type of Weld	Identification of Panel	
				ARL S No.	APDL No.
Relatively Sound	1/2"	Single-V Butt	TIG	278454	1
Relatively Sound	1"	Double-V Butt	MIG	278515	9B2
Microporosity	1/2"	Single-V Butt	MIG	278491	9A1
Microporosity	1/2"	Single-V Butt	MIG	278490	9A2
Microporosity with Some Scattered Porosity	1/2"	Single-V Butt	TIG	278462	6A
Linear Porosity	1/2"	Single-V Butt	MIG	278492	10A1
Linear Porosity (Artificial)	1"	Double-V Butt	MIG	278501	10B2
Scattered Porosity	1/2"	Single-V Butt	MIG	278496	11A2
Light Randomly Scattered Porosity	1"	Double-V Butt	MIG	278509	11B2
Scattered Porosity	1"	Double-V Butt	MIG	278596	11B3
Oxide Inclusions	1/2"	Single-V Butt	MIG	278598	12A5
Oxide Film	1"	Double-V Butt	TIG	278549	A5
Tungsten Inclusions	1/2"	Single-V Butt	TIG	278456	53
Tungsten Inclusions	1/2"	Single-V Butt	TIG	278486	53A
Lack of Interpass Fusion	1/2"	Single-V Butt	MIG	278493	5A1
Lack of Interpass Fusion	1"	Double-V Butt	MIG	278516	5B1
Lack of Root Fusion	1/2"	Single-V Butt	TIG	278459	26B
Lack of Root Fusion	1"	Double-V Butt	MIG	278511	6B2
Lack of Side Fusion	1/2"	Single-V Butt	MIG	278597	7A4
Lack of Side Fusion	1"	Double-V Butt	MIG	278518	7B1
Incomplete Root Penetration	1/2"	Single-V Butt	MIG	278488	8A1
Incomplete Root Penetration	1"	Double-V Butt	MIG	278504	8B2
Internal Longitudinal Crack	1"	Double-V Butt	MIG	278495	3B2
Craters (Face Pass)	1/2"	Single-V Butt	MIG	278522	2A1
Craters (Face Pass)	1"	Double-V Butt	MIG	278514	2B2
Craters (Root Pass)	1/2"	Single-V Butt	TIG	278461	46
Underbead Fold	1/2"	Single-V Butt	MIG	278502	13A1
Underbead Fold	1"	Single-V Butt	MIG	278505	13B1
Weld Bead Overlap	1/2"	Single-V Butt	MIG	278519	14A1
Weld Bead Overlap	1"	Single-V Butt	MIG	278512	14B1
Reasonably Sound (Used for Reheat Treating Tests)	1"	Double-V Butt	TIG	278548	A4
Complete Penetration with Roots of Weld Beads Interpenetrating about 1/8"	1/2"	Square Butt	TIG	285185	–
Same as Preceding	1/2"	Square Butt	TIG	285321	–
Penetration Barely Complete with Roots of Weld Beads Just Touching	1/2"	Square Butt	TIG	285322	–
Incomplete Penetration with Separation of about 1/64" Between Roots of Weld Beads	1/2"	Square Butt	TIG	285323	–
Incomplete Penetration with Separation of about 3/64" Between Roots of Weld Beads	1/2"	Square Butt	TIG	285324	–
Incomplete Penetration with Separation of about 1/16" Between Roots of Weld Beads	1/2"	Square Butt	TIG	285187	–
Same as Preceding	1/2"	Square Butt	TIG	285326	–
Incomplete Penetration with Separation of about 1/8" Between Roots of Weld Beads	1/2"	Square Butt	TIG	285221	–
Penetration Varying from Complete to Incomplete (Sample from NASA)	1"	Square Butt	TIG	278550	–

After a number of unsuccessful attempts to produce welds containing transverse cracks, it was concluded that the occurrence of this type of defect was extremely unlikely in inert gas shielded welds made in 2219 alloy plate with 2319 alloy filler, so further attempts were abandoned. It was likewise not possible to produce longitudinal cracks in any actual welding operation although a number of restraining schemes were used. This experience indicates that the occurrence of longitudinal cracks also is unlikely with the above welding procedure and alloys. A synthetic internal longitudinal crack was finally made by bending the panel after one or two passes had been laid down and then applying a cold pass over the resulting crack.

Table 3 gives the identification of the panels exemplifying the various weld conditions, the plate thickness, the type of joint and the welding procedure.

If the subsequent radiographic examination indicated that the desired weld condition had not been achieved, the panel was discarded, and an additional panel was welded with appropriate alterations in joint preparation and welding practice. In some instances sections were cut from the joints and examined to confirm the weld conditions.

A further check on the weld conditions was obtained from the ultrasonic, metallographic and tensile tests and from the examination of fractures in the tensile specimens. Some additional panels were made during the final stages of the test program when it became apparent that certain of the welds did not represent the desired weld conditions or the desired degrees of severity of those conditions.

The welded panels prepared by Alcoa for this investigation were supplemented by five panels with square butt welded joints received from the George C. Marshall Space Flight Center at Huntsville, Ala. (ARL S Nos. 290963 to S290967, inclusive). These panels were submitted primarily for a further evaluation of ultrasonic tests for detecting slight amounts of incomplete penetration which are discussed in a subsequent portion of this paper.

RADIOGRAPHIC EXAMINATION

In the initial examination of each panel, practically the entire length of the weld was radiographed. These radiographs are subsequently referred to as the "full-length" radiographs. When the ultrasonic tests were completed, a 24- × 5-in. section containing a 5-in. length of weld was cut from each panel and retained as a reference sample. The welds in these radiographic panels were re-radiographed after the panels had been cut from the original weldments. These sections, which are subsequently referred to as the "radiographic panels," were reserved for the production of additional radiographs if required.

Two General Electric Co. OX-140 radiographic units were used for the radiographic examinations. Table 4 gives the exposure conditions and types of film used.

The full-length radiographs provided a valuable basis for screening the panels to separate weld conditions suitable for use in the investigation from those that were not. In most instances, the radiographs of the panels selected for further study indicated that the desired weld conditions persisted over a significant portion of the weld length.

Table 5 lists the weld conditions that could be detected radiographically with reasonable assurance, those that could not be detected in this way, and those for which detection was questionable. The radiographic observations in Table 5 are based on three groups of radiographs: the full-length radiographs, those of the 5" radiographic sections and those of the tensile and bend specimens.

The weld conditions detected with reasonable assurance were linear porosity, scattered porosity, tungsten inclusions, lack of interpass fusion, lack of root fusion, lack of side fusion, incomplete root penetration, craters and crater cracks. Detection of incomplete root penetration in square butt welds became uncertain when the separation between the roots of the weld beads was about $\frac{1}{16}$ in. or less.

The conditions that were not detected radiographically were microporosity and an internal longitudinal crack. In the questionable detection category were oxide inclusions, underbead folds and weld bead overlaps. The oxide inclusions were quite apparent in the radiograph of a rather extreme example (S278596) produced by welding with a deficiency of shielding gas. However, an oxide film condition (S278549) was not observed radiographically. This undetected condition prevented proper bonding of weld metal to plate metal and seriously weakened a portion of the joint. Underbead folds and weld bead overlaps show up in radiographs as would unusually thick weld crowns or weld crowns with an unsymmetrical distribution of metal. It is difficult to determine radiographically whether the metal is actually fused into the surface of the plate or merely folded over mechanically. Ordinarily, underbead folds and weld bead overlaps can be more readily identified by a visual inspection of the weld.

TABLE 4

RADIOGRAPHIC EXPOSURE CONDITIONS AND TYPE OF FILM*

Type of Specimen	Position in Which Radiographed	Thickness Penetrated by X-Ray	KVP	Exposure Time	Film
24" × 18" panel of 1/2" plate (single-V groove)	normal†	1/2"**	70-80	135-150 sec.	Kodak AA
24" × 18" panel of 1/2" plate (square butt joint)	normal	1/2"	66	5 min.	Ansco Superay "B"
24" × 18" panel of 1" plate	normal	1"	105	3 min.	Kodak AA
24" × 5" radiographic panel of 1/2" plate	normal	1/2"	66	5 min.	Ansco Superay "B"
24" × 5" radiographic from 1/2" panel	normal	1"	94	5 min.	Ansco Superay "B"
Tensile specimen from 1/2" panel	normal	0.45-0.47"	66	5 min.	Ansco Superay "B"
Same as preceding	transverse†	1-1/2"	94	5 min.	Ansco Superay "B"
Tensile specimen from 1" panel	normal	0.95-0.98"	90	5 min.	Ansco Superay "B"
Same as preceding	transverse	1"	94	5 min.	Ansco Superay "B"
Guided bend (face and root from 1/2" and 1" panels)	normal	3/8"	63	5 min.	Ansco Superay "B"
Same as preceding	transverse	1-1/2"	94	5 min.	Ansco Superay "B"

* *All exposures made on General Electric Company OX-140 Radiographic Units with a tube current of 5 ma and a source-to-film distance of 36".*

† *"Normal" indicates that X-ray beam was normal to plate surface; "transverse" indicates that specimen was radiographed in an edgewise position with the X-ray beam parallel to the axis of the weld.*

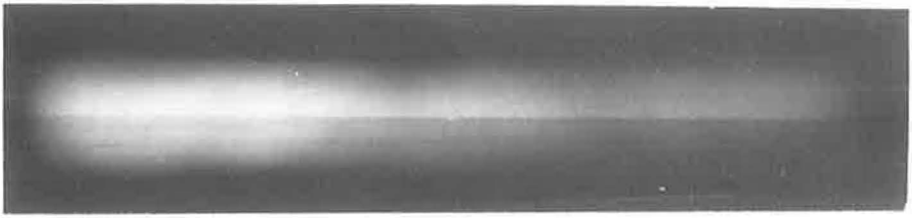
***All specimens except the machined tensile and bend specimens were radiographed with the crown on the welds so the maximum thickness penetrated by the X-ray beam is somewhat greater than the plate thickness.*

Radiographs of a number of the weld conditions under investigation are shown in Figures 1, 2 and 3. Unfortunately, it has not been possible to retain in the illustrations the degree of detail discernible in the radiographs themselves.

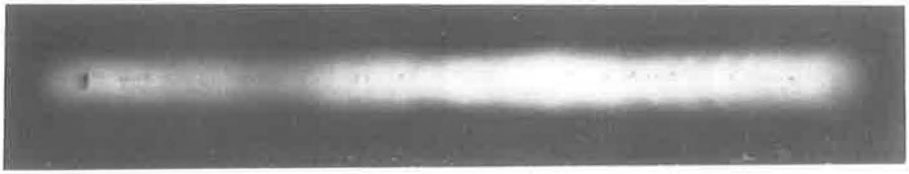
Figure 1 illustrates radiographs of a relatively sound weld, incomplete root penetration, linear and scattered porosity and lack of interpass fusion. The relatively sound weld contains some microporosity not discernible in the radiograph. Incomplete root penetration appears as a sharp line extending horizontally along the midportion of the weld bead. The linear porosity appears as an irregular scattering of faint spots along the centerline of the weld bead. The majority of the spots are in the right-hand third of the weld, but there are several just to the left of the center. Lack of interpass fusion appears as a discontinuous line of varying width and density extending along the centerline of the weld bead.

Figure 2 illustrates radiographs of welds containing tungsten inclusions, oxide inclusions and craters. Light patches associated with the high density tungsten inclusions stand out very sharply. The oxide inclusions require closer scrutiny and appear as small spots of porosity near the right-hand end of the weld bead. The craters appear as rounded zones with relatively dark centers.

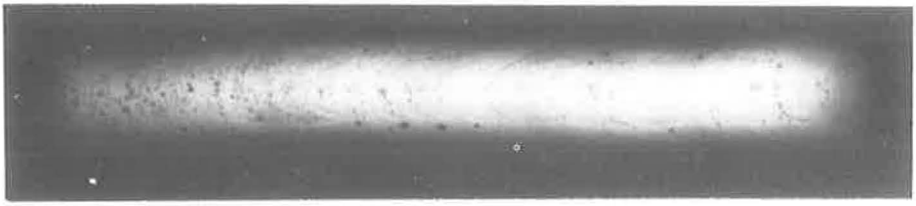
S278454 – RELATIVELY SOUND TIG WELD



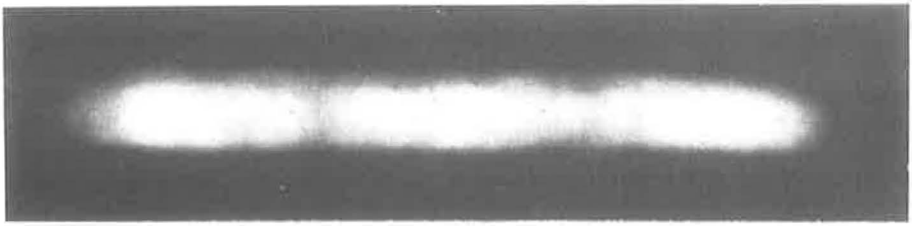
S278488 – MIG WELD WITH INCOMPLETE ROOT PENETRATION



S278492 – MIG WELD WITH LINEAR POROSITY

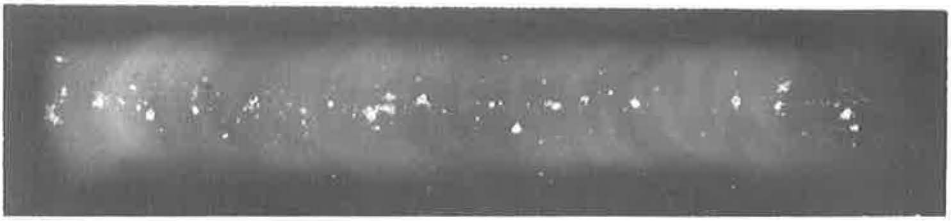


S278496 – MIG WELD WITH SCATTERED POROSITY



S278493 – MIG WELD WITH LACK OF INTERPASS FUSION

Figure 1. Radiographs of welds in $\frac{1}{2}$-in. 2219-T87 plate.

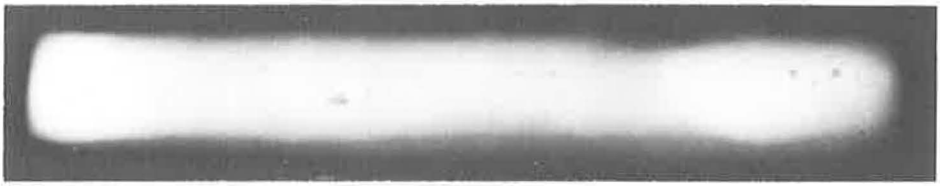


S278456 – TIG WELD WITH TUNGSTEN INCLUSIONS

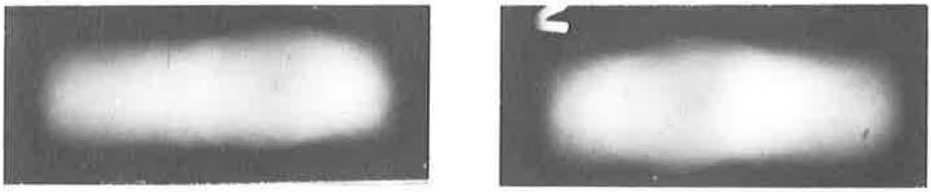
TENSILE
S278486-T2

BEND
S278486-B3

TENSILE AND BEND SPECIMENS WITH TUNGSTEN INCLUSIONS



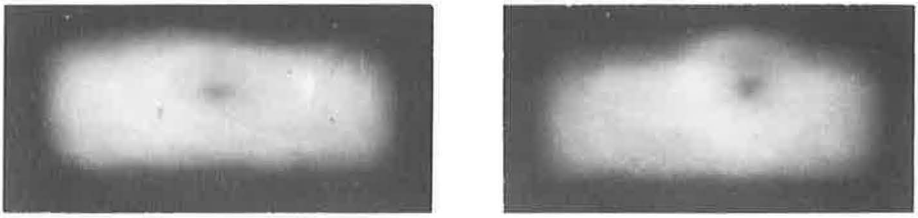
S278598 – MIG WELD WITH OXIDE INCLUSIONS AND POROSITY



S278522-T1

S278522-2

CRATERS IN TENSILE BLANKS
(MIG WELD – FACE PASS)

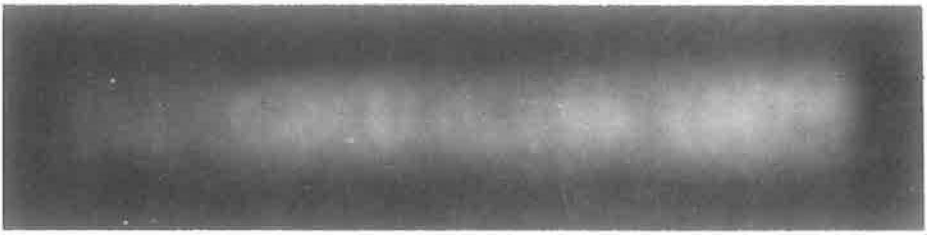


S278461-T1

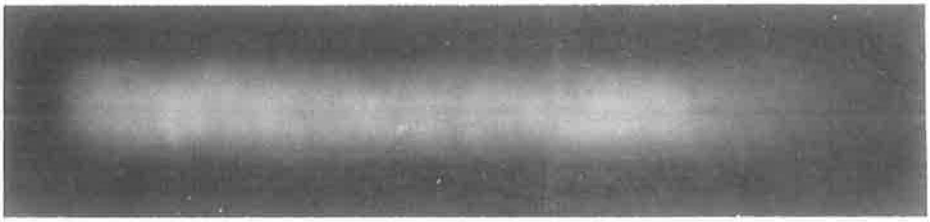
S278461-T2

CRATERS IN TENSILE BLANKS
(TIG WELD – ROOT PASS)

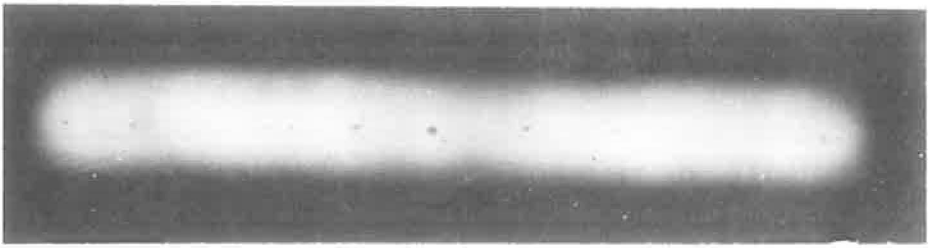
Figure 2. Radiographs of welds in $\frac{1}{2}$-in. 2219-T87 plate.



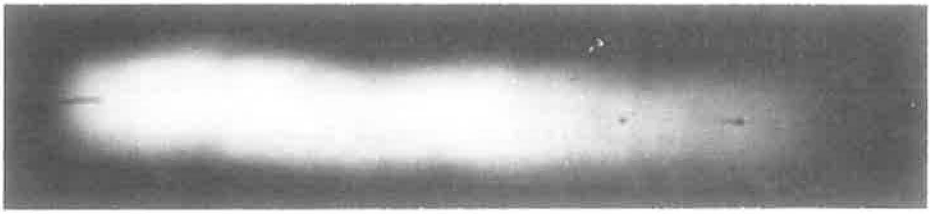
S278515 – RELATIVELY SOUND MIG WELD



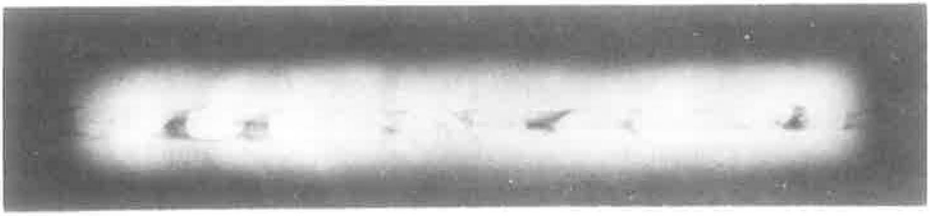
S278504 – MIG WELD WITH INCOMPLETE ROOT PENETRATION



S278501 – MIG WELD WITH LINEAR POROSITY



S278516 – MIG WELD WITH LACK OF INTERPASS FUSION



S278511 – MIG WELD WITH LACK OF ROOT FUSION

Figure 3. Radiographs of welds in 1-in. 2219-T87 plate.

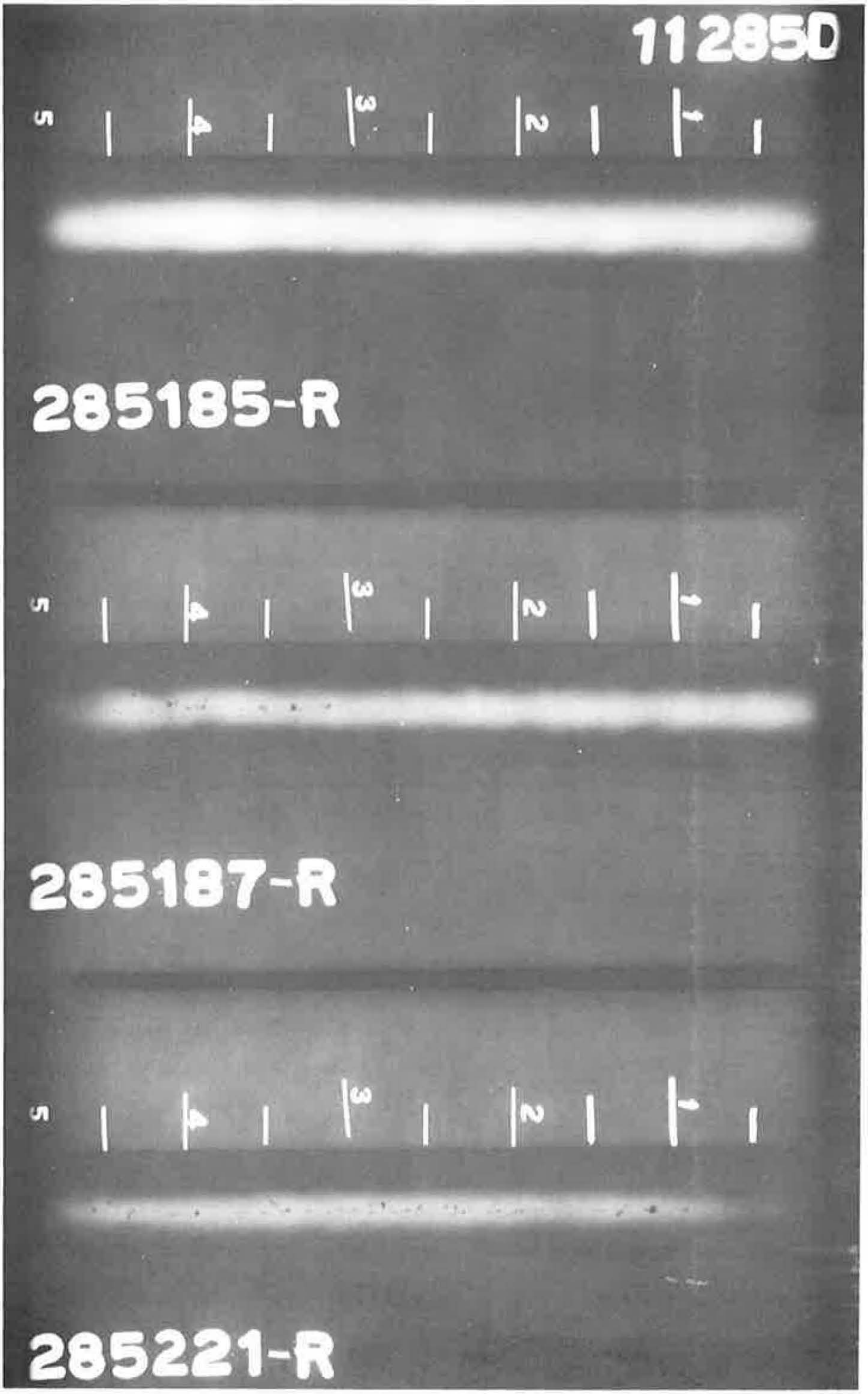
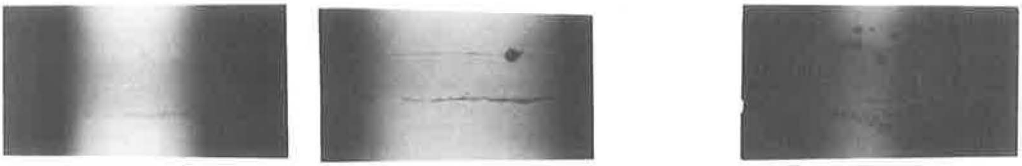


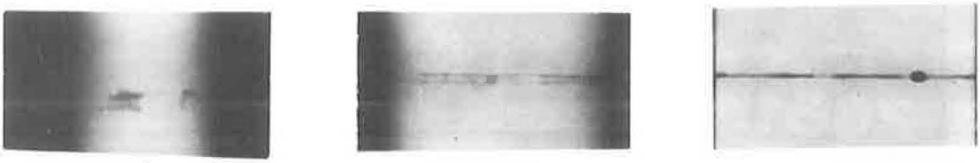
Figure 4. Radiographs of square butt welds in $\frac{1}{2}$-in. 2219-T87 plate representing various degrees of penetration: S285185-R, complete with interpenetration of weld bead roots; S285187-R, moderately incomplete; and S285221-R, markedly incomplete.



278518-T2† 278597-T2 278596-T1†

LACK OF SIDE FUSION

SCATTERED POROSITY



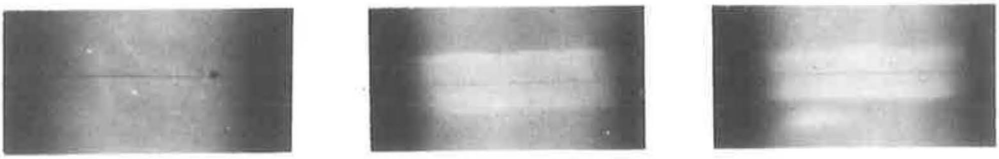
278511-T2† 278459-T2 278459-B2

LACK OF ROOT FUSION

†From 1" panels; all others from 1/2" panels.

278493-T2 278493-B2

LACK OF INTERPASS FUSION



278488-T2 285187-T2* 285221-T2*

278488-B4 285187-B1* 285221-B4*

INCOMPLETE PENETRATION

*Square butt joints; all others V-groove.

Figure 5. Radiographs of welds in some tensile specimens (-T) and bend specimens (-B).

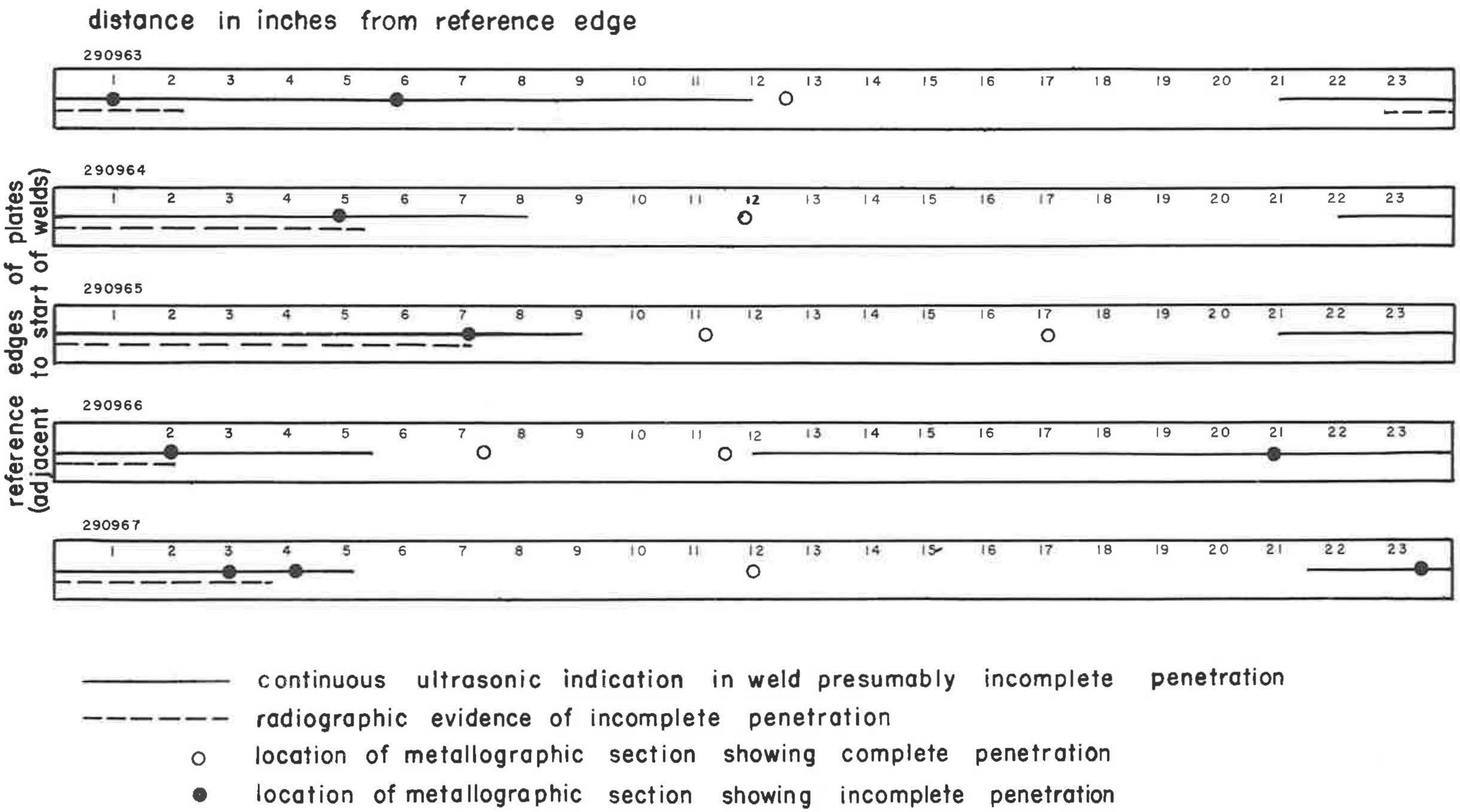


Figure 6. Results obtained from the ultrasonic, radiographic and metallographic tests for incomplete penetration.

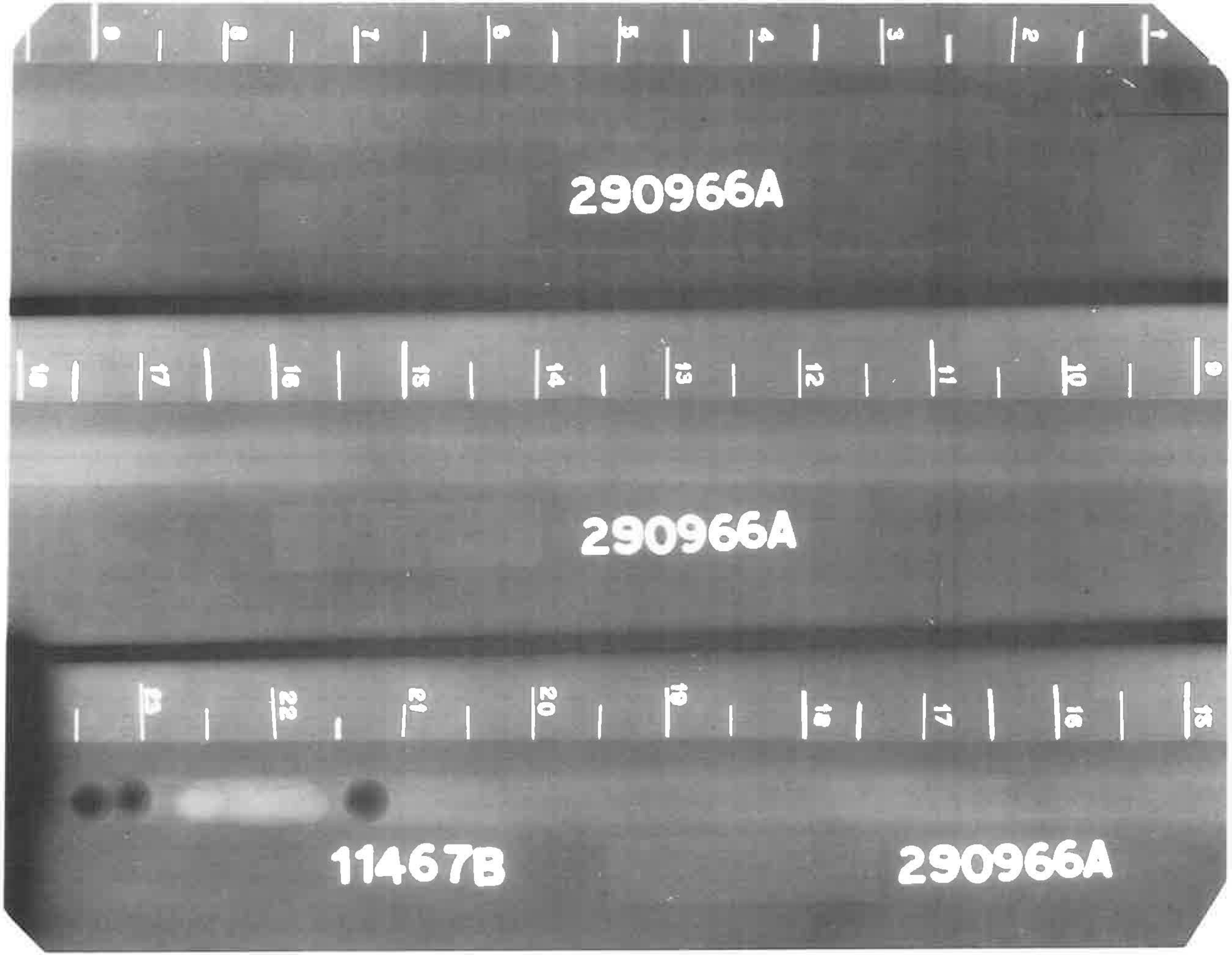


Figure 7. Radiograph of weld in panel S290966 after scarfing (about two-thirds original size). Weld starts about $1\frac{1}{4}$ in. from "reference" end of plate (upper right); incomplete penetration is evident for a distance of about three-fourths in. at beginning of weld; circular indentations (dark spots) may be associated with weld setup or attachment of equipment.

The radiographs in Figure 3 include a relatively sound weld containing some microporosity not discernible in the radiograph and welds with incomplete root penetration, linear porosity, lack of interpass fusion and lack of root fusion. The line of incomplete root penetration is broader and more diffuse than that in Figure 1. The lack of interpass fusion is evident as a few dark spots along a very faint, diffuse and discontinuous horizontal line through the mid-portion of the weld. The conspicuous dark spots in the bottom radiograph indicate voids of significant size along unfused portions of the weld root.

Figure 4 shows radiographs of square butt welds in $\frac{1}{2}$-in. plate with several degrees of penetration and fusion. The marked incomplete penetration in panel S285221-R (roots of two weld beads about $\frac{1}{8}$ in. apart) is plainly discernible and is associated with linear porosity. Panel S285187-R in which the roots of the weld beads are about $\frac{1}{16}$ in. apart, shows radiographic evidence of the incomplete penetration along only a portion of the weld length.

Radiographs of the welded joints in a number of machined tensile and bend specimens are reproduced in Figure 5. The weld conditions represented are lack of side, root and interpass fusion, incomplete penetration and scattered porosity.

Figure 6 shows the extent of incomplete penetration detected radiographically in the square butt welds from the George C. Marshall Space Flight Center. Figure 7 is a radiograph of one of these welds (S290966).

ULTRASONIC TESTS

All welds were inspected by an angle-beam shear-wave ultrasonic procedure in which the ultrasonic beam was directed through the plate and into the weld as shown in Figure 8. Four traverses of the search unit were made along lines roughly parallel to the weld and extending over its full length. These scans were made along each side of the weld and on each surface of the plate. Maximum response from discontinuities was obtained by slightly rotating the search unit about an axis normal to the plate surface and varying its distance from the weld.

A 2.25-mc lithium sulfate angle-beam shear-wave contact search unit and a Sperry Type UR Reflectoscope were used for most of the ultrasonic tests. The angle-beam search unit produced a shear-wave beam refracted to approximately 48 deg in the plate (angles of incidence and refraction are given with respect to a normal to the plate surface). Standardization was attained by adjusting the equipment for a 2.5-in. peak-to-peak indication from a $\frac{1}{8}$ in. diameter hole drilled through the $\frac{1}{2}$ in. dimension and normal to the surface of a $\frac{1}{2} \times 2\frac{1}{2} \times 14$ in. aluminum alloy angle beam reference plate.

A variable angle 2.25-mc lithium sulfate contact search unit was also employed for a limited number of tests. Other tests were conducted with experimental immersion testing apparatus employing higher test frequencies. A special lucite holder in which search units of the immersion type could be mounted was constructed for the latter tests. This holder contained a water column to provide coupling between the search unit and the part

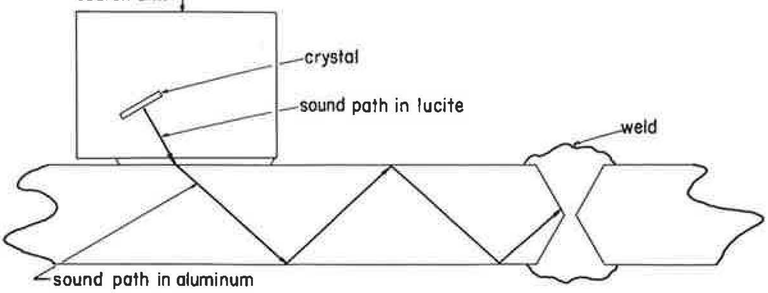


Figure 8. Shear wave search unit in position for an ultrasonic examination of 2219-T87 weldments.

Figure 9. Angle-beam search units used for ultrasonic weld inspection; unit in upper right is contact unit transmitting a shear wave into aluminum at a refracted angle of 48°, other unit is a liquid filled, variable angle unit.

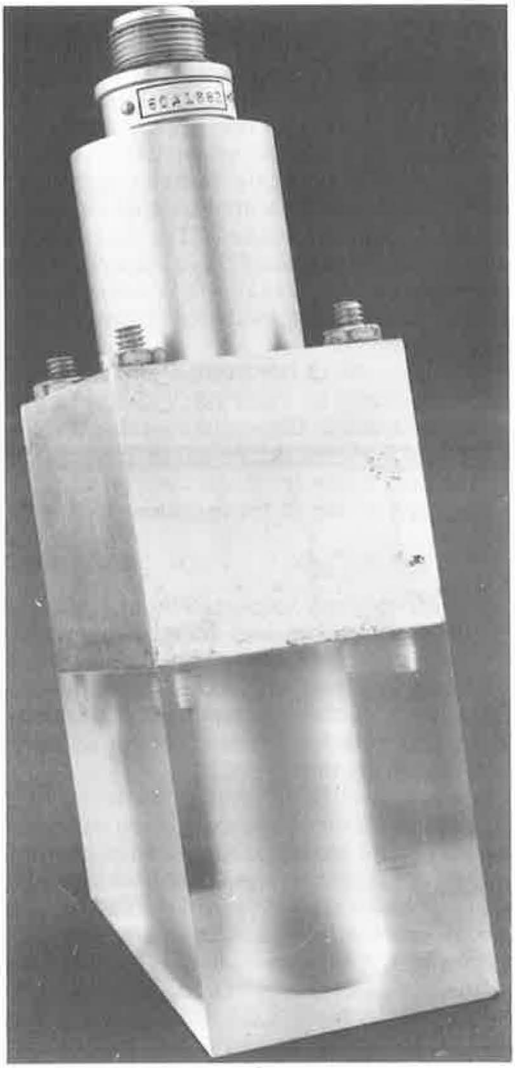


Figure 10. Special holder for immersion type search units.

being inspected. It was designed so that a shear-wave beam could be directed into the part at an optimum refraction angle of 45 deg. Tests were made with this unit at frequencies of 5 and 10 megacycles using lithium sulfate transducers of both the focusing and nonfocusing types. The three ultrasonic search units are shown in Figures 9 and 10.

After the initial ultrasonic inspections were concluded, weld beads on a number of samples were machined or ground flush with the plate surface and re-examined to determine whether extraneous ultrasonic indications were obtained from bead geometry or discontinuities in the crown of the welds. Samples containing weld crowns that appeared to be causing extraneous indications with the fixed-angle contact search unit were re-examined with the variable-angle search unit. These comparison tests were performed to establish a possible refraction angle other than 48 deg that might eliminate or minimize the extraneous indications.

The ultrasonic tests were not limited to the inspection of the as-welded panels. The tensile and bend specimens machined from the panels were also examined ultrasonically. The examination of the latter provided a further means of determining the effect of the weld crowns on ultrasonic response. The square butt welds previously referred to were examined with particular regard for incomplete root penetration.

The results of the ultrasonic tests on joints of the V-groove type are summarized in Table 5. The conditions readily detected ultrasonically include oxide inclusions, lack of interpass fusion, lack of root fusion, lack of side fusion, incomplete root penetration and internal longitudinal cracking.

TABLE 5

EFFECTIVENESS OF RADIOGRAPHY AND ULTRASONIC INSPECTION FOR DETECTING VARIOUS WELD CONDITIONS

	Condition Detected by Radiographic Examination			Condition Detected by Ultrasonic Examination*		
Weld Condition	**Yes**	**Questionable†**	**No**	**Yes**	**Questionable†**	**No**
Microporosity			X			X
Linear Porosity	X				X	
Scattered Porosity	X				X	
Oxide Inclusions		X		X		
Tungsten Inclusions	X				X	
Lack of Interpass Fusion	X			X		
Lack of Root Fusion	X			X		
Lack of Side Fusion	X			X		
Incomplete Root Penetration**	X°			X°°		
Crater Cracks	X				X	
Internal Longitudinal Crack			X	X		
Craters	X				X	
Underbead Fold		X††				X
Weld Bead Overlap		X††				X

* *With a few exceptions, ultrasonic tests were made with a 2.25 mc lithium sulfate contact angle-beam search unit producing a shear wave beam refracted at an angle of 48° to the normal in the aluminum. In most cases it was necessary to grind or machine the weld flush with the plate surface to avoid extraneous indications from the weld crown. A few tests made during the latter part of the investigation with a liquid-filled variable-angle search unit indicated that the extraneous indications might also be eliminated or minimized by introducing the sound beam at a suitable angle.*

† *This category includes instances where the condition was not detected with certainty or where it was detected in one sample but not in another.*

** *This condition was investigated in square butt joints as well as in the single-V and double-V groove joints used for all other phases of the investigation.*

° *Detection became uncertain when separation between roots of weld beads was about 1/16" or less.*

°° *Ultrasonic method appears superior to radiographic method for detecting slight incomplete penetration in square butt welds but exact limit of detection has not yet been determined.*

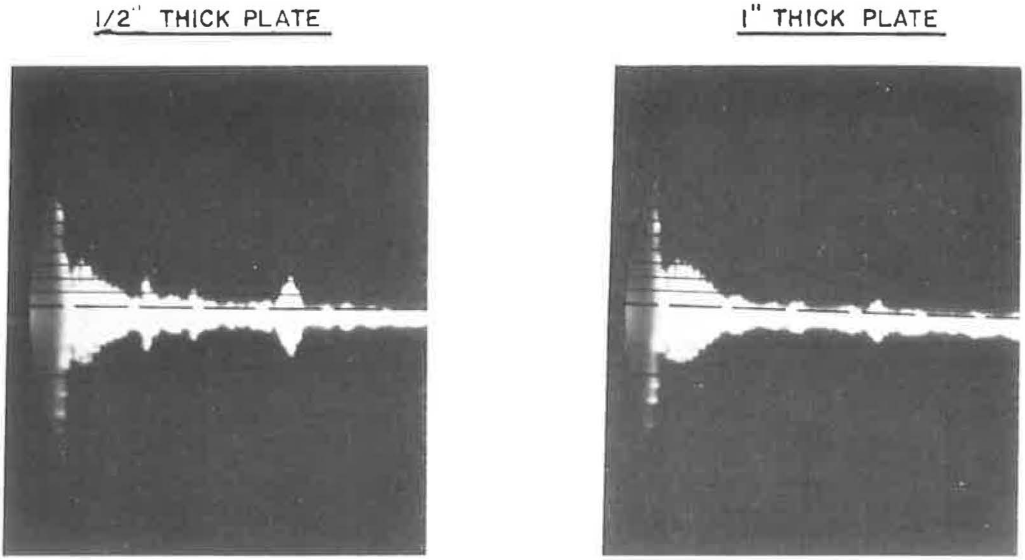
†† *Weld crown malformations are usually apparent in a radiograph but it might be difficult to relate them to a specific defect.*

The reflectograms reproduced in Figures 11 through 15 show the screen presentations obtained with relatively sound welds and welds containing a number of the discontinuities. The weld conditions reliably detected by ultrasonic testing usually gave well-defined indications. An ultrasonic noise level (hash) like that in Figure 11 was noted in testing most welds.

The weld conditions that were not detected consistently or with assurance in the ultrasonic tests include scattered porosity, linear porosity, craters and tungsten inclusions. In general, weld bead overlaps, underbead folds and microporosity were not detected by the ultrasonic tests.

Table 6 gives the ultrasonic response obtained from discontinuities in the square butt welds with various degrees of penetration. Figure 16 contains reflectograms corresponding to 3 of the square butt welds (S285221, S285107 and S285105) representing various degrees of incomplete penetration. Detection of incomplete penetration in welds of this type becomes uncertain when the separation of the two weld bead roots is less than about 1/16 inch.

The five square butt welds obtained from the George C. Marshall Space Flight Center were examined ultrasonically with the conventional 2.25-mc angle-beam shear-wave



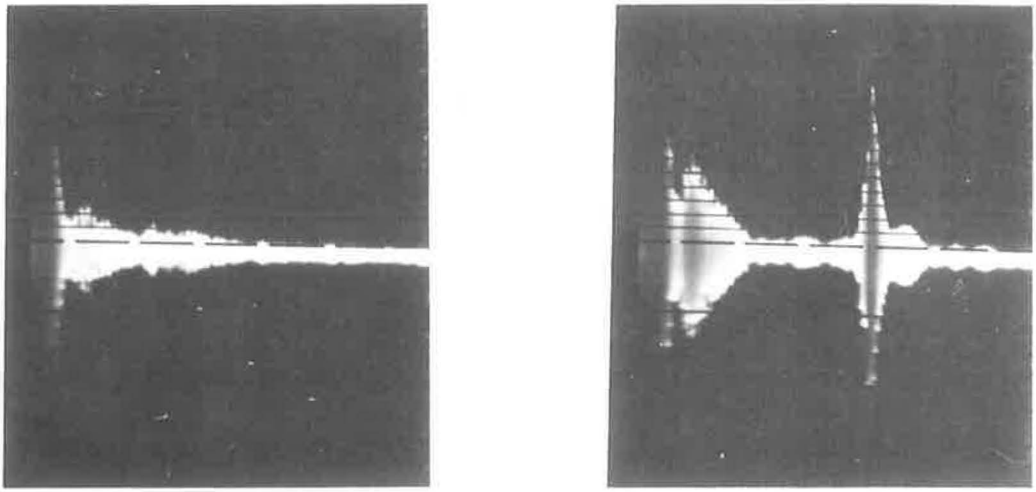
1/2" THICK PLATE

1" THICK PLATE

278454-T1

278515-T1

relatively sound and some microporosity



278522-T2

278514-T1

craters

Figure 11. Reflectograms showing ultrasonic indications corresponding to various weld conditions.

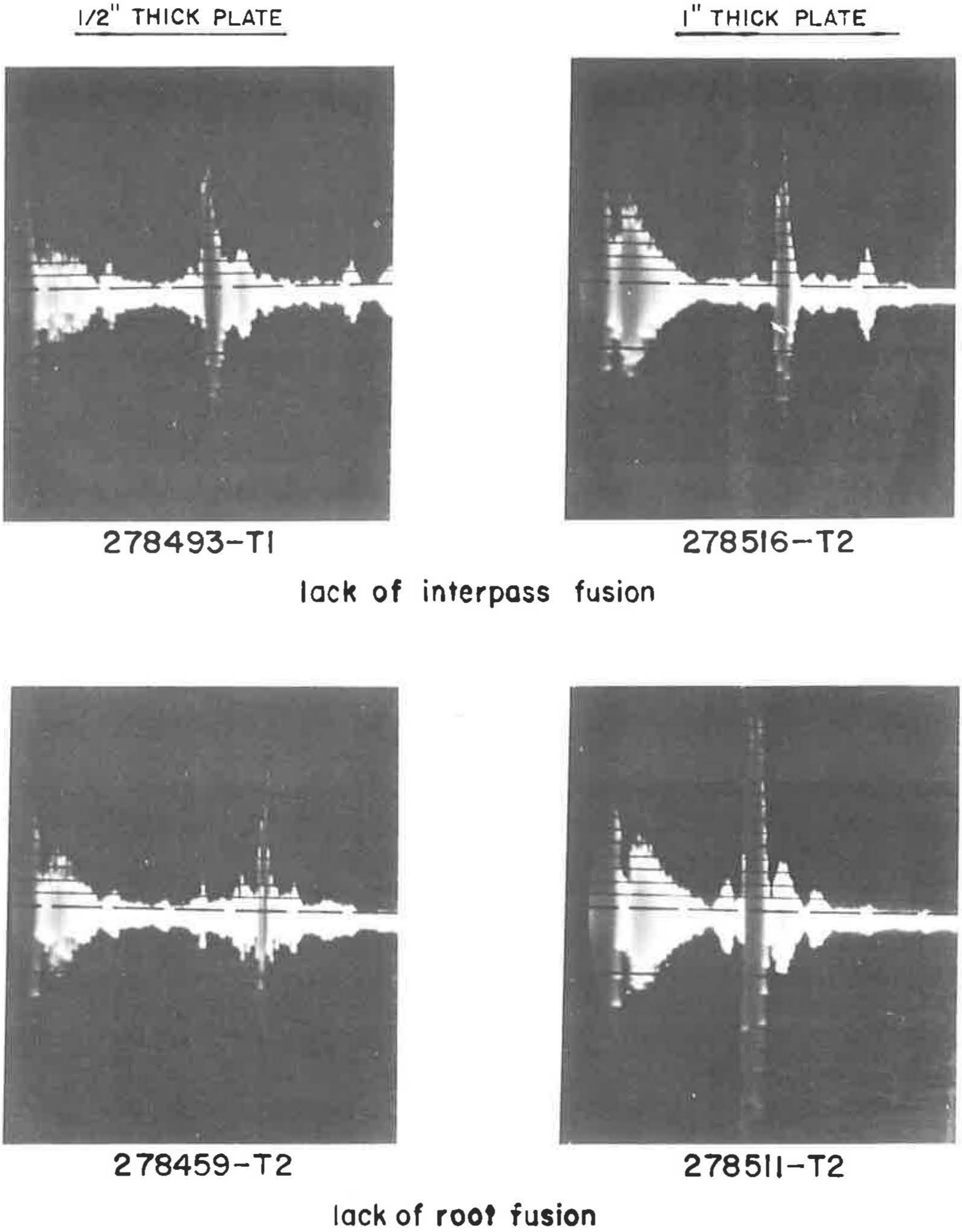
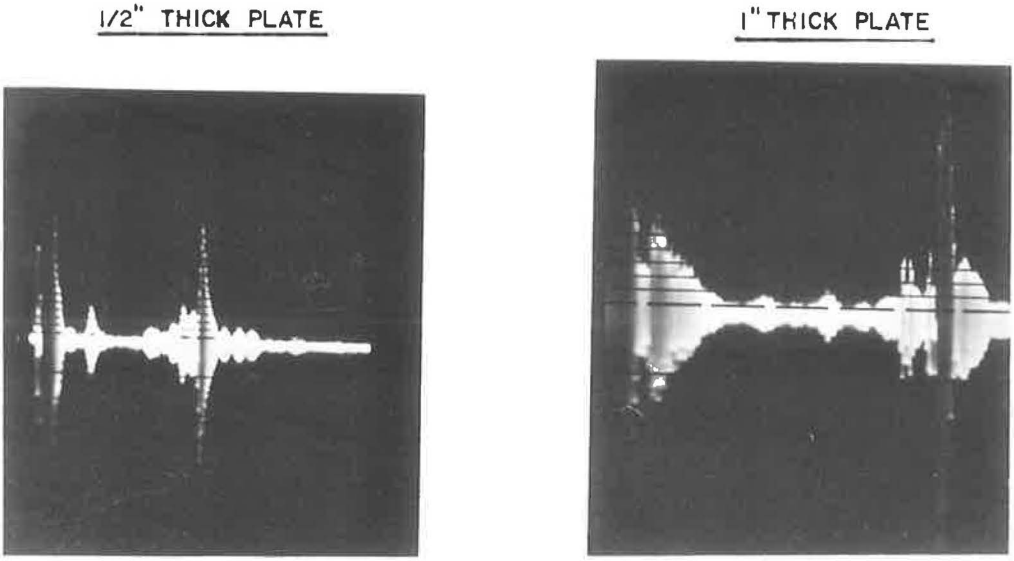
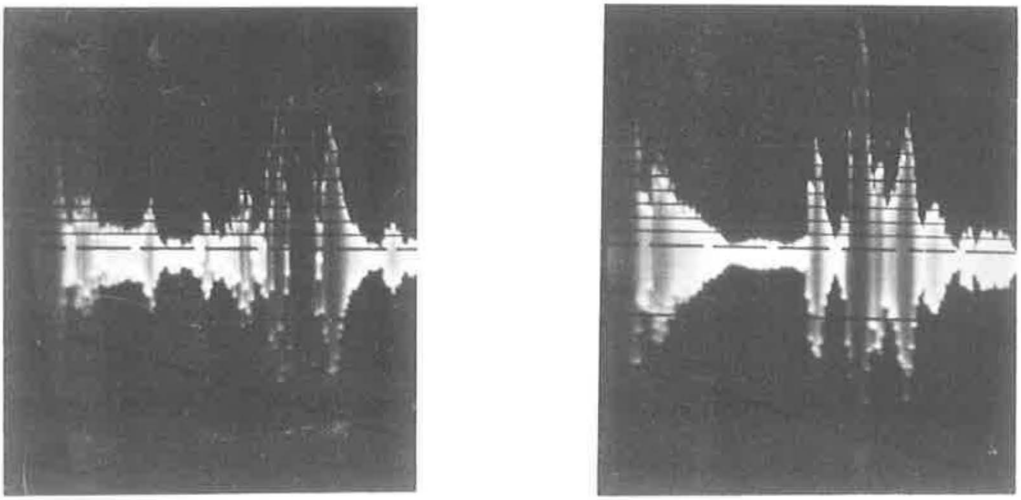


Figure 12. Reflectograms showing ultrasonic indications corresponding to various weld conditions.



278597-R 278518-T1

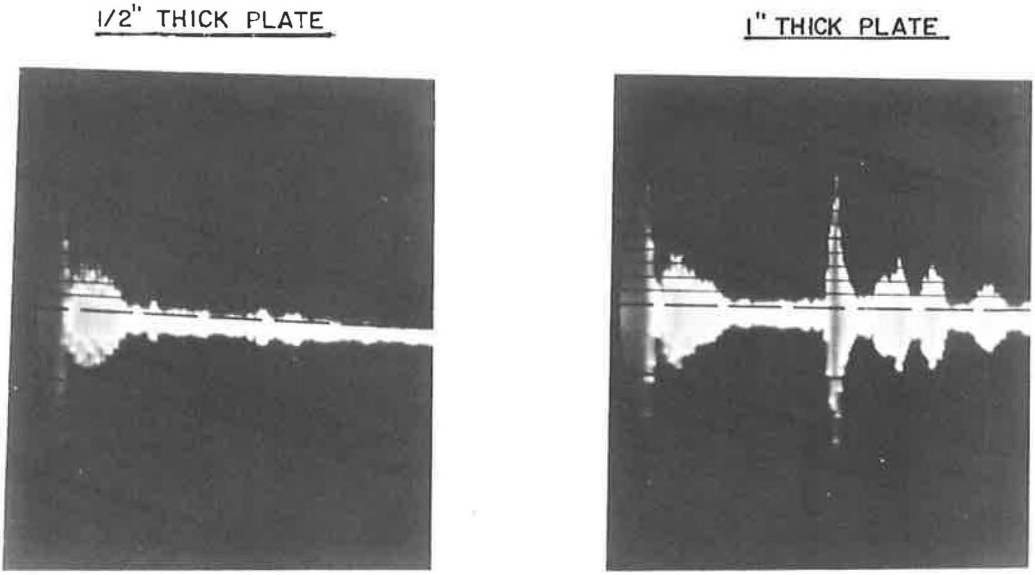
lack of side fusion



278488-T2 278504-T1

incomplete root penetration

Figure 13. Reflectograms showing ultrasonic indications corresponding to various weld conditions.



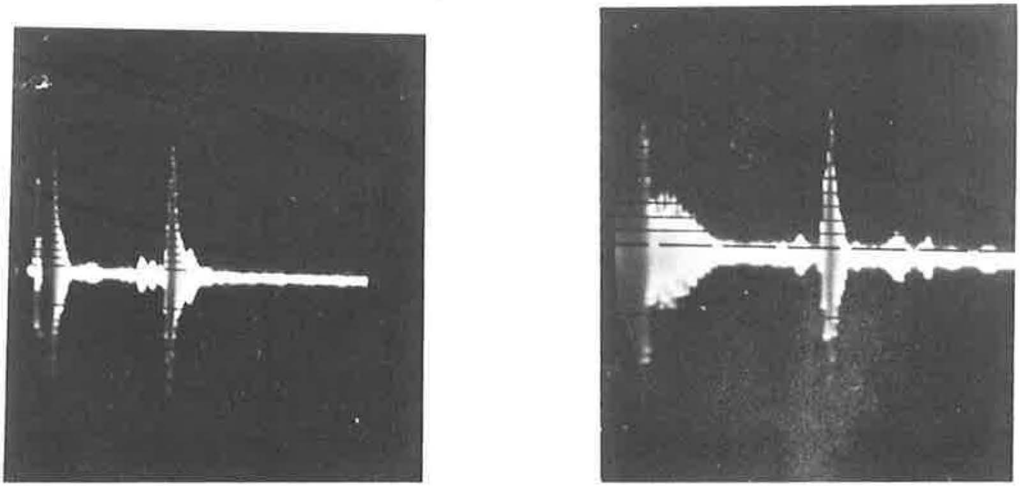
1/2" THICK PLATE

1" THICK PLATE

278496-T1

278509-T2

scattered porosity

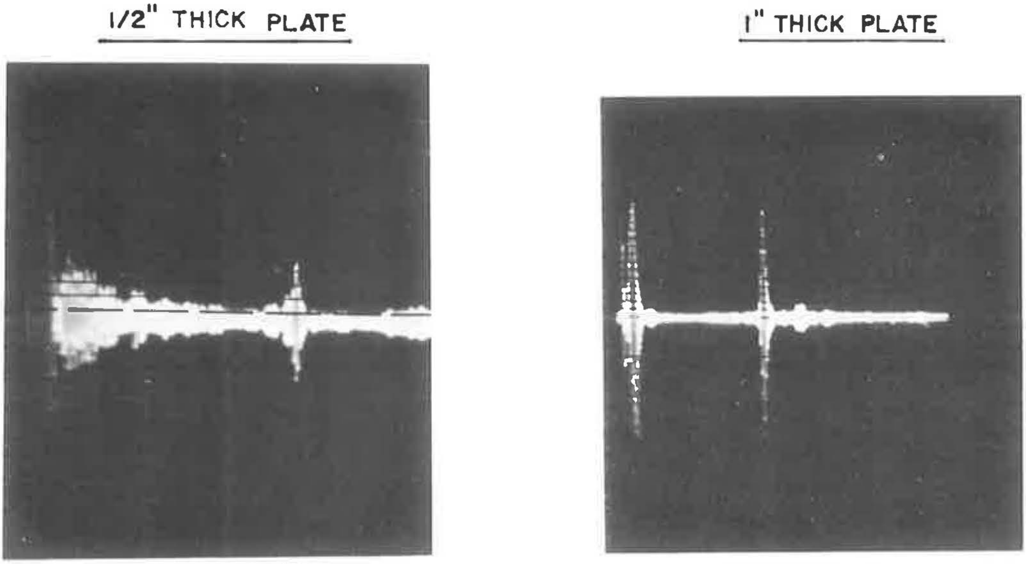


278598-T1

278549-T2

oxide inclusions

Figure 14. Reflectograms showing ultrasonic indications corresponding to various weld conditions.



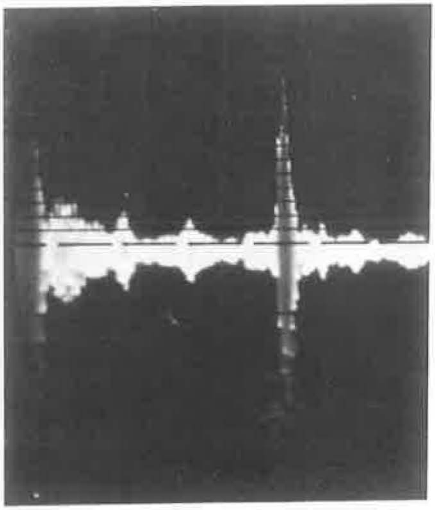
1/2" THICK PLATE

1" THICK PLATE

278492-T1

278501-R

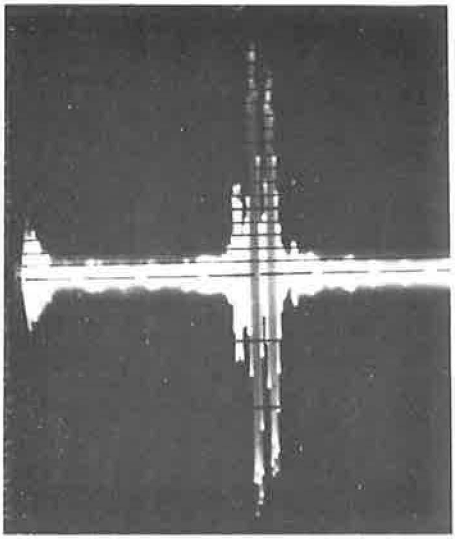
linear porosity



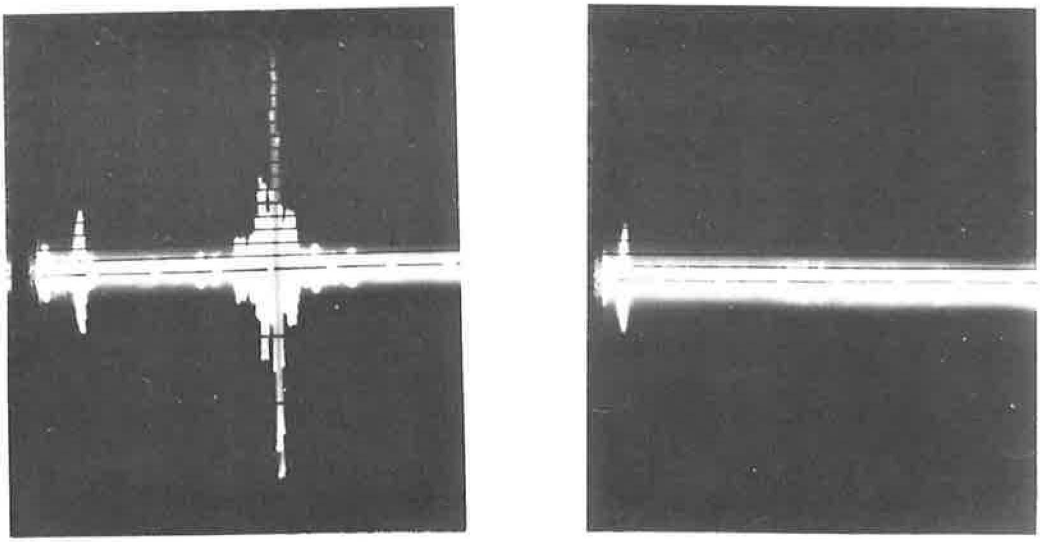
278486-T2

tungsten inclusions

Figure 15. Reflectograms showing ultrasonic indications corresponding to various weld conditions.



A- indication from incomplete penetration S-285221



B- indication from incomplete penetration S-285187

C- screen presentation from complete penetration S-285185

Figure 16. Reflectograms showing ultrasonic indications from varying degrees of penetration.

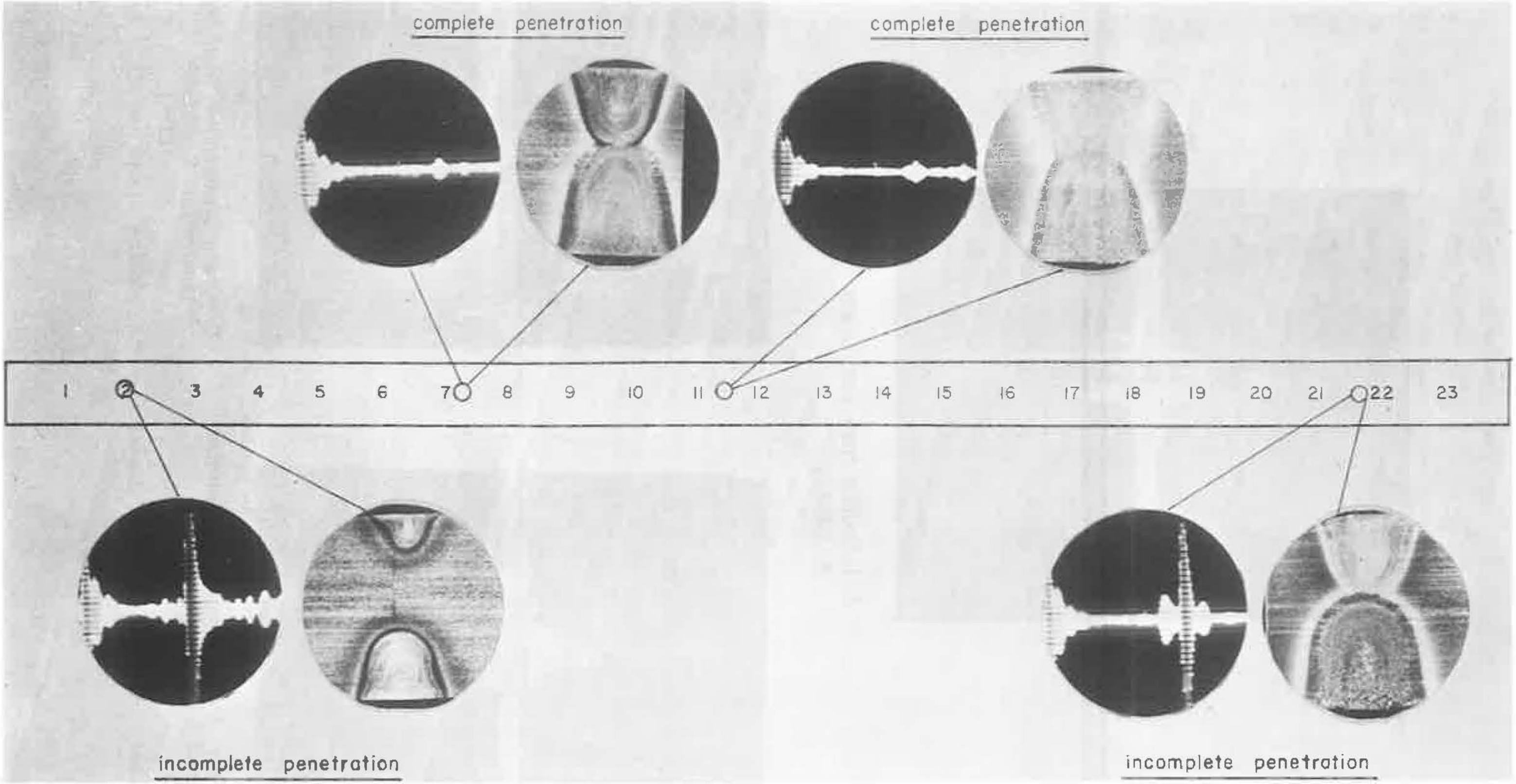


Figure 17. Reflectograms and macrographs from corresponding locations in weldment numbered 290966.

TABLE 6

ULTRASONIC INDICATIONS FROM VARIOUS DEGREES OF PENETRATION IN SQUARE BUTT WELDS.

S No.	Penetration Sought	Measured Bead Separation or Interpenetration	Ultrasonic Indication Height
285185	Complete with some interpenetration	Int. Approx. 3/32"	0.3" p-p†
285187	Incomplete with a small root separation	Sep. Approx. 1/16"	2.4" p-p
285221	Incomplete with substantial root separation	Sep. Approx. 1/8"	3.2" p-p
285321	Complete with roots interpenetrating about 1/8"	Int. 5/32"*	0.2"p-p†
285322	Barely complete with roots just touching	Sep. 0.046"*	0.7" p-p
285323	Incomplete with root separation of about 1/64"	Int. 1/32"*	0.4" p-p
285324	Incomplete with root separation of about 3/64"	Sep. 0.066"*	1.0" p-p
285326	Incomplete with root separation of about 1/16"	Sep. 0.060"*	2.2" p-p

* *Average of two measurements on metallographic sections: other values are for one section.*

† *Normal hash level; no isolated indications.*

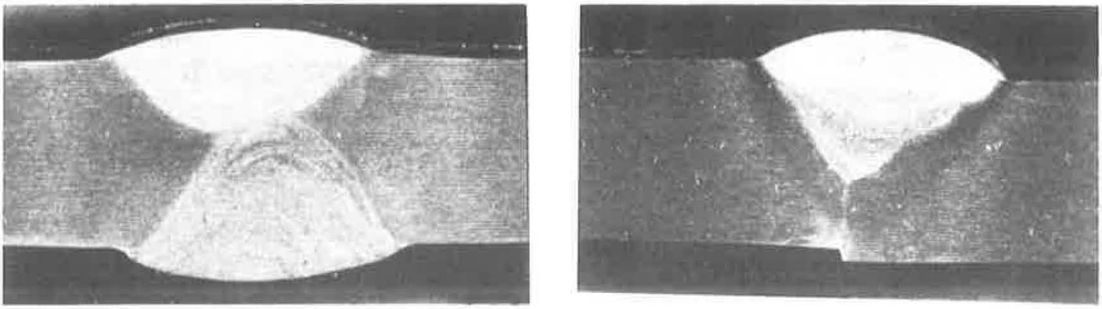
test and with the special immersion test using 5- or 10-mc lithium sulfate search units in a lucite holder. The results of the conventional tests were shown graphically in Figure 6, which also shows the results of the radiographic examinations previously described. Figure 17 shows reflectograms and corresponding macrosections representing several locations along one of these welds (S290966). In one instance, incomplete penetration that escaped detection in the ordinary ultrasonic test was detected in the special test using higher frequencies.

METALLOGRAPHIC EXAMINATIONS

Following the ultrasonic examination of the original 18- × 24-in. panels, transverse sections through the welds were removed for metallographic examination. In the majority of the welds, this examination was limited to a macroscopic study at low magnification but in some instances, it was necessary to make examinations at higher magnification to check on specific conditions.

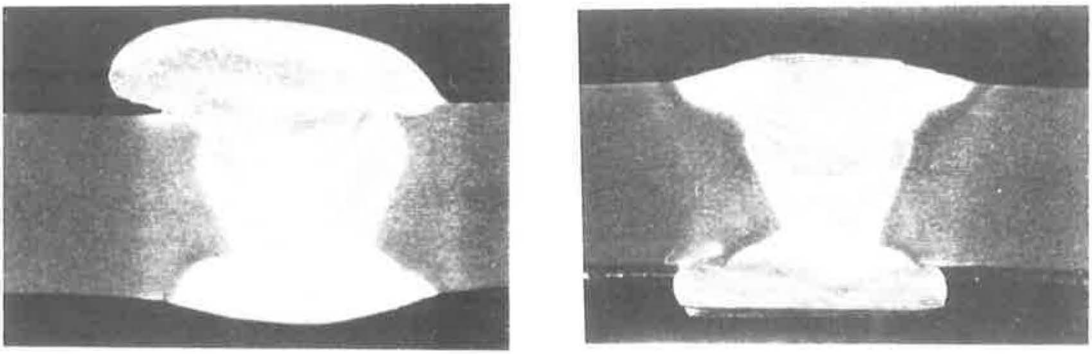
Closely related to the metallographic studies was examination of the fractures in the specimens subjected to the tensile and bend tests. These examinations were made to obtain further information on weld structure and soundness.

The macroscopic examinations and fracture studies helped to confirm the weld conditions sought, most of which had previously been identified by radiographic examination. Metallographic examinations also showed the presence and extent of conditions such as microporosity, oxide inclusions and incomplete penetration. (In this paper



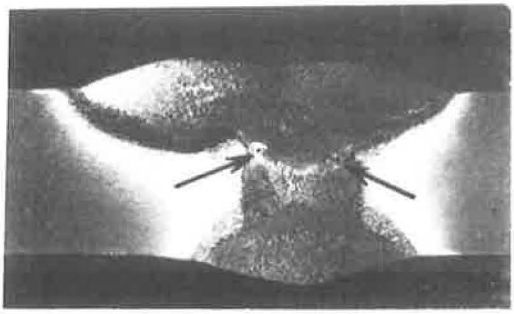
S278454 – RELATIVELY SOUND WELD (Etch 10% NaOH)

S278488 – INCOMPLETE ROOT PENETRATION (Etch 10% NaOH)



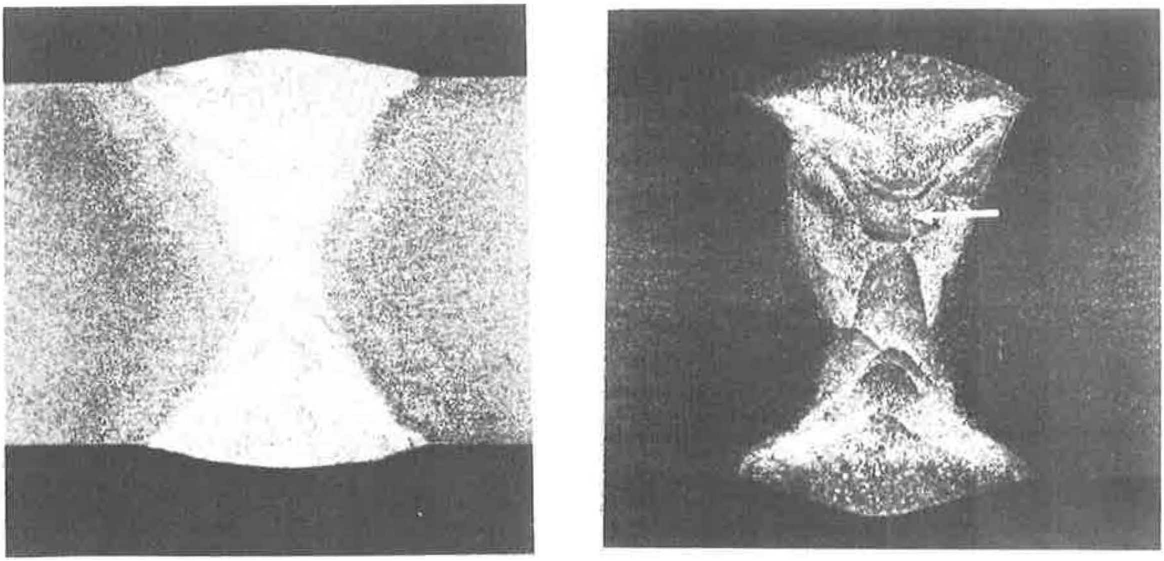
S278519 – WELD BEAD OVERLAP (Etch 10% NaOH)

S278502 – UNDERBEAD FOLD (Etch 10% NaOH)



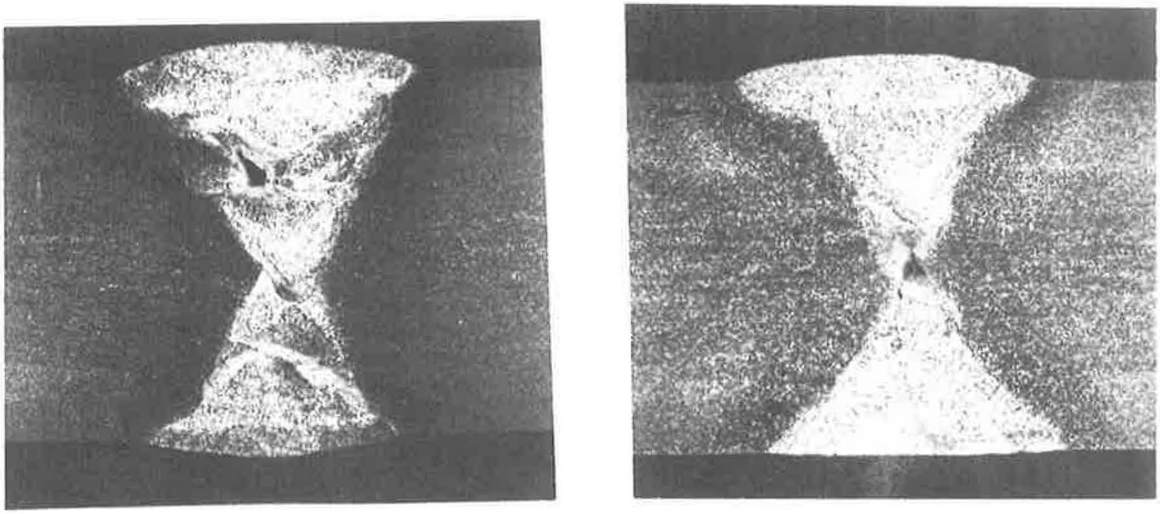
S278597 – LACK OF SIDE FUSION (Etch Keller's)

Figure 18. Macrographs of sections through butt welds in $\frac{1}{2}$-in. 2219-T87 plate (mag. 2X).



278515 – RELATIVELY SOUND WELD

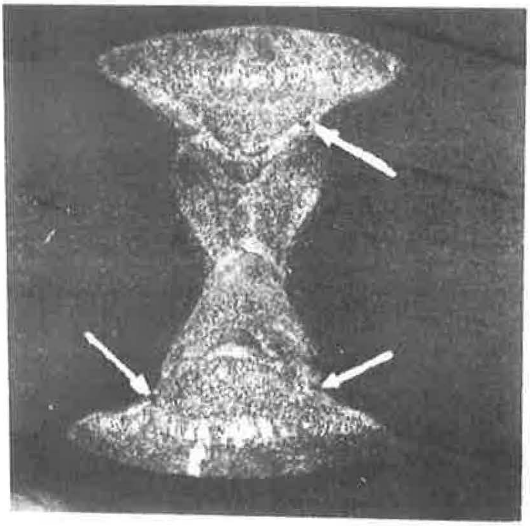
S278495 – INTERNAL LONGITUDINAL CRACK



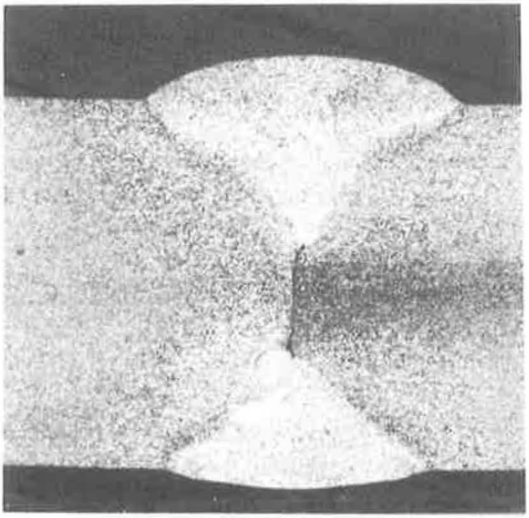
S278516 – LACK OF INTERPASS FUSION

S278511 – LACK OF ROOT FUSION

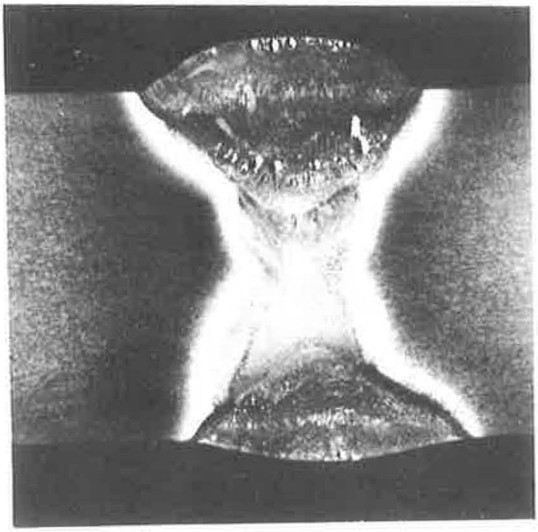
Figure 19. Macrographs of sections through butt welds in 1-in. 2219-T87 plate (mag. 2X, etch 10% NaOH).



S278518 – LACK OF SIDE FUSION (Etch 10% NaOH)

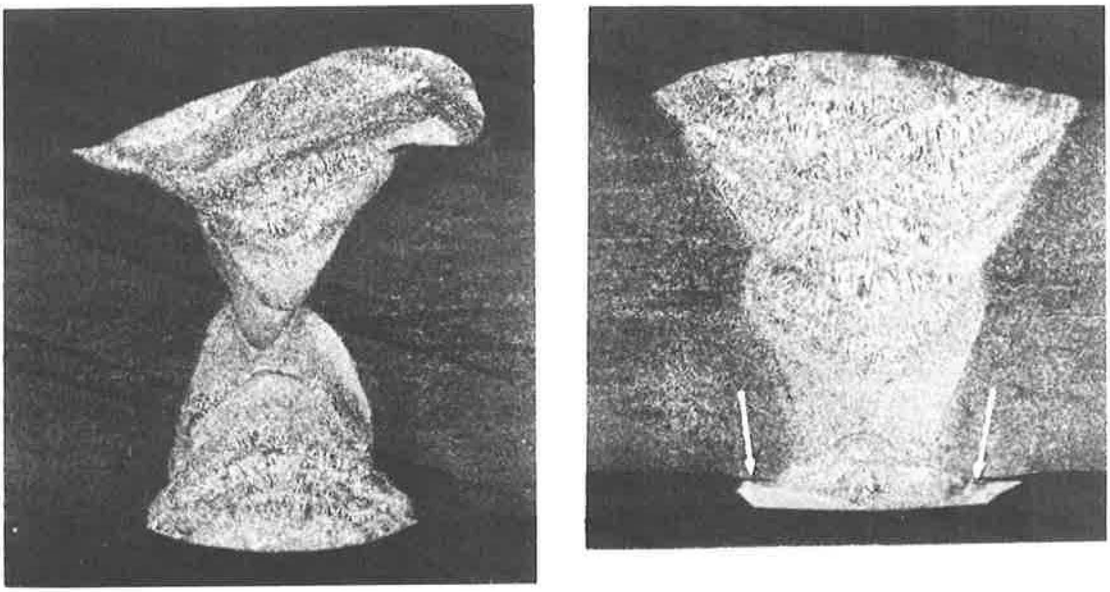


S278504 – INCOMPLETE ROOT PENETRATION (Etch 10% NaOH)



S278596 – SCATTERED POROSITY (Etch Keller's)

Figure 20. Macrographs of sections through butt welds in 1-in. 2219-T87 plate (mag. 2X).



S278512 - WELD BEAD OVERLAP

S278505 - UNDERBEAD FOLD

Figure 21. Macrographs of sections through butt welds in 1-in. 2219-T87 plate (mag. 2X, etch 10% NaOH).

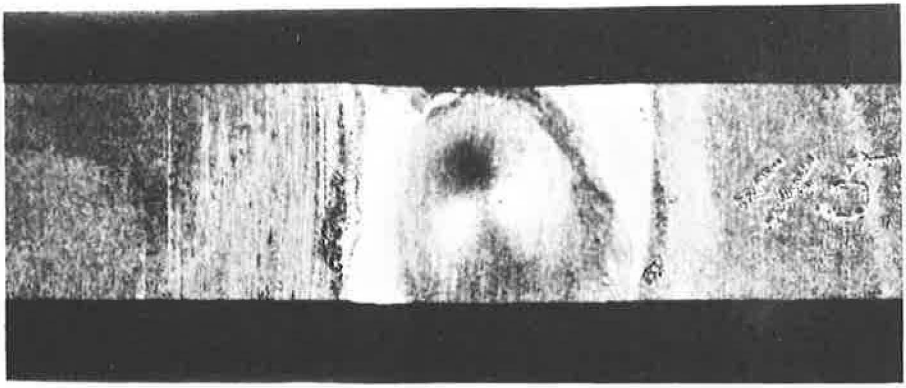


Figure 22. Crater on root pass of TIG butt weld in 2219-T87 plate (S-278457, mag. 2X).

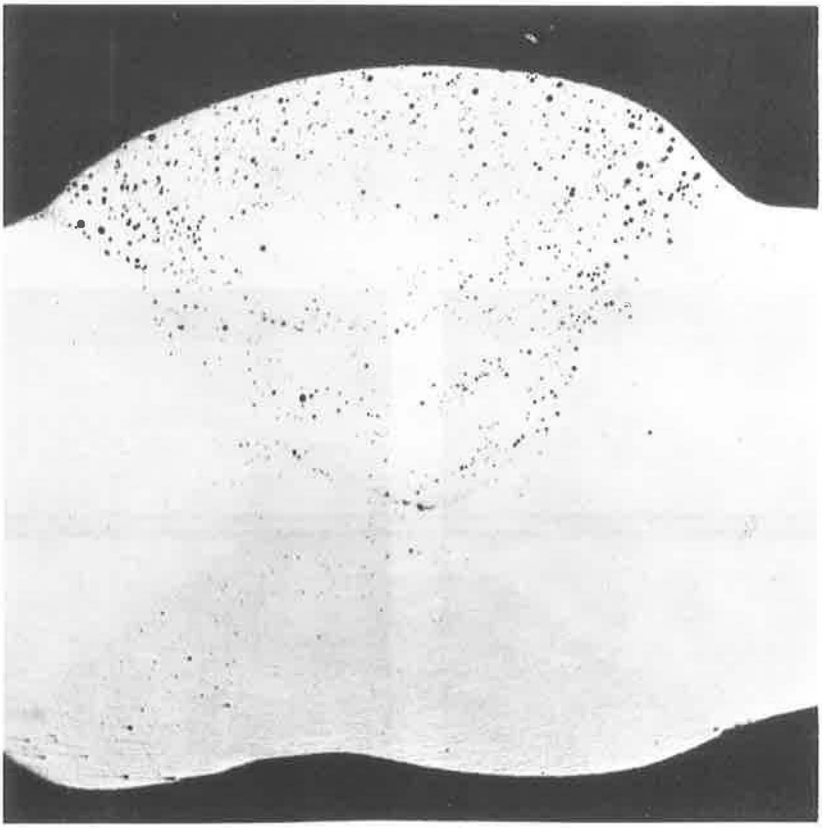


Figure 23. Macrograph of section through weld and crater (max. 5X, as-polished).

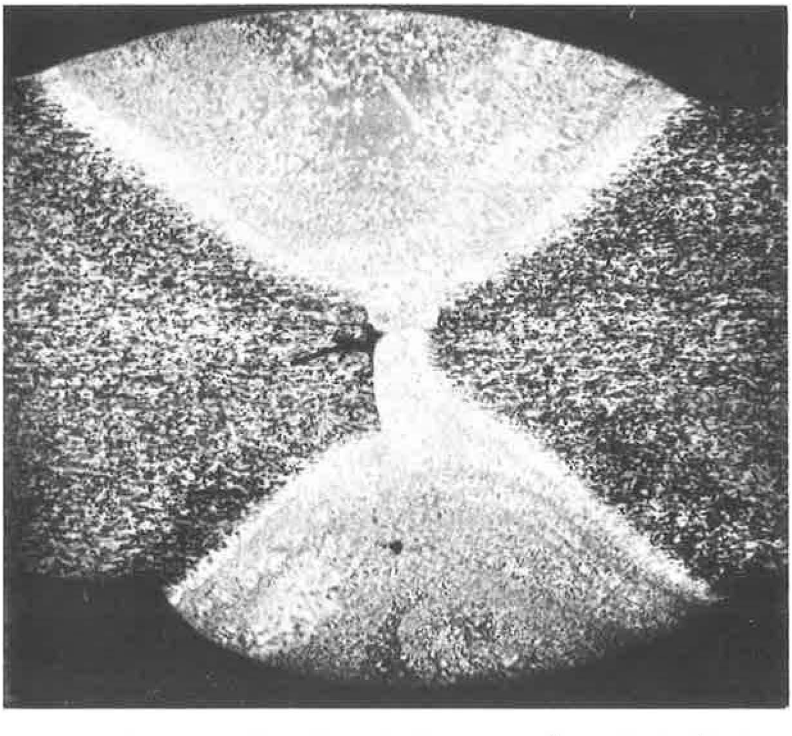


Figure 24. Macrograph of section through TIG weld in $\frac{1}{2}$-in. 2219-T87 plate; arrow indicates lack of root fusion (S-278459, mag. 5X, etch Keller's).

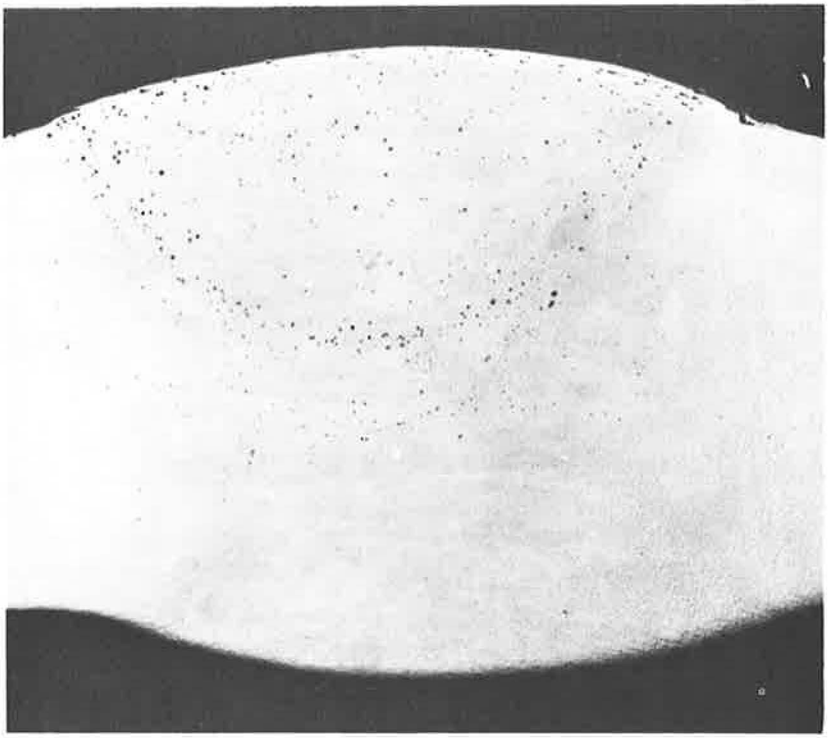


Figure 25. Macrograph showing microporosity in an otherwise sound TIG weld in $\frac{1}{2}$-in. 2219-T87 plate (S-278454, mag. 5X, as-polished).

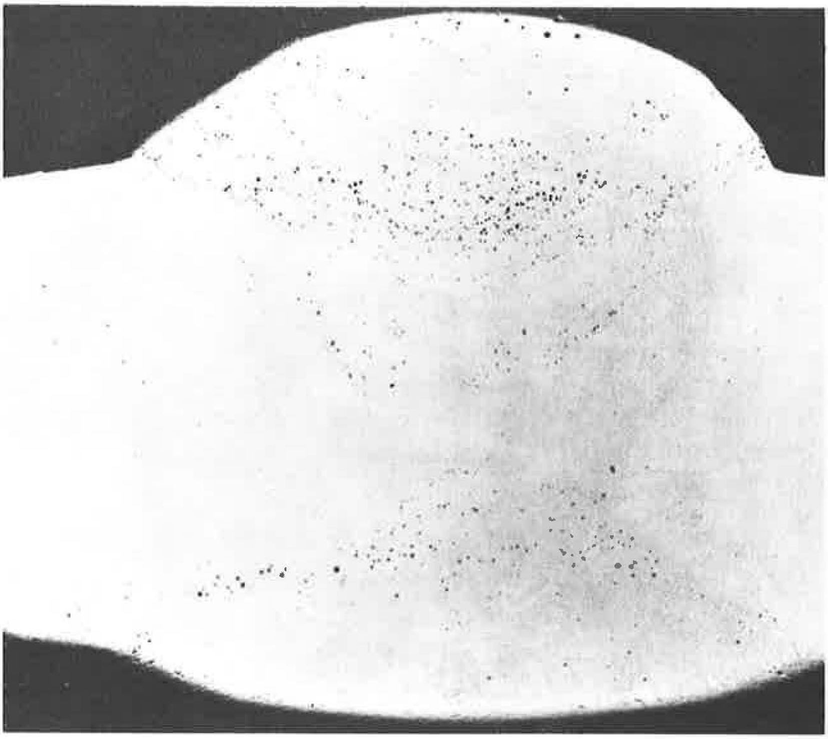


Figure 26. Macrograph showing microporosity in a MIG weld in $\frac{1}{2}$-in. 2219-T87 plate (S-278490, mag. 5X, as-polished).

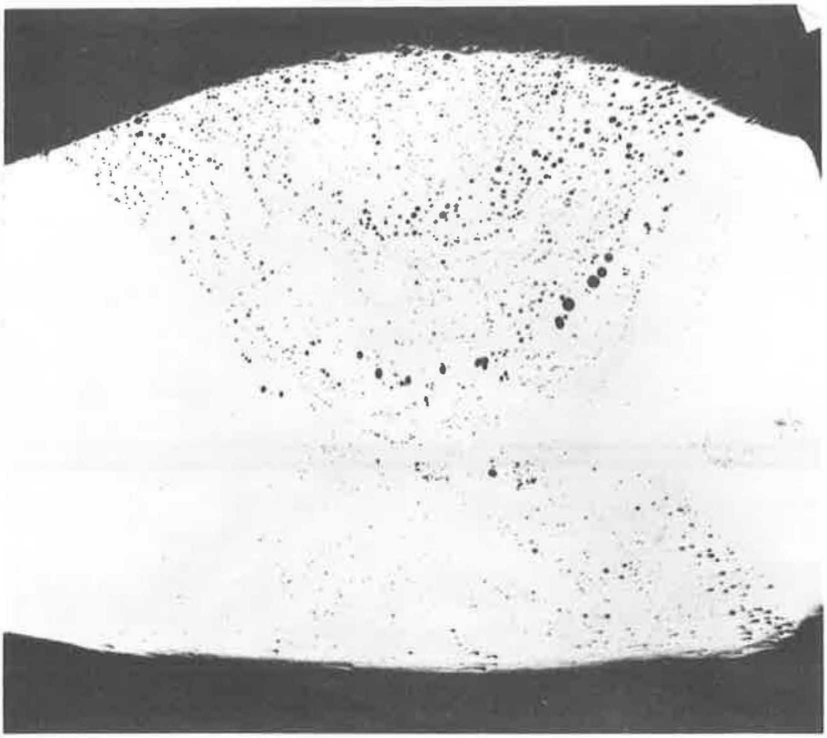
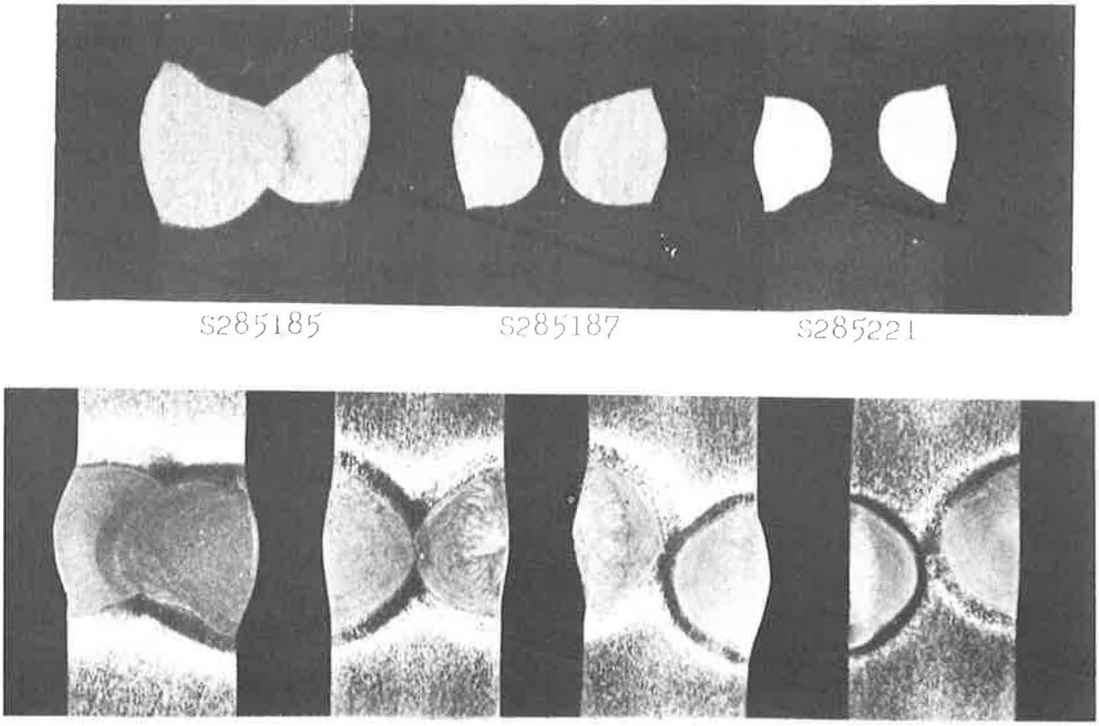


Figure 27. Macrograph showing porosity in a TIG weld in ½-in. 2219-T87 plate (S-278462, mag. 5X, as-polished).

Figure 28. Micrographs showing oxide inclusions in MIG weld in ½-in. 2219-T87 plate (S-278598, mag. 500X, etch Keller's).



S285185 S285187 S285221

S285321-M1 S285323-M1 S285322-M1 S285324-M1

Figure 29. Macrographs of sections through square butt TIG welds in 2219-T87 plate showing various degrees of penetration (mag. 2X, etch: top row 10% NaOH, bottom row Keller's).

microporosity is arbitrarily defined as porosity in which the voids have diameters less than about 0.01 in. which is approximately the smallest void discernible to the unaided eye.) Various weld conditions are shown in the macrosections included in Figures 18, 19, 20 and 21.

Figure 22 is a 2× photograph of a crater on the root pass of a TIG butt weld in ½-in. plate. A macrosection through the weld and crater appears in Figure 23. Fine porosity is rather generally distributed through the weld bead on the face side but the root side bead is comparatively sound. A more detailed metallographic examination of the section failed to reveal any significant effect of the crater on the structure of the surrounding weld metal.

Figure 24 shows a macrograph of a section through a TIG weld in ½-in. plate. An arrow indicates lack of root fusion. Figures 25 and 26 illustrate microporosity in otherwise sound welds in ½-in. plate. Figure 27 shows rather generally distributed porosity in a TIG weld in ½-in. plate. The larger pores are in the macro range and the finer ones in the micro range. Figure 28 shows oxide inclusions in a MIG weld in ½-in. plate. The weld was made with a reduced flow of shielding gas to favor oxide formation. The macrographs in Figure 29 illustrate various degrees of penetration in the square butt welds previously referred to.

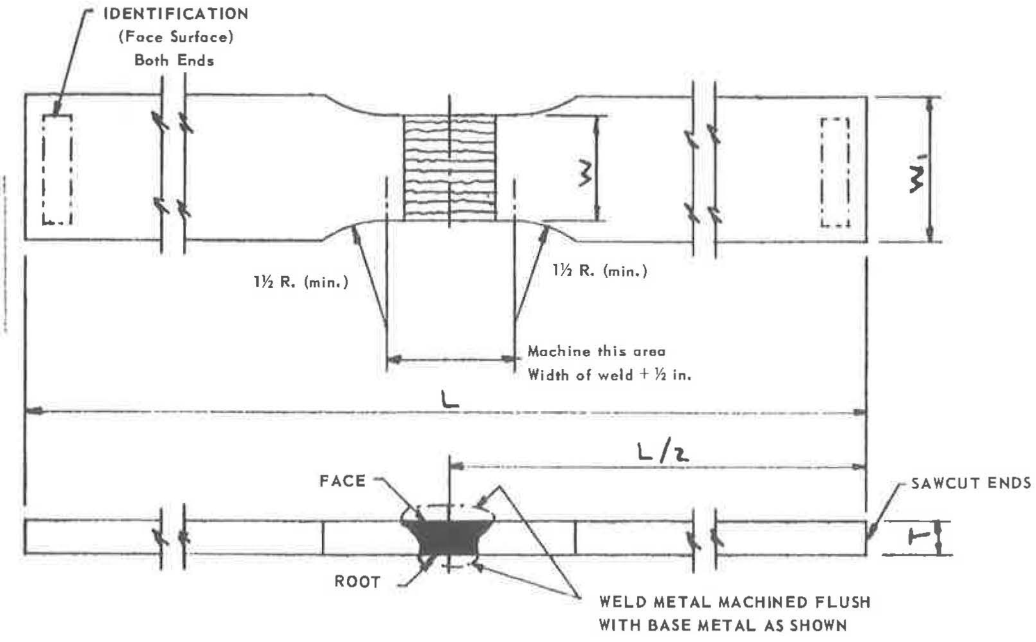
Metallographic measurements of the extent of interpenetration or separation of the weld bead roots in the square butt welds were summarized in Table 6, previously referred to in conjunction with the ultrasonic tests.

DISCUSSION OF NONDESTRUCTIVE TESTS

As previously pointed out (see Table 5) a substantial fraction of the weld discontinuities can be detected both radiographically and ultrasonically. Radiographic examination provides more information on the exact nature of the weld conditions but the ultrasonic procedure would be faster for large-scale commercial inspection and more amenable to automation.

One shortcoming of the ultrasonic method that probably can be overcome is associated with extraneous indications originating from the crowns on the welds. In some instances it is necessary to scarf the weld to determine whether an ultrasonic indication is associated with an actual defect. A few preliminary tests with the variable-angle liquid-filled search unit suggested that a search unit angulating technique could be developed for minimizing the extraneous indications originating from the weld bead. Extraneous ultrasonic indications were also consistently reduced by merely smoothing the weld crowns before testing.

Substantial incomplete penetration in the square butt welds (root separations in excess of about $^1/_{16}$ in.) could be detected by both the radiographic and the ultrasonic procedures. However, the ultrasonic procedure was much more effective for detecting this condition when the weld bead roots were separated by the smaller distances associated with only slight amounts of incomplete penetration.



SPECIMEN DIMENSIONS

NOTE: Specimen thickness greater than decimal dimension (last No. 1st Col.) shall be machined in accordance with the dimension shown for the next higher specimen thickness range.

NOTE: For specimen layout allow 3/16 in. for sawcut and finish of edges.

Nominal Thickness, in. (T)	Total Width, in. (Wi)	Width at Weld, in. (W)	Minimum Length, in. (L)
1/4 to 0.356	2	1½	18
3/8 to 0.475	2	1½	20
1/2 to 0.720	2	1½	22
3/4 to 0.963	2	1½	24
1" to 1.455	1½	1"	28
Greater than 1-1/2	1½	1"	30

Figure 30. Reduced-section tensile specimen.

TABLE 7

TENSILE STRENGTHS OF ARC WELDED 2219-T87 PLATE WITH SINGLE-V AND DOUBLE-V BUTT JOINTS*

S No.	APDL No.	Type of Weld	Plate Thickness	Nominal Weld Condition	Tensile Test Spec. No.	Tensile Test T.S.+ psi
278454	1	TIG	1/2"	Relatively sound but some microporosity	T1	36200(a)
					T2	39000(a)
					Av.	37600
278515	9B2	MIG	1"	Relatively sound but some microporosity	T1	41900(c)
					T2	41900(c)
					Av.	41900
278491	9A1	MIG	1/2"	Microporosity	T1	38400(a)
					T2	38600(a)
					Av.	38500
278490	9A2	MIG	1/2"	Microporosity	T1	38900(a)
					T2	39100(a)
					Av.	39000
278462	6A	TIG	1/2"	Microporosity with some scattered macroporosity	T1	32500(c)
					T2	35700(c)
					Av.	34100
278492	10A1	MIG	1/2"	Linear porosity	T1	34300(a)
					T2	34900(a)
					Av.	34600
278496	11A2	MIG	1/2"	Scattered porosity	T1	34800(c)
					T2	33600(c)
					Av.	34200
278509	11B2	MIG	1"	Light randomly scattered porosity	T1	29300(c)
					T2	29800(a)
					Av.	29550
278596	11B3	MIG	1"	Scattered porosity	T1	32800(a)
					T2	37700(a)
					Av.	35250
278598	12A5	MIG	1/2"	Oxide inclusions	T1	16500(a)
					T2	18000(a)
					Av.	17250
278549	A5	TIG	1"	Oxide film	T1	25200(c)
					T2	19600(c)
					Av.	22400
278486	53A	TIG	1/2"	Tungsten inclusions	T1	34700(b)
					T2	29600(a)
					Av.	32150

(Continued)

TABLE 7 (Continued)

TENSILE STRENGTHS OF ARC WELDED 2219-T87 PLATE WITH SINGLE-V AND DOUBLE-V BUTT JOINTS*

					Tensile Test	
S No.	APDL No.	Type of Weld	Plate Thickness	Nominal Weld Condition	Spec. No.	T.S.+ psi
278493	5A1	MIG	1/2"	Lack of interpass fusion	T1	32300(a)
					T2	31800(a)
					Av.	32050
278516	5B1	MIG	1"	Lack of interpass fusion	T1	33300(a)
					T2	32500(a)
					Av.	32900
278459	26B	TIG	1/2"	Lack of root fusion	T1	16500(a)
					T2	17900(a)
					Av.	17200
278511	6B2	MIG	1"	Lack of root fusion	T1	27300(a)
					T2	27300(b)
					Av.	27300
278597	7A4	MIG	1/2"	Lack of side fusion	T1	27700(a)
					T2	27200(a)
					Av.	27450
278518	7B1	MIG	1"	Lack of side fusion	T1	33100(b)
					T2	32700(a)
					Av.	32900
278488	8A1	MIG	1/2"	Incomplete root penetration	T1	9800(a)
					T2	10100(a)
					Av.	9950
278504	8B2	MIG	1"	Incomplete root penetration	T1	21500(a)
					T2	21100(a)
					Av.	21300
278522	2A1	MIG	1/2"	Craters (face pass) (Specs. T1 and T2 include craters; T3 and T4 do not)	T1	33700(a)
					T2	30300(a)
					Av.	32000
					T3	37700(a)
					T4	38500(a)
					Av.	38100
278514	2B2	MIG	1"	Craters (face pass) (Specs. T1 and T2 include craters; T3 and T4 do not)	T1	32500(a)
					T2	34500(a)
					Av.	33500
					T3	40000(c)
					T4	42500(b)
					Av.	41250
278461	46	TIG	1/2"	Craters (root pass) (Specs. T1 and T2 include craters; T3 and T4 do not)	T1	24700(c)
					T2	24800(c)
					Av.	24750
					T3	34100(c)
					T4	32800(c)
					Av.	33450

(continued)

TABLE 7 (Continued)

TENSILE STRENGTHS OF ARC WELDED 2219-T87 PLATE WITH SINGLE-V AND DOUBLE-V BUTT JOINTS*

S No.	APDL No.	Type of Weld	Plate Thickness	Nominal Weld Condition	Tensile Test Spec. No.	 T.S.+ psi	
278548	A4	TIG	1"	Reasonably sound--(Specs. T1 and T3 tested in as-welded condition; T2 and T4 reheat-treated and aged to -T62 temper before testing.)	T1	29900(a)	(As welded)
					T3	25500(a)	(As welded)
					Av.	27700	(As welded)
					T2	46400(a)	(Reheat treated)
					T4	47100(a)	(Reheat treated)
					Av.	46750	(Reheat treated)

*Reduced-section specimens used for all tensile tests. Single-V butt joints used for all 1/2" plates and double-V butt joints for all 1" plates. All specimens tested in as welded condition.

+Letters in parentheses after tensile values indicate path of fracture: (a) through weld, (b) at edge of weld and (c) partly through and partly at edge of weld.

TENSILE TESTS

In order to determine the effect of various weld conditions on joint strength and ductility, reduced-section tensile tests and face and root guided bend tests were made on specimens representing all but a few of the weld conditions included in the investigation. These tests were omitted in the case of a few welds containing the synthetic defects previously mentioned. Because the significance of the bend tests was questionable, their results also have been omitted.

With one exception, the joints were tested without reheat treatment although it was recognized that joint properties could be influenced by the heat of welding as well as by the weld condition. To obtain some indication of this heat effect, four reduced section

TABLE 8

EFFECT OF DEGREE OF PENETRATION ON TENSILE STRENGTH OF SQUARE BUTT WELDED SPECIMENS OF 2219-T87 PLATE*

S No.	Penetration	Tensile† Strength psi
285185	Complete. Roots of two weld beads interpenetrate one another to depth of about 1/8".	42,600
285187	Moderately incomplete. About 1/16" separation between roots of two weld beads.	30,000
285221	Markedly incomplete. About 1/8" separation between roots of two weld beads.	26,400

*Welds made in 1/2" plate by TIG-DCSP procedure using 2319 filler wire and one pass on each side of joint. Test specimens conform with Section IX of ASME Boiler and Pressure Vessel Code, 1962 Edition. Values are averages for two tests.

† Reduced-section specimens.

tensile specimens were machined from a 1-in. TIG welded plate of 2219-T87 alloy. Two of these specimens were reheat treated and aged to the -T62 temper (heat-treated 1½ hr at 1,000° F, quenched in cold water and aged 36 hours at 375° F) before testing while the remaining two were tested in the as-welded condition. It was not feasible to restore the original -T87 temper as this requires a strain-hardening step between solution heat treatment and aging.

In the case of several panels containing weld craters, some of the tensile blanks were cut to include craters, and others were cut from portions of the same welds that were free from craters. The type of reduced-section specimen employed for the tensile tests is shown in Figure 30.

The results of the tensile tests on specimens from the panels with single-V and double-V joints are given in Table 7. With two exceptions (S278548-T2 and -T4) these specimens were tested in the as-welded condition.

It appears unlikely that microporosity has had any significant adverse effect on weld strength although a completely sound weld was not available for comparison. However, in certain instances the coarser forms of porosity appeared to affect the strength of the weld adversely. Weld strength also appears to have been adversely affected by oxide inclusions and film, tungsten inclusions (particularly in the case of specimen S278486-T2), lack of interpass, root and side fusion, and incomplete root penetration.

Craters appeared to exhibit an adverse effect on tensile strength in spite of the fact that the actual crater cavities were removed in machining the specimens. The average reduced section tensile strengths for specimens with and without craters from 2 welded panels are as follows:

Panel S No.	Tensile Strength, psi	
	With Craters	Without Craters
278461	24750	33450
278514	14250	33500
278522	32000	38100

The data for the last group (S278548) of specimens listed in Table 7 give a rough indication of the extent to which joint strengths have been influenced by the heat of welding. The average tensile strength of 27,700 psi for the as-welded specimens was increased to 46,750 psi by reheat treatment and aging to the -T62 temper.

Table 8 gives reduced section tensile test data for some of the TIG welded square butt joints in ½-in. plate. It is evident that even moderately incomplete penetration with a root separation of about 1/16-in. has had a marked effect in reducing the tensile properties of this type of joint.

EXAMINATION OF FRACTURES

Examination of the fractures in the tensile specimens helped to confirm the following weld conditions: incomplete root penetration; lack of root, interpass and side fusion; linear and scattered porosity and oxide inclusions and film. Photographs of tensile fractures associated with these conditions are shown in Figures 31 and 32. The fractures shown in Figure 31 are from ½-in. panels and those in Figure 32 from 1-in. panels.

In fracture S278488 (incomplete root penetration) the sawed surface of the unpenetrated land is plainly evident. Fracture S278459 (lack of root fusion) shows the wavy lower edge of weld metal that has not fused into the plate. This metal has taken the imprint of saw marks on the groove. A fissure extends in from the left side for about half of the specimen width.

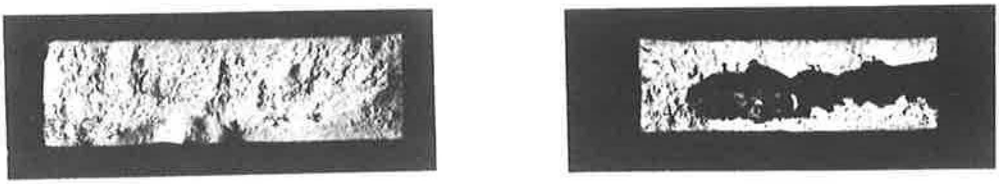
The lack of interpass fusion in S278493 appears as a dark line or shallow fissure extending almost completely across the fracture about ⅛ in. below the top surface.

S278488
INCOMPLETE ROOT PENETRATION

S278459
LACK OF ROOT FUSION

S278493
LACK OF INTERPASS FUSION

S278597
LACK OF SIDE FUSION



S278492
LINEAR POROSITY

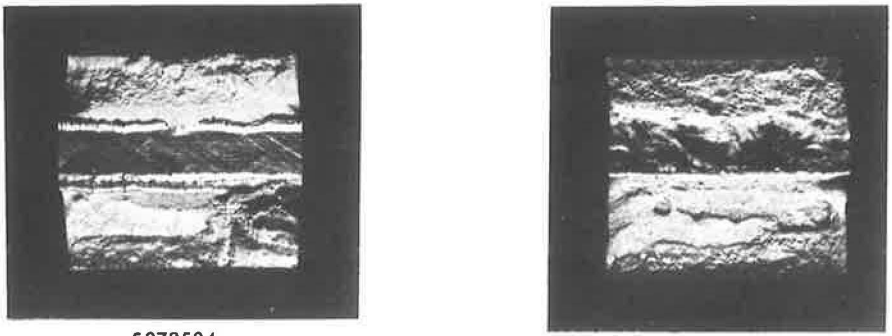
S278598
OXIDE

Figure 31. Tensile fractures in specimens from welded $\frac{1}{2}$-in. 2219-T87 plates (natural size or slightly enlarged).

Lack of side fusion in S278597 appears as a shallow tapering cavity extending from the left edge about two-thirds across the fracture. There are two isolated cavities near the right side. A few small cavities associated with the linear porosity appear in the lower part of fracture S278492. The dark surface that covers over one-third of the fracture in S278598 had a carbon-like appearance which is probably associated with finely dispersed oxide.

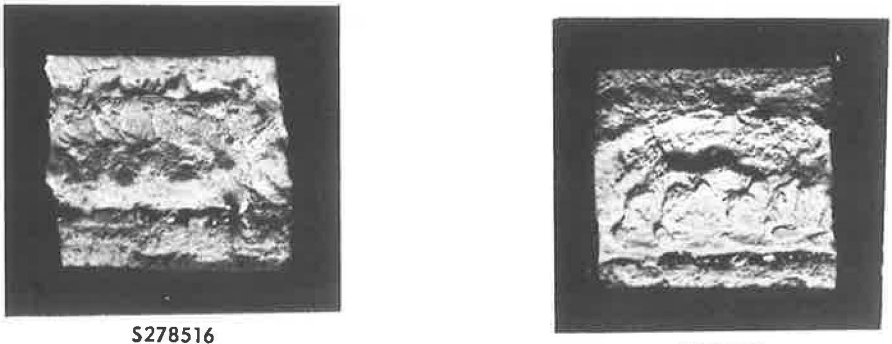
The first fracture in Figure 32 is associated with incomplete root penetration. The surface of the unpenetrated land in S278504 forms a conspicuous band about $\frac{1}{4}$-in. wide extending completely across the fracture. The dark areas just above the horizontal centerline in fracture S278511 are cavities associated with the lack of root fusion that this specimen exemplifies.

In the fracture of S278516 (lack of interpass fusion) a narrow band that is generally dark but which contains some small white spots extends horizontally across the fracture about $\frac{5}{16}$-in. above the lower edge. This band represents an unsound region associated with the lack of interpass fusion. Fracture S278518 (lack of side fusion) exhibits a narrow band that is generally dark but which contains small light spots and patches. This band extends across the greater part of the fracture about $\frac{3}{16}$ in. above the lower edge. It represents an unsound portion of the joint associated with the lack of side fusion. The scattered porosity in fracture S278596 is conspicuously evident in a zone about $\frac{3}{16}$-in. extending horizontally across the fracture a short distance below the top edge.



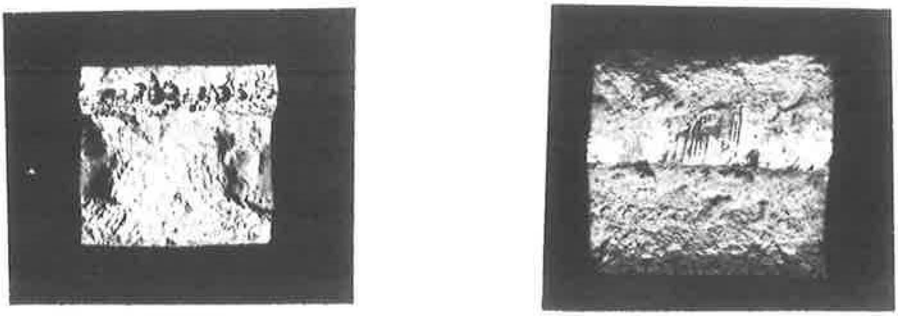
S278504
INCOMPLETE
ROOT PENETRATION

S278511
LACK OF ROOT FUSION



S278516
LACK OF
INTERPASS FUSION

S278518
LACK OF SIDE FUSION



S278596
SCATTERED POROSITY

S278549
OXIDE FILM

Figure 32. Tensile fractures in specimens from welded 1-in. 2219-T87 plates (natural size or slightly enlarged).

The white areas just above the horizontal centerline in fracture S278549 (oxide film) represent portions of the fracture where an oxide film is believed to have prevented bonding between the weld metal and the metal of the plate. The weld metal has actually taken the imprint of saw marks on the groove but did not fuse to it.

Fracture studies and a metallographic examination indicated that the lower strength of the specimens with craters might be related to a concentric ring pattern of coarse and fine grains apparent in the fracture and thought to be connected with the crater formation, but further work would be necessary to adequately explain the effect of the craters on weld strength.

CONCLUSION

Radiographic examinations and ultrasonic tests are valuable and effective procedures for determining the structural integrity of welds in aluminum alloy structures. The former procedure gives a more definitive picture of the actual weld condition. Nevertheless, it is probable that ultrasonic examination will gradually replace radiography for the inspection of long lengths of weld because this method is faster and more readily automated.

Certain of the discontinuities deliberately introduced into the welds for this investigation significantly impaired strength. It is important to note, however, that a number of the specimens were extreme examples of the conditions they represented. Welds containing limited amounts of certain of the discontinuities might be entirely suitable for many applications. In setting up rejection limits for radiographic or ultrasonic inspection of welds, consideration must be given to the requirements for the application in which the welds are to be used. Otherwise, the unwarranted rejection of usable assemblies may result in a substantial financial loss.

ACKNOWLEDGMENT

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Discussion

SIMON A. GREENBERG, Industrial Consultant, Flushing, N.Y.—This paper presents an interesting initial investigation of the defects which might be encountered in inert gas welding of aluminum. It also offers a first attempt at the evaluation of the feasibility of defect detection by nondestructive methods and an evaluation of the effects of such defects on structural integrity.

Being a beginning, the work reported in this paper does not cover any aspect it treats in depth. The greatest benefit to be derived from this paper will be from the prompting it gives to further work in exploring each of the subjects covered separately and in greater depth.

A separate study of the different techniques of radiography and ultrasonics as applied to aluminum welds would be most beneficial.

As the authors point out, their study of the effects of weld defects was done with welds containing unusually large amounts of defects. If a study were made to establish the margin of acceptance of each type of defect, it should lead to reasonable, valid specification acceptance standards. This would permit fullest use of aluminum, yet allow for screening out those welds which are structurally unsound.

Although the authors surely did not intend it, this paper would serve the structural field very well indeed if it prompted a study of the effects of weld defects in steel on their structural behavior.

Our present requirements are probably safe, but they are born of opinion and subjective experience. In some instances they are vague for lack of valid data on which to base more specific requirements.

A study of weld defects in steel might permit relaxation of some of the requirements and answer the clamor of many that this be done—which we cannot do at present for lack of data on which to base such relaxations. It might even be found that acceptance standards for some defects should be more stringent for some combinations of service conditions.

Most important, such studies, for whatever materials they are made, will permit more efficient use of the material and a closer approach to its full utilization in structural design and fabrication. Thus, we can closer approach the economic design of structures, something that is too often overlooked by our designers today.