Corrosion Performance of Aluminum Culvert

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This paper discusses corrosion characteristics of aluminum and how these characteristics might be affected by burial in soil. The influence of various types of soil on aluminum are discussed in the light of experience gained through monitored culvert installations including a compendium of field performance with aluminum culvert and an appraisal of the over-all performance of the product.

•MORE THAN 20,000 installations of aluminum culvert have been made since its introduction approximately four years ago. No problems involving corrosion have been encountered in any of the major Great Soil groups during this period. Since aluminum culvert became available, its resistance to attack by soils has been of interest to the culvert buyer. A thorough investigation of the corrosion performance of many representative installations has been made to record their condition.

An earlier report (1) detailed the structural characteristics and performance of aluminum culvert. This paper discusses the influence of soil characteristics on corrosion of aluminum, describes the test program initiated to evaluate corrosion performance, and reports the results of in-place inspections of culvert and laboratory evaluation of representative samples removed during inspection.

FUNDAMENTALS OF ALUMINUM CORROSION

Aluminum like many other metals is dependent on a surface film for corrosion resistance. Its superiority for many applications is based on the properties and characteristics of this film as compared with films on other metals. Aluminum oxide forms instantaneously on a bare aluminum surface when oxygen is present. This oxide film possesses a number of beneficial properties. It is tough; it does not flake or break away as the metal surface is distorted, formed, or subjected to temperature or humidity variations. It is inert to a range of chemical environments from strong acid to alkaline but generally within a pH range of 4 to 9. It is a good electrical insulating material. It immediately re-forms, if damaged mechanically or corroded, and the new film has properties similar to the one replaced. Should the film be disrupted as the result of corrosion, the corrosion products that collect at the point of attack tend to stifle further corrosion reaction by providing an effective barrier between the metal surface and the aggressive environment.

Corrosion of metals is an electrochemical mechanism. It can therefore be seen that the presence of a tough, uniform, renewable film that serves as an inert barrier between the metal and its environment and acts as an insulator in an ionic circuit would inhibit electrochemical reaction.

ALUMINUM'S RESISTANCE TO CORROSION

The corrosion resistance of aluminum has been reported for many applications. Most of these reports note that aluminum is not immune to some attack. They establish that attack does not proceed at a linear rate, but decreases within a short time to

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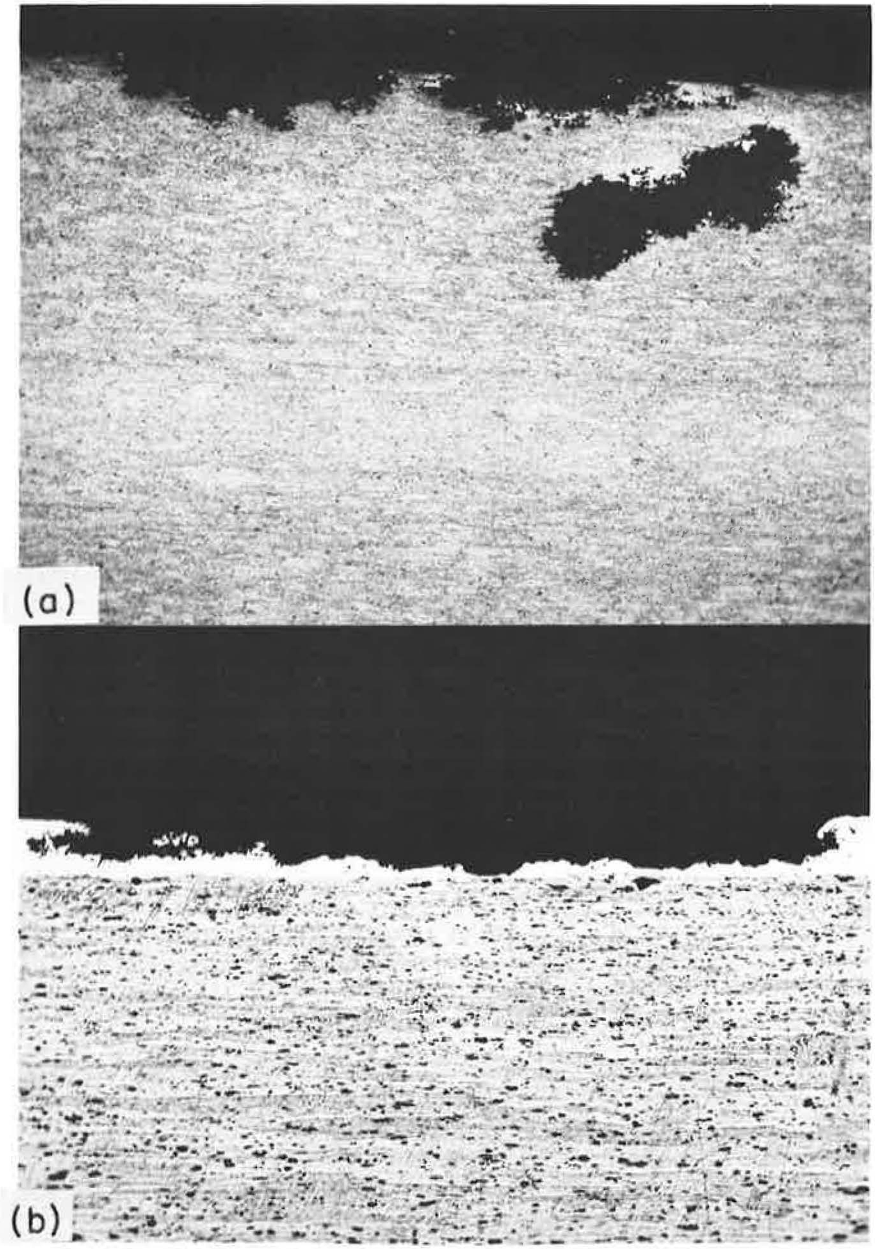

Figure 1. Type of attack on (a) bare and (b) clad aluminum surfaces, caustic fluoride etch, 100X.

TABLE 1

CORROSION PERFORMANCE OF UNPROTECTED ALUMINUM ALLOYS IN SEAWATER (3, 23)

Alloy and Temper	Maximum Pit Depth (mils)		Percent Change in Tensile Strength			
	0.5 Yr	8.0 Yr	0.5 Yr	1.0 Yr	2.0 Yr	8.0 Yr
3003-H14	9.0	7.0	- 3	- 2	- 4	- 1
Alclad 3004-H18	—	2.5[a]	—	—	—	0
5050-H34	11.0	12.0	- 2	- 1	- 5	- 3
5052-H34	12.5	10.5	- 2	- 2	- 3	- 2

[a] Depth of pitting confined to the cladding.

TABLE 2

TYPICAL VALUES[a]

Alloy	Potential (v)
1100	0.84
2024-T4	0.69
3003	0.83
3004	0.84
5052	0.86
5086	0.88
6061-T6	0.83
7072	0.96

[a] In aqueous solution containing 57 gm/liter NaCl and 3 gm/liter H_2O_2 at 25C, using a 0.1 N calomel reference electrode.

virtual arrestment. Excellent long-term evidence of this characteristic is the ASTM 20-yr data for aluminum alloys exposed in various industrial, marine, and rural environments (2). Similar performance has been observed in sea water tests as shown by the pit count data presented in Table 1 (3).

Improvement of Corrosion Resistance

Alloying. —Pure aluminum is of little interest to a structural engineer because of its low mechanical properties. Some elements that are added to improve these properties also improve the corrosion resistance of the metal. Examples of such elements are magnesium and manganese as used in alloy 3004, the core material for aluminum culvert sheet. Other elements such as copper greatly detract from the corrosion resistance of pure aluminum.

Cladding. —Further improvement of corrosion resistance can be gained by cladding each side of one aluminum alloy with another aluminum alloy that is more electronegative. In illustrating the purpose of cladding, it should be explained that attack of aluminum usually occurs at highly localized point sources. These points are believed to represent defects in the oxide film which are more vulnerable to penetration by aggressive ions. If attack occurs, these small areas become the anodes of corrosion cells which tend to penetrate into the metal rather than causing a general removal of metal over large areas; however, the penetrating attack is generally self arresting. By adding a more electronegative cladding to the surface of the alloy, galvanic protection of the alloy is provided. Then, should corrosion occur, the attack will spread laterally over the clad layer rather than into the core, as shown in Figure 1. The corrosion products formed at any point of attack on this clad surface have the same tendency to arrest further attack as do those on any corrosion-resistant aluminum alloy. Even should the alloy 7072 cladding be completely removed, the 3004 core alloy of culvert sheet possesses a high order of corrosion resistance.

The typical solution potentials for some of the more common alloys are given in Table 2. It can be seen that alloy 7072 is sufficiently anodic to provide protection to all the alloys listed.

INFLUENCE OF SOIL CHARACTERISTICS ON CORROSION

Soil Resistivity

One of the most widely used measurements for indicating soil corrosivity is resistivity. Because corrosion is an electrochemical phenomenon, the importance of resistivity is evident. The higher the resistance the lower the current flow for a given driving force and consequently the lower the metal loss. Flow of corrosion currents are further reduced by adding the resistance of the aluminum oxide film to the resistance offered by the soil.

A minimum soil resistivity of 1, 500 ohm-cm has been suggested as a threshold value below which corrosion of aluminum may occur (4). In soils having a lower resistivity, protection of the aluminum has been advocated for successful performance. This minimum figure was obtained through considerable field experience with aluminum pipelines. Other uses of resistivity have been proposed to classify the aggressiveness of soils (5, 6, 7). 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

Soil pH

Soil chemistry is believed to contribute to the corrosivity of a soil (8, 9). Various construction materials theoretically display varying resistances to corrosion within the range of pH encountered in soils. Aluminum oxide is generally inert to chemical attack within the range of pH 4 to 9 (10). This range accounts for nearly all soils in the United States because it almost covers the entire range of pH listed by the U. S. Department of Agriculture (11).

Other Factors

Other factors that contribute to soil corrosion are permeability, moisture content, and the homogeneity of the surrounding soil electrolyte. A number of investigators feel that corrosion of buried metals is caused by the non-uniform nature of the contacting soil (12, 13). This lack of uniformity is related to the consistency of soil compaction and its subsequent influence on aeration and moisture retention. Uncontrolled backfill can foster the establishment of differential concentration cells on a metal surface. These can exist until soil compaction reaches that of the undisturbed stage. Aluminum, of course, is no more subject to such corrosion than other metals commonly used underground.

SOIL CLASSIFICATION

Many classifications have been applied to soils. These may be broadly subdivided into two groups, structural and pedological. It should be noted that all soil classifications are general. Within each classification area there might be considerable variation of certain soil characteristics. From a corrosivity standpoint, certain soil groups might be mild in one geographical area and severe in other areas. Nonetheless, it is useful to discuss the soil associations and relate them to the corrosion characteristics of soils previously discussed.

Structural Classification

The structural series of soils is of particular importance in construction uses. There are several of these: the Unified Soil Classified System (14); the U. S. Bureau of Public Roads and Highway Research Board Classification, adopted by the American Association of State Highway Officials (15); and the Civil Aeronautics Administration Classification of Soils for Airport Construction (16). These systems rate soils in engineering terms, using bearing strength, drainage characteristic, plasticity, and liquid limit. The FHA (17) and the U. S. Army (18) have provided generalized ratings of structural and corrosion performance of soils based on the engineering classification. The textural Classification Chart (16) rates soils on the basis of material, sizing, and grading.

Pedological Classification

The Pedological classification system of soils (Table 3) has been broadened and improved by the U. S. Department of Agriculture (19). This classification describes soils through the geological similarity, including climate, vegetation, parent material, and age. There is also a similarity in chemical composition. This system provides the best insight into a means of determining the chemical forces present and relating them to corrosion studies of aluminum culvert.

TABLE 3

CHEMICAL CHARACTERISTICS OF THE GREAT SOIL GROUPS

Group	General Location in United States	Common Range of Reaction
Desert	Western States, inland from Pacific Coast to Rocky Mountains	Neutral to strongly alkaline (pH 6.6 - 8.5)
Chestnut and Brown	Western Great Plains, North Dakota to Texas	Neutral to strongly alkaline (pH 6.5 - 8.5)
Chernozem	Northern and Central Great Plains	Slightly acid to neutral (pH 5.6 - 7.0)
Prairie	Central Midwest, Minnesota to Kansas	Medium acid to neutral (pH 5.6 - 7.0)
Gray-Brown Podzolic	Central East Mississippi River to Atlantic Ocean, Kentucky to Michigan, Northwest Pacific Coast	Strongly acid to slightly acid (pH 5.1 - 6.1)
Red-Yellow Podzolic	Southeast, Virginia to Texas, and Missouri	Very strongly acid to medium acid (pH 4.5 - 5.5)
Podzol	Northern Great Lakes, New England	Extremely acid to strongly acid (pH 4.0 - 5.5)

TABLE 4

CHEMICAL COMPOSITION OF THE SPECIAL SOIL GROUPS

Group	Major Location in United States	Common Range of Reaction
Alluvial	River channels or basins, valley bottoms	Variable, from strong alkaline, reflects character of great soil
Sand	Western Nebraska, pockets in Southwest	Neutral
Saline water and soil	All sea coast areas, narrow belt in Uplands to wide belt in Coastal Plains. Selected roads in northern Midwest	Slightly acid to alkaline
Peat	Southern Florida, western Great Lakes, California delta	Very strongly acid to slightly acid (pH 4.0 - 6.5)
Ground Water Podzol	Coastal areas, Georgia to Mississippi	Acid to alkaline
Peat and Silt, Muck or Half Bogs	Southern Georgia, Southern Florida, Gulf Coast	Very strong acid to neutral (pH 4.5 - 7.3)
Clay Muck	Gulf Coast bayous, river mouth banks, Southern Atlantic Coastal Plain	Extremely acid to neutral (pH 3.0 - 7.3)
Sulfuric Acid or Sulfides	Isolated locations in northern California, Yellowstone, in coal belts, western Pennsylvania to Missouri	Extremely acid to neutral (pH 4.0 - 7.0)

Other groups from the Great Soil classification and special groups have been treated separately in Table 4. These groups are of particular interest when examining soils for characteristics that might affect aluminum performance. To maintain a true perspective of the incidence of these special soils, it is pointed out that as a group they total less than five percent of the United States, with three groups, saline water and soil, alluvial, and sand, making up the vast majority.

CURRENT EVALUATION

Previous investigations of aluminum's resistance to soil corrosion were found to be quite limited as to the alloys or soils studied (12, 20, 21, 22). However, a study of all available information indicated the more corrosion-resistant aluminum alloys should perform well in that broad category of soils that are acceptable structurally to the highway engineer.

Early Tests

Prior to the introduction of aluminum culvert, a field service program was undertaken to determine its resistance to soil corrosion. Test pipes incorporated several aluminum alloys of previously demonstrated high corrosion resistance. Initial field installations were made in selected soils, attempting to cover the five basic chemical soil classifications used by the National Bureau of Standards (12). Subsequently, an

TABLE 5

ALUMINUM CULVERT PERFORMANCE IN GREAT SOIL GROUPS

Location	Exposure (yr)	pH		Soil Resistivity (ohm-cm)			Remarks
		Soil	Water	2.5 Ft	5.0 Ft	10.0 Ft	
Desert Soil:							
Royal City, Wash.[a]	3.1	7.0 - 7.9	—	11,000	18,200	32,500	Random points of attack confined to the cladding
Fallon, Nev. 1[a]	3.5	8.0 - 8.8	8.0	1,484	1,867	1,474	One area of light etching on an otherwise unaffected surface
Yerington, Nev.	2.0	—	—	—	—	—	No attack
Dixon Hill, N. M.	1.5	—	—	—	—	—	No attack
Wickenburg, Ariz.	1.0	—	—	—	—	—	No attack
Fallon, Nev. 2[a]	3.5	8.8 - 8.9	8.9	766	1,101	1,053	Slight surface stain, no corrosion
Chestnut and Brown Soil:							
Hebron, N. D.	1.2	7.6 - 8.6	8.1 - 8.3	1,920	958	709	Stained plus a few pits confined to the cladding
Dickinson, N. D.	1.2	7.6 - 7.8	8.1	2,585	1,628	479	Stained but no attack
Washburn, N. D. 1	1.0	7.7 - 7.9	—	4,690	6,800	9,950	Very light stain, no attack
Washburn, N. D. 2	1.0	7.6 - 7.8	—	670	928	1,052	Moderate staining, no attack
Dunn County, N. D.	1.2	—	—	—	—	—	Applique of stain, no attack
Lovell, Wyo.	1.3	—	—	—	—	—	No attack, moderate stain
Pikes Peak, Colo.[b]	—	—	—	—	—	—	No attack, slight roughening of invert
Silver Cliff, Colo.	1.5	High salt content	—	—	—	—	No attack
Chernozem Soil:							
Breckenridge, Minn.	1.75	—	—	670	823	1,130	Moderate water stain, no corrosion
Minot, N. D.	1.2	—	—	3,160	2,776	3,062	Moderate water stain, no corrosion
Mekinock, N. D.	1.2	7.5	—	—	—	—	Applique of stain, no corrosion
Grand Forks, N. D.	1.2	7.0	—	—	—	—	Dark staining with random points of surface etching which are apparently arrested
Prairie Soil:							
Nashville, Mo.	1.2	—	—	19,152	24,895	30,640	Random light stain
Liberal, Mo.	0.5	—	6.8	—	—	—	Unaffected
Moundville, Mo.	1.2	—	—	6,703	6,611	5,554	Aluminum unaffected
Cedar Springs, Mo.	1.5	—	6.2	—	—	—	No attack
Milford, Mo. 1	1.3	—	—	16,758	16,278	9,742	Dark staining, no corrosion
Springfield, Ill.	3.0	—	—	—	—	—	No attack
Spokane, Wash.[a]	3.5	5.5 - 6.3	—	9,810	12,925	20,100	Considerable staining, no attack
Gray-Brown Podzolic:							
Ravenswood, W. Va. 1[a]	2.5	—	—	9,575	5,270	2,680	Moderate stain, no attack
Ravenswood, W. Va. 2[a]	2.5	—	—	3,830	3,925	—	Light stain, no corrosion
Vineland, N. J.	0.8	5.4 - 5.7	7.0	47,870	67,000	74,600	Mottled light stain, no attack. Invert has light pitting (industrial pollution)
Cumberland, N. J.	3.0	—	—	20,600	30,150	47,850	Light stain, no attack
Green County, Va.[b]	2.0	5.4	6.9 - 7.0	26,328	—	—	Some stain, several spots of light etch in cladding (believed caused by concrete splatter)
Gambrills, Md.	—	—	6.7	—	—	—	Unaffected except for several small etched spots caused by concrete splatter
Granite Falls, Wash. 1[a,b]	3.0	5.3 - 5.9	—	—	—	—	Light stain, no attack. Invert roughened
Granite Falls, Wash. 2[a,b]	3.0	5.3 - 6.3	—	—	—	—	Light stain, light roughening of invert
Coshocton County, Ohio	0.4	—	—	—	—	—	No attack
Bridgeville, Calif.[b]	1.5	—	—	—	—	—	No attack
Red-Yellow Podzolic:							
Atlanta, Ga.[a]	3.0	5.6 - 6.8	—	—	—	22,024	Moderate staining, no corrosion
Dudley, Ga.	2.0	—	—	—	—	—	Unaffected
Nansemond County, Va.	2.0	5.3	5.9 - 6.1	30,000	24,000	10,500	Light stain, no corrosion
Podzol:							
Minneapolis, Minn.	3.0	7.0 - 7.5	—	—	—	—	Unaffected except for two isolated pits in cladding
Colorie, N. Y.	2.0	Slightly acid	—	—	—	—	No attack

TABLE 5 (Cont'd)

ALUMINUM CULVERT PERFORMANCE IN GREAT SOIL GROUPS

Location	Exposure (yr)	pH		Soil Resistivity (ohm-cm)			Remarks
		Soil	Water	2.5 Ft	5.0 Ft	10.0 Ft	
Alluvial:							
Salton Sea, Calif.	2.0	7.5 - 8.0	—	50	—	—	Random light surface etch confined to cladding
Hayward, Calif. 1[a]	3.25	7.4 - 7.9	—	1,006	958	1,072	Mottled stain, no attack, random pitting of clad in invert
Hayward, Calif. 2[a]	3.25	—	8.0 - 8.1	—	—	—	No attack
Concord, Calif.[a]	3.6	7.6 - 7.8	—	1,053	1,197	1,264	Mottled light stain with a few small areas of etching confined to the clad
Saline Water and Soil:							
Dunedin, Fla.	2.5 - 3.0	—	—	Sea water	—	—	Invert stained, some fouling, no attack
Pumpkin Creek, Colo.	1.5	—	—	—	—	—	No attack
Woodside, Utah	1.0	Alkaline	—	50	—	—	Up to 13.9% salt (8% Mg_2SO_4)—no corrosion
Wendover, Utah	1.5	Alkaline	—	50	—	—	No attack on soil side. Random slight etching of cladding in invert
Oxnard, Calif.	1.5	—	—	—	—	—	Dull, matte appearance, no attack
Nags Head, N. C.	1.0	—	—	756	1,053	766	No attack, heavy stain on invert, no corrosion
Port Charlotte, Fla.	3.0	—	—	3,970	2,870	2,105	Soil side stained, no attack, random light pitting in the invert
Peat Soil:							
Cle Elum, Wash.[a]	3.0 +	6.3	—	10,050	10,500	14,350	Slight water stain, no attack
Belle Glade, Fla.	2.0	7.4 - 8.0	6.8 7.1	622	909	1,395	Invert discolored but no corrosion
Manotowish, Wis.	1.1	3.2 - 4.4	5.7 - 6.4	16,758	22,023	22,981	Light water stain, no attack
Ground Water Podzol:							
Waycross, Ga.	2.0	4.2 - 4.6	5.4	47,878	83,150	93,900	Lustrous, generally unaffected except for a few cladding pits
Sarasota, Fla.[a]	3.5	4.8 - 5.2	5.0 - 6.0	143,400	79,400	32,000	Unaffected
Bermont, Fla.	2.5	—	6.0	33,500	23,940	8,400	A few random cladding pits, otherwise unaffected
Citrus Center, Fla.	3.0	6.8 - 7.8	7.9 - 8.3	13,400	8,610	6,300	Uniform light stain, no attack
Brunswick, Ga.	2.0	7.4 - 7.8	7.1	440 - 6,470	1,530	153	Cladding uniformly removed over much of surface, attack confined to cladding
Silt Muck or Half Bog:							
Chalmette, La. 1[a]	3.0	7.2 - 7.5	—	766	939	708	Stained, no corrosion
Chalmette, La. 2[a]	3.0	7.5	—	957	1,053	881	Moderate stain, no attack
Greenwich, N. J.	3.0	4.1	7.8	852	1,149	1,550	Random attack, confined to cladding
Clay Muck or Bog:							
Gramercy, La. 1[a]	3.5	6.9 - 7.1	—	479	507	574	Applique of etching in the clad layer
Gramercy, La. 2[a]	3.5	6.5 - 7.0	—	—	—	—	Applique of etching in the clad layer
Sulfuric Acid or Sulfides:							
Liberal, Mo.	0.5	—	2.7	—	—	—	Clad gone in invert, core alloy pitting
Moundville, Mo.	—	—	3.1	—	—	—	Severely corroded invert
Osceola, Mo.	1.2	—	2.6	—	—	—	Severely corroded invert
Oroville, Calif.	2.0	—	—	—	—	—	Invert cladding gone, metal perforated
Redding, Calif.	2.0	—	—	—	—	—	Invert cladding gone, metal perforated
Coshocton County, Ohio 1	0.4	—	4.1 - 4.2	—	—	—	Slight attack
Coshocton County, Ohio 2	0.4	—	3.1	—	—	—	Cladding gone in invert, metal perforated

[a] Inspected periodically as part of original test program.

[b] Erosion site.

increasing number of installations in all types of exposure were added to the original placement. Exposures were made in all the basic Great Soil types.

Present Study

Approximately 500 installations were screened early in 1963. Some were inspected in detail and have been reported. These represent typical performances in the various exposures mentioned. In addition to an evaluation of soil corrosion per se, it was of interest to determine the performance of aluminum culvert with particular effluents. These included runoff which is acidic due to the oxidation of sulfides and runoff which is erosive due to entrained particulate matter.

Culvert Examination

At each installation reported, a section of the culvert was uncovered and examined closely to determine its condition. Samples, approximately 6 by 6 in., were removed from those culverts comprising the original test program and from certain others where permission from such removal could be readily obtained. An effort was made to include any questionable surface condition in the sample. In addition to observations of the culvert soil-side performance, a check was made of the condition of the invert or waterside surfaces.

Measurements of the soil resistivity were generally taken with a Model 263A Vibroground equipped with a harness for obtaining the average resistivity through 2.5-, 5.0- and 10.0-ft depths. Soil and water pH readings were made with a Beckman Model 180 pocket pH meter. Some readings were omitted because of lack of water flow at the time of inspection, or because of lack of interest in specific measurements due to the overriding influence of other characteristics affecting culvert performance, such as erosion or acid runoff.

Culvert samples were returned to the laboratory where they were cleaned and examined more closely. Sections were taken from samples showing corrosion for metallographic determination of the nature and extent of attack. Areas of stain or unusual surface condition were similarly examined.

The results of these inspections are given in Table 5. An attempt has been made to place each of the installations within the proper Great Soils group to facilitate comparisons within and among the groups.

RESISTANCE TO CHEMICAL ATTACK

A study of the data indicates that the performance of aluminum is relatively consistent throughout each soil group. Within the entire listing of Great Soil groups in Table 3 (more than 95 percent of the geography of the United States) there is no evidence of general corrosion attack on aluminum. The pH range of 4.0 to 9.0 removes the prospect of chemical attack on the oxide film. Typical of the attack observed on aluminum culvert in certain cases is the sample from Royal City, Wash. This installation has been inspected at the end of 0.5-, 1-, 2- and 3.1-yr exposure. Random superficial attack was noted on this culvert at the end of 0.5 yr that was similar to that seen after 1 yr (Figs. 2, 3 and 4). Subsequent inspections and sampling indicated that the attack had not progressed to any measurable degree (Figs. 5, 6 and 7).

Alluvial soils do not seem to follow any consistent pattern with respect to their chemical activity. The increase in fines in such soils, however, tends to reduce their resistivity. In areas of less rainfall, these soils may become alkaline as in Concord, Calif. The low resistivity mildly alkaline soil there has caused no significant attack. Differential coloration in the two corrugation valleys (Fig. 8) was caused by the chromic-phosphoric acid cleaning solution. A section through the lacy patterns of etching noted on that sample shows the attack to be superficial (Fig. 9).

Experience with salt water exposure (23) and experience gained during this evaluation indicate that aluminum can serve satisfactorily in saline environments. However, it is possible for the corrosion of aluminum culvert stock to proceed at significant rates in the presence of chlorides under anaerobic conditions. This should not be construed to

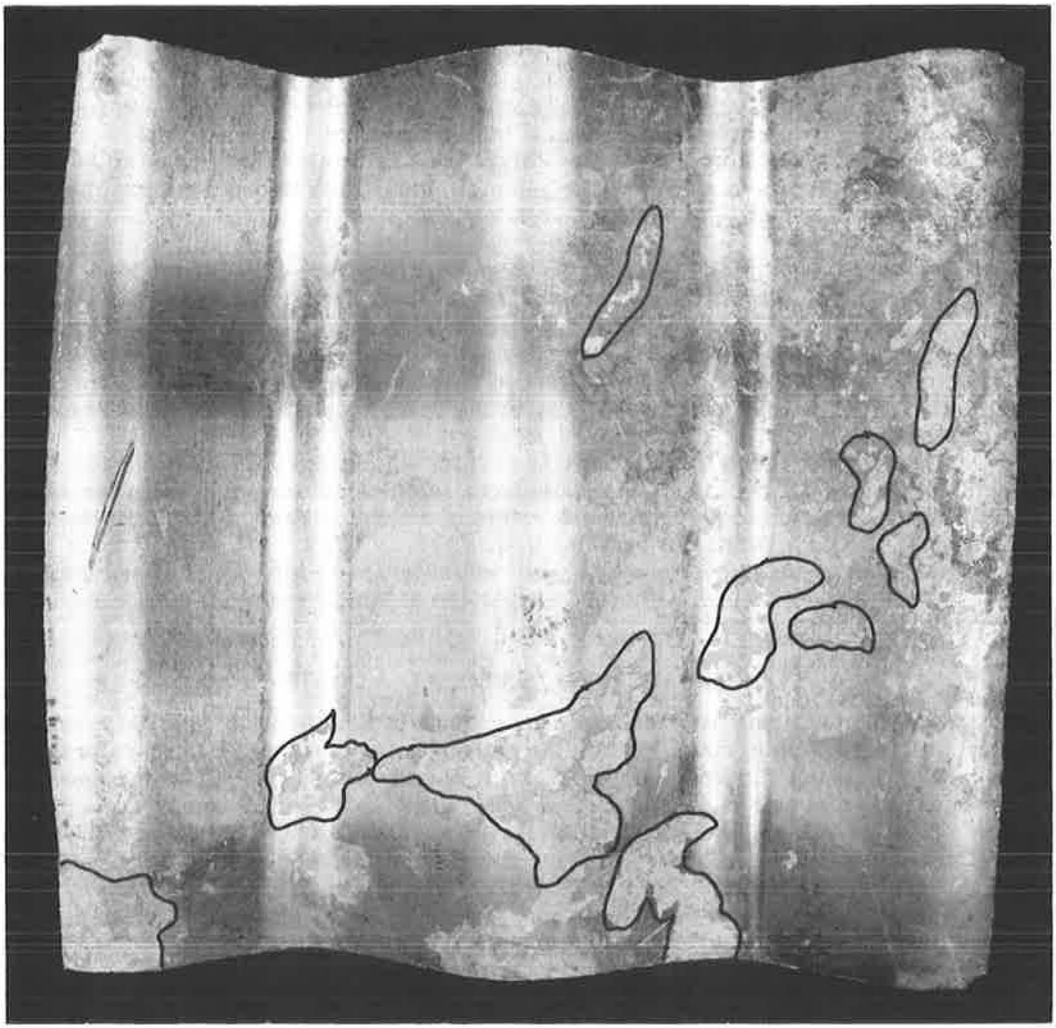

Figure 2. Random superficial attack of aluminum culvert at Royal City, Wash., after 1 yr, no etch, 5/6 X.

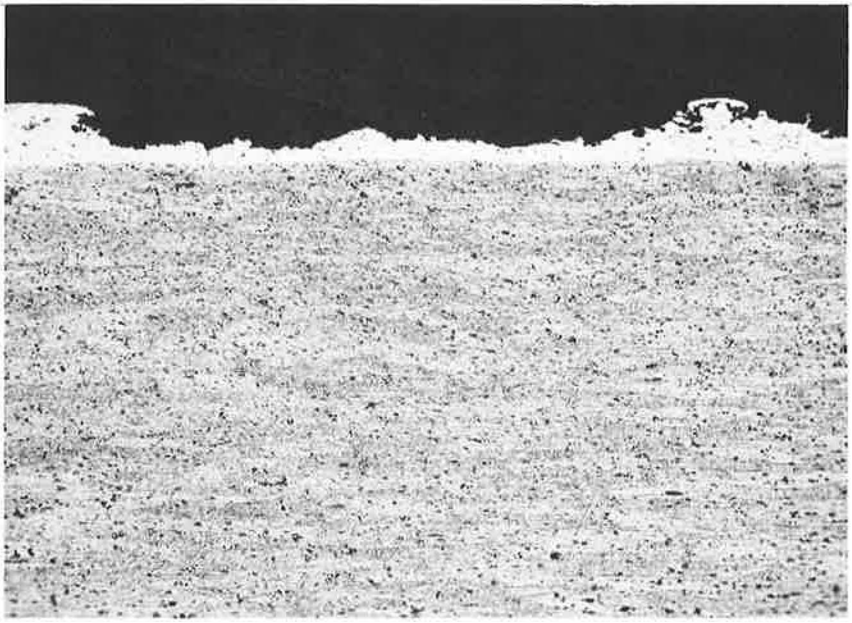

Figure 3. Random attack of aluminum culvert at Royal City, Wash., after 1 yr, caustic fluoride etch, 100X.

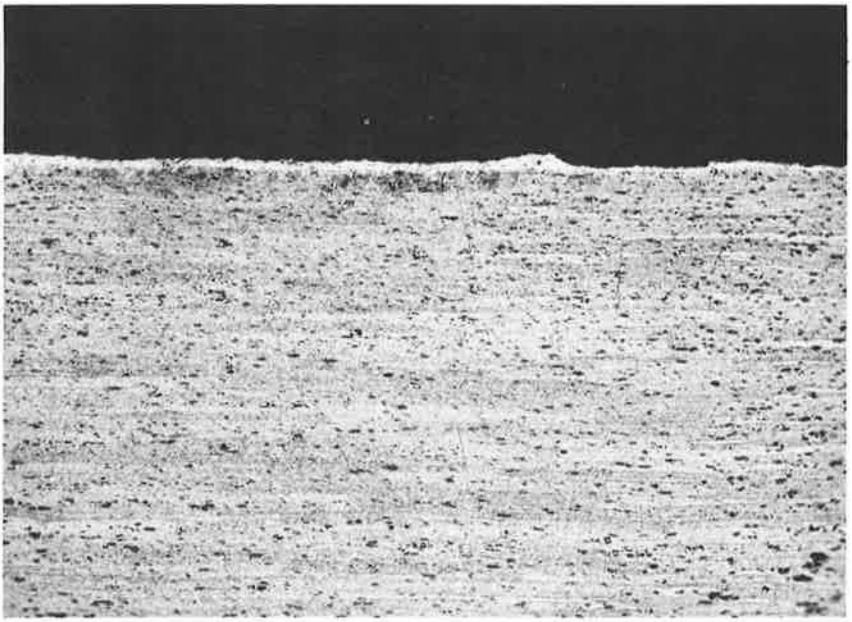

Figure 4. Random attack of aluminum culvert at Royal City, Wash., after 1 yr, caustic fluoride etch, 100X.

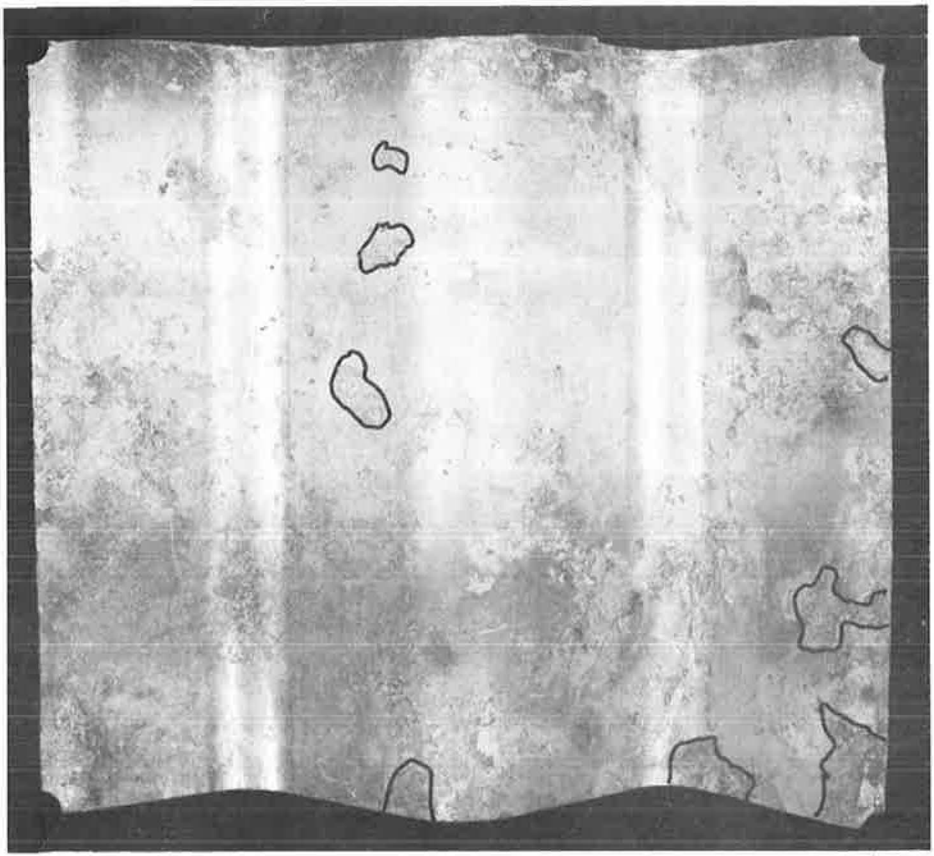

Figure 5. Random superficial attack of aluminum culvert at Royal City, Wash., after 3.1 yr, no etch, 5/6 X.

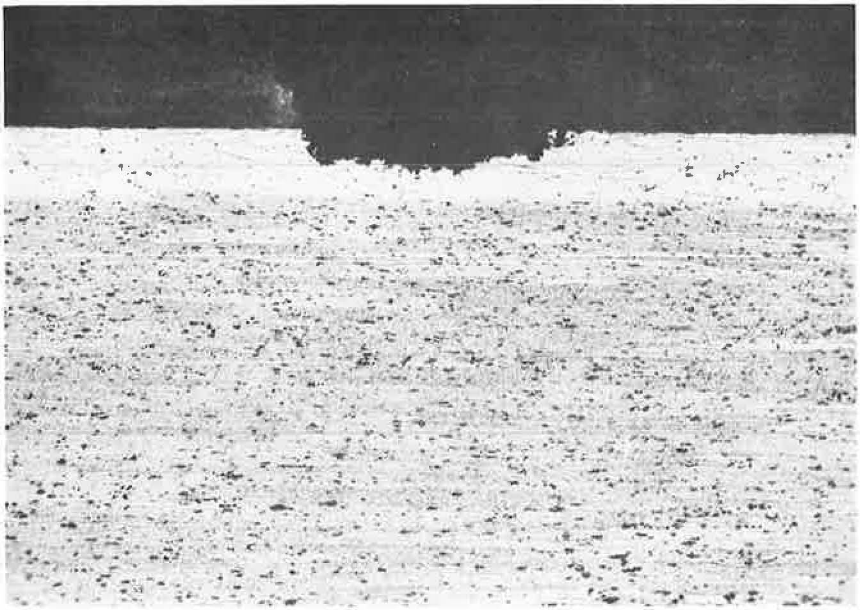

Figure 6. Random attack of aluminum culvert at Royal City, Wash., after 3.1 yr, caustic fluoride etch, 100X. Depicted here is the unaffected condition of most of the surface and the nature and extent of pitting which appear as small dark spots on the surface.

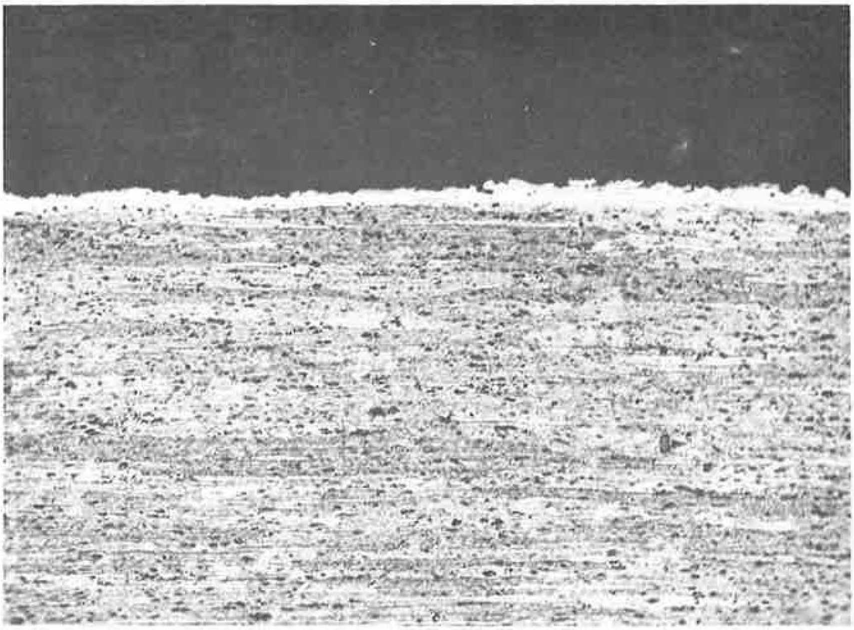

Figure 7. Random attack of aluminum culvert at Royal City, Wash., after 3.1 yr, caustic fluoride etch, 100X. The area showing maximum depth of attack has some clad alloy remaining on the surface.

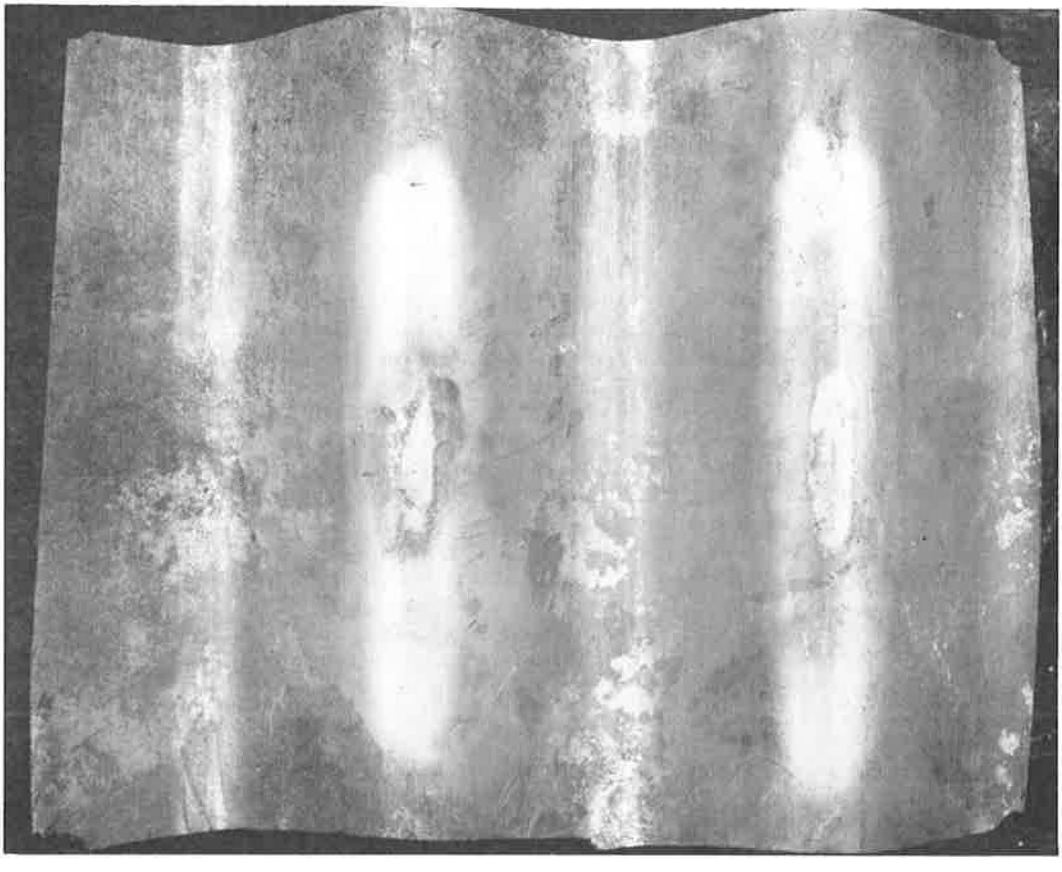

Figure 8. Aluminum culvert, Concord, Calif., after 3.5 yr, no etch, 5/6 X. Coloration in the corrugation valley was caused by chromic-phosphoric acid cleaning solution.

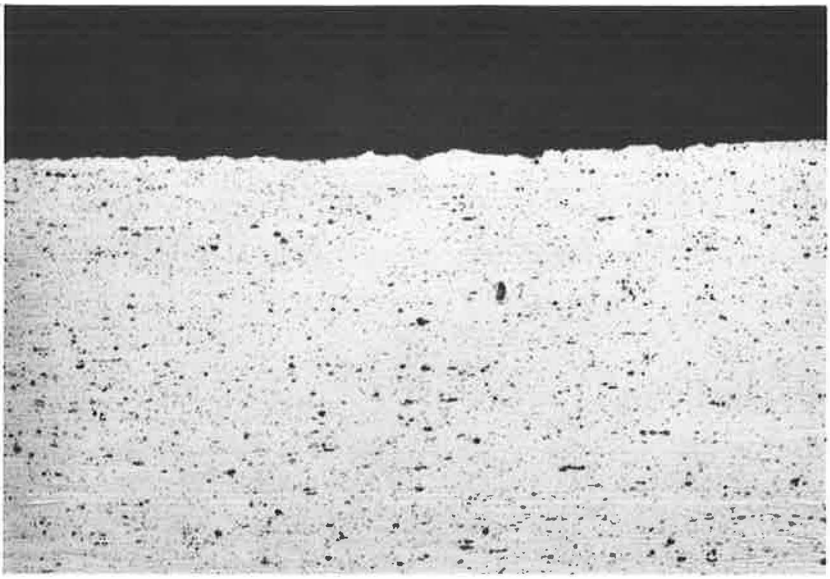

Figure 9. Aluminum culvert, Concord, Calif., after 3.5 yr, no etch, 100X. Chemical attack was superficial on the soil-side surface.

indicate problems with aluminum due to anaerobic bacteria such as the sulfate reducers. There is considerable information attesting its compatibility in the acid hydrogen sulfide environments caused by these bacteria.

The peats, bogs, and mucks are normally very poor construction soils (14, 15, 16, 17, 18) and are, therefore, generally rejected in favor of selected backfill for structural reasons. Nonetheless, for reasons of understanding soil corrosion, they are of interest.

The organic acids usually associated with peat do not cause corrosion of aluminum. In addition to the installations shown under "peat" and "ground-water podzol" in Table 5, aluminum has provided nine years of satisfactory performance for buried irrigation lines in a Grayland, Wash. bog.

Performance of aluminum in silt mucks will depend upon soil characteristics such as pH and resistivity combined with chemical content of the soil, primarily chlorides, and the extent to which good backfill compaction practices are followed.

Clay-rich mucks present an extreme case. They drain poorly and consequently afford poor aeration characteristics. They are difficult to compact, thereby offering numerous opportunities for heterogeneous soil conditions on the culvert surface. Resistivities are usually low, therefore concentration cell activity may proceed at significant rates. The typical appearance of aluminum culvert after 3.5 yr service in a clay muck at Gramercy, La. is shown in Figure 10. Original surface can be seen on much of the sample. The photomicrograph in Figure 11 indicates the condition which prevails over most of the remaining surface—a thin layer of cladding is still present. Deepest attack of the core alloy 2.0 mils is shown in Figure 12. Fortunately, the occurrence of clay-rich mucks is quite limited. They usually occur at the point where a river empties into the ocean or in a few isolated swamp areas of the United States.

Sulfuric acid or exposed natural sulfide deposits can produce acid conditions of pH less than 4.0. In this case, corrosion of aluminum can occur through dissolution of the oxide and aggressive attack of the underlying metal. Some areas where sulfuric acid of this concentration occurs have been located. In northern California, natural sulfide deposits lie near the surface in a few isolated areas. When uncovered, they promote the formation of acid runoff. Volcanic sulfuric acid is created by subsurface action in Lassen National Park, and aggressive concentrations are also found in the Yellowstone Park region. Many instances of sulfuric acid runoff below pH 4.0 have been observed

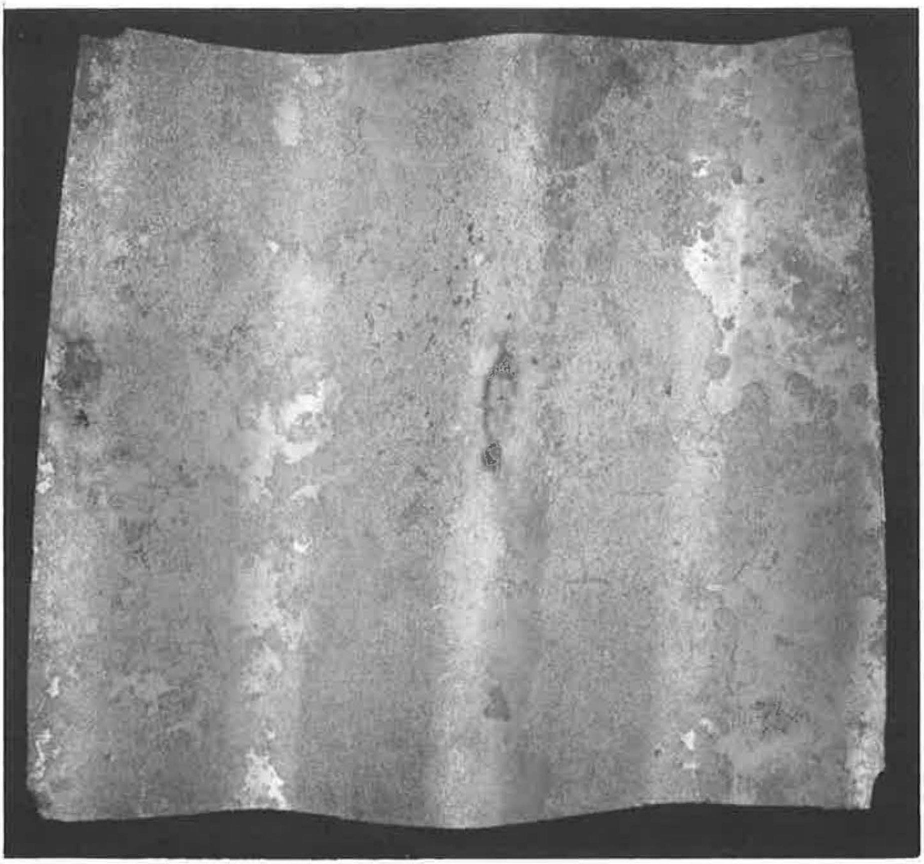

Figure 10. Aluminum culvert, Gramercy, La., after 3.5 yr in clay muck, no etch, 5/6 X. Areas which have not been attacked can be distinguished from those on which the cladding has been etched.

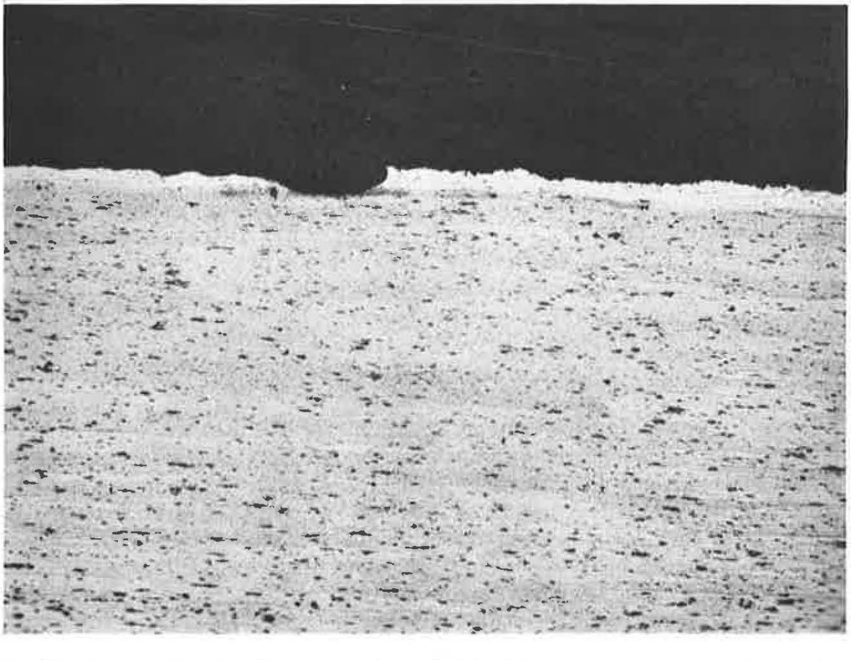

Figure 11. Aluminum culvert, Gramercy, La. Soil-side section represents typical condition of etched surfaces on sample, caustic fluoride etch, 100X.

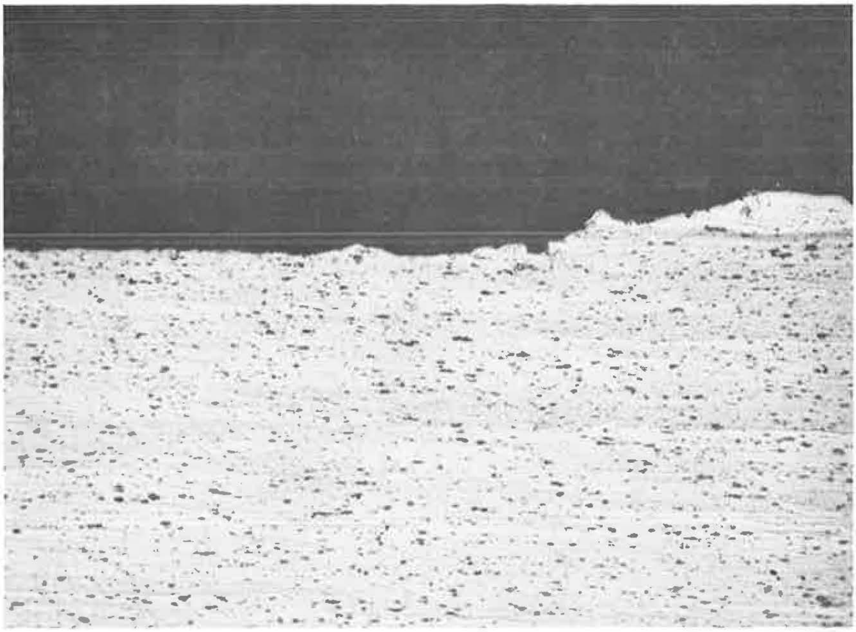

Figure 12. Aluminum culvert, Gramercy, La. Areas of deepest attack typified by this soil-side section occurred on the corrugation crest, caustic fluoride etch, 100X.

in the coal-rich Western Appalachians from Pittsburgh, Pa. to Missouri and Mississippi. These are generally well located by previous experience, color of the runoff area, or lack of vegetation.

It is of academic interest to note that aluminum can provide satisfactory performance in acid areas if dilution raises the pH value to above 4.0. Such a case exists in Meigs County, Ohio where corrosion has caused rapid destruction of non-aluminum corrugated culvert. Aluminum culvert was tested there in 1960. No readings more acid than pH 5.0 have been taken during the interim, and the aluminum is unaffected. The culverts in Coshocton County, Ohio offer another case where runoff below pH 4.0 is causing severe attack and above 4.0 is causing only insignificant attack.

RESISTANCE TO EROSION

Discussion of corrosion of aluminum culvert must include consideration of the effects of abrasive forces on the over-all performance or service life of the structure. A program of field evaluation has been established to observe the behavior of aluminum and, in some cases, galvanized steel culvert in a variety of aggressive exposures. Some of the installations are noted in Table 5.

Preliminary investigation indicates that bed load type and water velocity at the invert, which combine to become the destructive energy, are the basis for comparing the various installations. Observations indicate that a bed load of sandy material alone will not remove significant amounts of metal from the aluminum surface even at substantial velocities. It will, however, cause slight roughening of the invert. Bed loads consisting of stones would be expected to provide higher energy at a given velocity. Where significant roughening or metal movement has been noted, the bed load included a substantial quantity of rocks 3 in. or more in diameter.

Experience to date with heavy bed loads has been at velocities up to 8 fps, 8 to 10 fps, 13 fps, and 25 to 30 fps. No significant roughening occurred below 8 fps. A slight roughening has been observed in the 8 to 10 fps range causing surface displacement of a random nature (Fig. 13). In this instance, the energy is sufficient to abrade zinc and

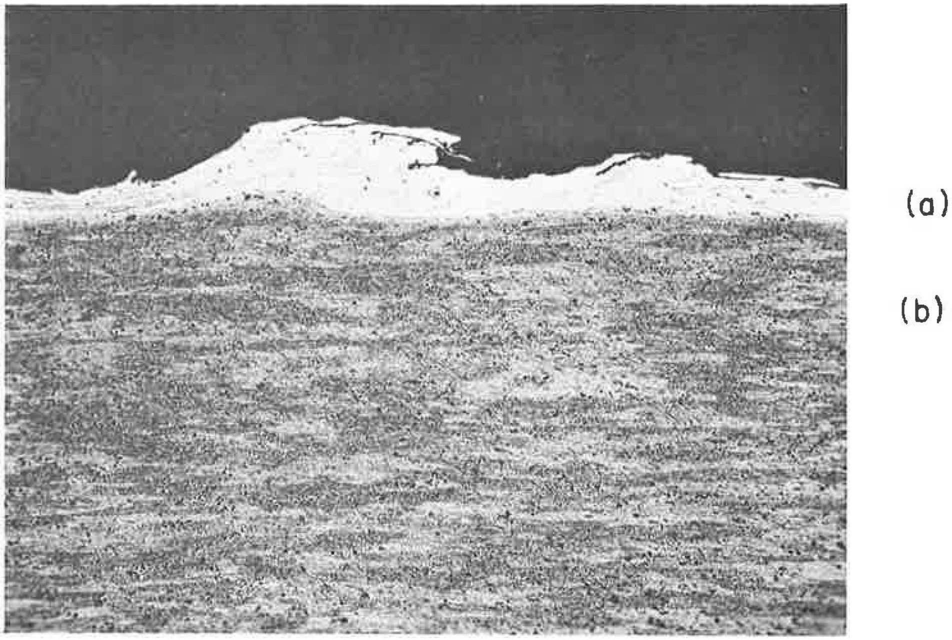

Figure 13. Aluminum culvert, Granite Falls, Wash: (a) clad alloy, (b) core alloy, caustic fluoride etch, 100X. This section from the invert shows distortion of the cladding layer that occurs as a result of the peening action of particles carried by the runoff.

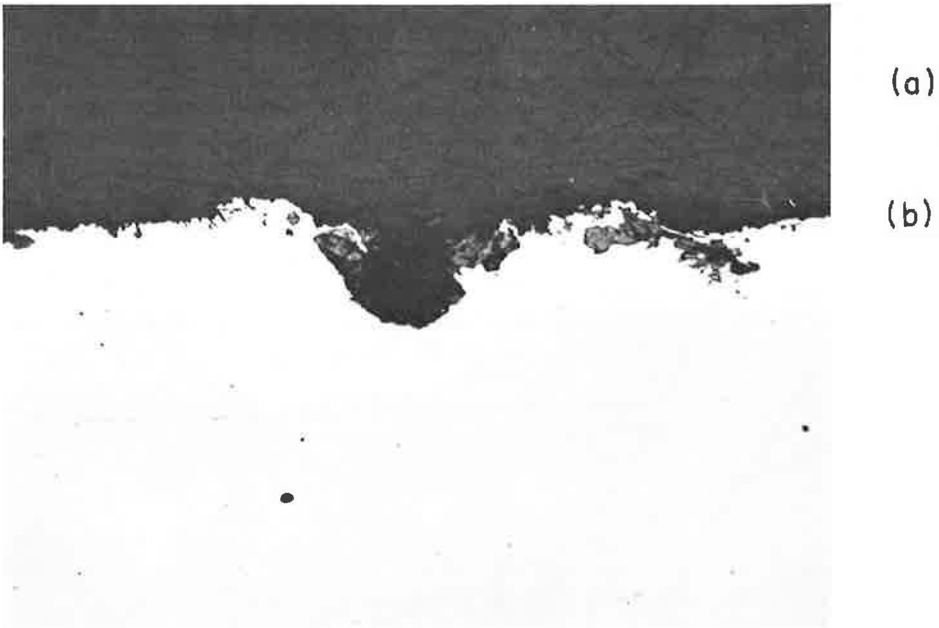

Figure 14. Galvanized steel culvert, Granite Falls, Wash: (a) bakelite mounting, (b) steel core, no etch, 100X. This section from the invert shows that the zinc coating has been removed from the galvanized steel invert and pitting of the underlying steel has started.

iron oxide. To date, typical performance of the steel at this site is shown in the photomicrograph (Fig. 14). One culvert in which velocity is 13 fps shows definite signs of metal removal due to wear energy. An experimental installation where water velocity was 25 to 30 fps provided destructive energy of such force that neither corrugated metal (aluminum or steel) nor concrete could resist rapid wear that caused thinning and destruction of the inverts by tearing.

Thus, from the preliminary program, it appears that hydraulic design of aluminum culvert might well be limited to sustained velocities below 10 fps where a heavy rock-laden bed load is anticipated. Where the bed load is sandy, higher velocity limits are possible.

CONCLUSIONS

On the basis of aluminum culvert inspection results of nearly 500 installations in the major Great Soil groups, the following tentative conclusions can be drawn:

1. Aluminum culvert is resistant to attack by soils of the Great Soil groups that comprise almost all of the soil in the United States. It is being used successfully throughout the country.
2. The corrosivity of a soil to aluminum roughly follows its structural rating, that is, corrosion possibilities increase as the structural desirability of the soil decreases. Exceptions are the Peat and associated groups that are good draining, highly organic materials. In these soils, aluminum is performing well.
3. The corrosion attack observed on the soil-side surface of some aluminum culvert is believed to be the result of non-uniform 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.
4. The 7072 alloy cladding on aluminum culvert stock is providing adequate protection to the 3004 alloy core.
5. Effluents normally encountered with culverts are causing no corrosion problem. However, acid runoffs having a pH of 4.0 or lower can cause aggressive attack of aluminum. Bare aluminum is not recommended for these highly acid flows.
6. Service performance of aluminum in abrasive or erosive runoff is very satisfactory. The results of inspections reported here indicate that use of aluminum culvert should be limited to runoff velocities below 10 fps if a heavy rock-laden bed load is anticipated. Higher velocities are permissible when the bed load is primarily sand.
7. Soil resistivity, soil pH, or a combination of these characteristics do not offer a completely reliable basis for predicting soil corrosivity. These factors can, however, have an influence upon the over-all corrosivity.

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