Corrosion Evaluation of Aluminum Culvert Based on Field Performance

T. A. LOWE and R. H. VATERLAUS, Kaiser Aluminum, and
R. I. LINDBERG and L. R. LAWRENCE, Reynolds Metals

Nearly 1000 uncoated aluminum culverts were inspected to develop a broad base for analysis of performance. From this group 583 were examined in detail, with water, soil, and metal sampled for laboratory examination. The service history of all culverts inspected averaged 4.7 years. Approximately 20 percent of those sampled had been in service for 6 years or more. The results are compared with corrosion behavior of aluminum in other environments. Only in a few unusual exposures was significant attack noted, and these cases were predictable from published parameters. From this it can be concluded that aluminum culvert behavior closely follows that expected in normal aqueous and atmospheric environments.

Graphic comparisons are made with water pH and resistivity, as well as with soil pH and minimum resistivity. These comparisons confirm earlier pH recommendations limiting use of uncoated aluminum alloy culvert to soils and waters within a pH range of 4 to 9, but suggest a minimum soil resistivity of no less than 500 ohm-cm. This resistivity value is lower than that recommended in an earlier investigation based on the minimum value of several field measurements made with a Vibroground. The present current recommendation is based on laboratory measurement of minimum soil resistivity. Exceptions to the resistivity limit occur in granular soils contaminated with such low resistivity media as sea water (30 ohm-cm); in such areas, aluminum performs satisfactorily. Two exposure conditions do cause significant corrosion of uncoated aluminum alloy culvert: (a) runoff containing sulfuric acid at pH less than 4, and (b) low minimum resistivity clay mucks. The inconsequential degree of attack represented by the large majority of culverts now in place allows one to conservatively extrapolate to a 50-year service life.

•ALUMINUM CULVERT has been available since 1960. Since that time a number of investigators have reported on selected short-term corrosion results. The number of culverts covered in these evaluations was necessarily limited. Nonetheless the results are reviewed here for later comparison with the present evaluation.

Nordlin and Stratfull made a preliminary study (1) based on 0.8 to 2.4 years' exposure of eight simulated culvert installations. The sites selected represented the most severe exposures available: three represented naturally formed sulfuric acid (pH < 4); two represented aggressive abrasion sites; one represented San Joaquin peat; one represented seawater-contaminated tidal zone clay; and one represented low-resistivity alkaline soil. As expected, the sulfuric acid sites produced aggressive corrosion, abrasion was severe at the abrasion sites, and the remaining sites showed

Paper sponsored by Committee on Metals in Highway Structures and presented at the 48th Annual Meeting.

TABLE 1

ALUMINUM CULVERT INSPECTION SUMMARY BY STATE

State	No. of Culverts Logged	No. of Culverts Sampled	No. With 6 or More Years Service
Alabama	14	14	–
Arizona	9	9	1
California	297	254	27
Colorado	2	2	–
Florida	42	42	20
Georgia	4	4	3
Illinois	14	14	–
Indiana	9	9	1
Iowa	20	20	16
Kansas	126	15	–
Kentucky	1	1	–
Louisiana	71	8	–
Maryland	26	26	20
Michigan	8	8	–
Mississippi	3	3	–
Missouri	8	8	6
Nebraska	8	8	–
New Mexico	3	3	–
New York	30	30	–
North Carolina	3	3	–
Ohio	7	7	4
Oklahoma	166	10	–
Oregon	28	28	–
South Dakota	3	3	2
Tennessee	2	2	–
Utah	1	1	1
Virginia	4	4	2
Washington	40	32	8
Wisconsin	11	11	6
Wyoming	4	4	–
Totals	965	583	117

varying degrees of corrosion, generally limited to the cladding.

Berg (2) evaluated 16 culverts installed in typical bedding for 2 to 4 years. The most severe corrosion occurred with oyster-shell backfill in a tidal drainage ditch, but in no case did pitting go beyond the cladding.

Haviland, Bellair, and Morrell (3) published results on 34 aluminum uncoated culverts with 3 to 6 years' exposure. Some staining and limited corrosion was observed—attack was confined to the cladding.

Lowe and Koepf (4) discussed performance of 71 selected uncoated aluminum culverts with 0.4 to 3.5 years' exposure. The soil and water environments represented a wide range of exposure conditions, and results reflected this. Where exposures were severe, such as in runoff containing sulfuric acid, aggressive corrosion resulted. Culverts installed under more typical exposures were unaffected or, at worst, showed corrosion confined to the cladding.

The application of aluminum alloy culvert has developed to a point where clearly definitive performance may be observed. To establish this performance, the Aluminum Association undertook an extensive culvert inspection program that included development of location information, installation characteristics, and samples of water, soil, and metal.

A national inspection program was initiated having the distribution given in Table 1. As wide a range of conditions as possible was included; 965 individual uncoated culverts were inspected and from this group 583 culverts were sampled. Service life averaged 4.7 years; 20 percent of all culverts sampled had a service history of 6 or more years. Table 2 gives a breakdown of exposure history.

These exposure periods are the longest yet reported and are considered adequate in time and quantity to provide meaningful data for (a) evaluating performance, (b) establishing recommended limits of environmental conditions, and (c) extrapolating to expected service life. The data are sufficient for comparison with published data on other atmospheric, aqueous, and underground corrosion of aluminum. The underground corrosion characteristics of aluminum are shown to be similar to those in other types of exposures.

TABLE 2

BREAKDOWN OF EXPOSURE HISTORY OF ALL CULVERTS INSPECTED

Years Service to Date of Last Inspection	Number of Culverts
7 and over	19
6 to 7	98
5 to 6	266
4 to 5	335
3 to 4	202
2 to 3	29
Under 2	16
Total inspected	965

THE NATURE OF ALUMINUM CORROSION

A detailed discussion of aluminum corrosion principles is beyond the scope of

this paper. Excellent discussions are published elsewhere (5, 6). Some comment on corrosion does, however, seem appropriate to complement subsequent interpretations.

Oxide Film

Aluminum depends on a thin film of aluminum oxide for its corrosion resistance. The aluminum oxide film is tough and highly tenacious, an excellent dielectric, and inert to a wide range of environments. When damaged it forms again instantaneously.

Since corrosion is an electrochemical phenomenon, these film characteristics play a major role in providing aluminum its corrosion resistance. The oxide film produces high electrical resistance in the circuit between anodes and cathodes, thereby reducing current flow and the amount of corrosion. Thus, in an environment in which the oxide film is chemically stable, corrosion is virtually nil.

Pitting

How does aluminum corrode if the film is so inert? The aluminum that we encounter is not pure aluminum, but an aluminum alloy. Other metals are added primarily to improve strength. Certain elements present as purposeful additions or as impurities are believed to affect the structure of the oxide film. In other words, we have point-site imperfections in the protective film. When attack occurs at these imperfections, the imperfection is enveloped by aluminum oxide resulting from corrosion of the metal substrate, or it is displaced by the oxide. The resulting build-up of oxide protects the underlying metal, and attack is effectively arrested. This, and similar processes occurring as the result of other mechanisms, accounts for the localized attack, or pitting, associated with the corrosion of aluminum. Long-term exposure data affirm the "self-stopping" nature of pitting attack on aluminum alloys in atmospheric and aqueous environments (5, 7).

Control of Corrosion by Cladding

Cladding consists of nothing more than making a "sandwich" of the stronger alloy core and outside layers of an alloy that is anodic to the core material. These layers are metallurgically bonded during the rolling operation. Aluminum alloy culvert sheet is clad in this manner—the core being alloy 3004 and the cladding alloy 7072. Both alloy components of culvert sheet exhibit a high order of corrosion resistance; however, the cladding is galvanically expended should corrosion occur, thereby preventing attack of the core until a substantial area of cladding is removed laterally. Table 3 compares the relative resistance with other widely used aluminum alloys (6).

TABLE 3

RELATIVE CORROSION RATINGS[a]

Type of Alloy	Commercial Examples	General Corrosion	
		Temper	Rating[b]
Unalloyed Al	1100	All	A
Al-Mn	3003	All	A
Al-Mg	5005, 5050, 5052	All	A
Al-Mg	5056, 5154	All	A[c]
Al-Mg-Mn	3004, 5454	All	A
Al-Mg-Mn	5086, 5083, 5456	All	A[c]
Al-Mg-Si-Cu	6061	All	B
Al-Zn	7072	All	A

[a] Modified from Van Horn (6).

[b] Relative ratings A through E (no C through E alloys are shown for the purposes of this comparison) are in decreasing order of merit, based on exposure to sodium chloride solution by intermittent spraying or immersion. Alloys with A and B ratings can be used in industrial and seacoast atmospheres with protection.

[c] Rating may be changed for material held at elevated temperature for long periods.

pH and Resistivity

In chemical media, which includes soils and waters, pH alone does not define corrosivity. Use of aluminum is generally satisfactory within a pH range of 4 to 9. Exceptions occur when heavy metals (usually copper) are present.

Resistivity provides another insight into the potential corrosivity of soils and waters. This property indicates the relative ease with which current can flow in the media.

When used alone, resistivity cannot predict aluminum corrosion performance. For example, the alloys listed in Table 3 show excellent resistance to seawater over long periods of time. Not only do they provide satisfactory service, they display that all-important faculty of corrosion arrestment in such an aggressive environment. The resistivity of seawater is in the range of 35 ohm-cm. Rarely does a soil reach this value.

ABRASION

Culverts are subject to abrasion where flows carry considerable rock. Culvert abrasion has been treated by Koepf (8) and will not be discussed here. Aluminum's abrasion performance should generally be divorced from corrosion since most natural waters are not aggressive toward aluminum. Usually an aluminum culvert installation is of interest for either its corrosion performance or its abrasion performance. No installation was found during this inspection program in which a combination of abrasion and corrosion condition existed for the same pipe.

FIELD INSPECTION PROGRAM

Site Selection

Since the introduction of aluminum culvert, the aluminum industry has maintained an inspection program of selected installations. A listing of culvert locations initiated in 1963 provides a wide geographical representation of soils and waters and was used by the Highway Applications Committee of the Aluminum Association for this study.

A large number of inspections were made in California where a variety of exposure conditions exist. The Pacific Northwest provided mild organic acid sites. The Midwest was represented from Kansas to Ohio, and the Great Plains from Oklahoma to South Dakota. Florida provided saltwater and sand as well as dense clays. Missouri, Indiana, Ohio, and California provided sulfuric acid runoff from either natural strata or mine waste. Wisconsin offered acid peat soil exposures. Northern Michigan waters and soils contained copper in small concentrations. Virginia and Maryland provided organic acid exposures characteristic of the Middle Atlantic and Northeastern region. Thus, a wide range of exposures was accumulated. The large number of samples allows a broadly based evaluation of aluminum culverts.

In Kansas, Oklahoma, and Louisiana, where many culverts are installed on roads having similar soil and water conditions, early inspections demonstrated that performance is also similar; in these cases only representative samples were taken.

TABLE 4

RATING CLASSIFICATIONS FOR ALUMINUM CULVERT INSPECTIONS

Rating	Appearance Description	Description of Corrosion
A	Excellent	1. No observed corrosion or significant metal surface staining.
B	Very Good	1. Superficial corrosion in the form of occasional pits confined to surface and/or cladding. Pits no more than 5 percent of surface; or 2. Extensive surface staining, grey cast in alkaline exposures to orange cast in organic acid exposures.
B/C	Good	1. Significant corrosion confined to cladding. Pit frequency unlimited except that surface etching less than 50 percent of the surface on the worst square foot observed. Usually evidence of corrosion build-up in pits. Staining may accompany attack but will be incidental to the overall effect.
C	Fair	1. Attack covering more than 50 percent of the surface on the worst square foot observed with corrosion limited to cladding. Will give appearance of etched surface. Occasional pit may appear to penetrate into core.
D	Poor	1. Attack, but not perforation, of the core alloy, generally accompanied by extensive surface corrosion.
E	Very Poor	1. Perforation of the metal.

Visual Rating

A rating system was developed to insure uniform reporting of on-site observations. The log sheet, shown in Figure 1, provides for culvert location, size, slope, and flow character.

CULVERT INSPECTION REPORT

SAMPLE NO. 68-____

ROAD
STATE/COUNTY/CITY
ROUTE/PROJECT
MILE/STATION/INTERSECTION

REF. LOG NO.
TYPE INSTALLATION
DIAMETER GAUGE JOINT/SEAM
SLOPE LENGTH COATED/PAVED
INLET/OUTLET FILL HEIGHT
TERRAIN & FLOW

DATE SAMPLE BY
FLOW
ROCKS/DEBRIS
ALIGNMENT CONDITION
JOINTS CONDITION
PIPE CONDITION
COMMENT

PHOTOS B/W
PHOTOS C
SOIL
WATER
COUPON

PIPE MARKINGS

RATING OF PIPE (RATE INSIDE AND OUTSIDE SURFACES SEPARATELY)

RATING	DESCRIPTION	CORROSION	ABRASION
A	EXCELLENT	___NO CORROSION/STAINING	___NO EFFECT
B	VERY GOOD	___SUPERFICIAL CORROSION/STAINING	___SLIGHT ROUGHENING NO METAL LOSS
B/C	GOOD	___RANDOM CORROSION/STAINING	___SLIGHT EROSION LITTLE METAL LOSS
C	FAIR	___OVER 50% SURFACE CORROSION NO ATTACK OF CORE METAL	___EROSION-SLIGHT PROGRESSIVE METAL LOSS, SMALL DENTS
D	POOR	___HEAVY CORROSION ENTIRE SURFACE DEEP PITTING INTO CORE METAL	___ABRASION-SLOW PROGRESSIVE METAL LOSS, DENTS & GOUGES
E	VERY POOR	___VISIBLE PERFORATIONS	___ABUSIVE-CONSIDERABLE METAL LOSS, DENTS, GOUGES

RATING OUTSIDE
INSIDE
ABRASION

DATE INSTALLED YEARS SERVICE TO DATE
ESTIMATED LIFE (CORROSION) (ABRASION)

SOIL PH (LAB) r (LAB)
WATER PH (LAB) r (LAB)

Figure 1. Log sheet for on-site observations.

The visual rating system is described in Table 4. Similar ratings applied to the abrasion condition. Visual inspection was the principal means for determining uniformity of results throughout a culvert, or from one culvert to the next.

The interior was examined thoroughly. The invert was of greatest interest and where significant differences appeared between the invert and upper surfaces they were noted. The joints were examined for evidence of attack, cleanliness, and alignment. Where dirt was deposited in the invert a reasonable area was uncovered for inspection. Surface stain, pits, and substantial corrosion were recorded by using the rating scale.

The exterior surface of the culvert was uncovered to the extent practical within the limits of the site and the surface examined and rated for corrosion. When soil adhered to the culvert, it was wiped, washed, or lightly brushed to permit examination.

Sampling

A quart of soil taken adjacent to the culvert and a pint of water (when available) were collected for laboratory evaluation.

The final inspection step was to collect representative specimens of the metal culvert by use of a battery-driven hole saw, which removed a 1-inch diameter coupon. Samples were taken from invert, waterline, and, in some instances, the top of culverts. The orientation of the specimens was marked and coupons shipped with water and soil to the laboratory for examination. It should be noted that coupons were taken in locations where the most severe attack was observed.

Alternate Evaluation Method

It is possible to estimate the rate of corrosion of buried metal culverts by running polarization curves. The method has been published by Schwerdtfeger (9) as well as others. Equipment and methods have been reported by Lindberg (10), whose procedure permits calculation of the rate of corrosion occurring at the time of the test. In order to judge metal loss over a period of time, periodic testing is required so that an average rate may be found. The method has been tried on culverts in a number of areas but not over a long enough period to justify statements on cumulative metal loss. It was found, however, that in all cases the instantaneous corrosion rates indicated very little metal wastage. This was supported by the condition of the pipe sections.

LABORATORY EXAMINATION

The water pH and resistivity were measured using procedures and equipment specified in California Division of Highways Test Method 643-B (11). California Test method 643-B was also used as the basis for laboratory examination of the soil.

In a previous investigation (4), all soil resistivity measurements were taken in the field with a ground resistance tester (Model 263A Vibroground, Associated Research Inc., Chicago) at 2.5, 5.0, and 10-foot depths. This method was suspended in favor of the minimum resistivity technique (3).

The evaluation of metal coupons consisted of the following steps:

1. Examining visually as received from field;
2. Cleaning in chromic phosphoric acid;
3. Re-examining visually and at low magnification, rating for corrosion condition, and marking areas for metallographic sectioning, at least one section representing the most severe attack noted;
4. Preparing and polishing mounts, and then etching in 5 percent HF-10 percent H_2SO_4 for 30 to 40 seconds;
5. Photographing the complete mount at 5x, photographing areas of significant interest, and adjusting the corrosion rating if required.

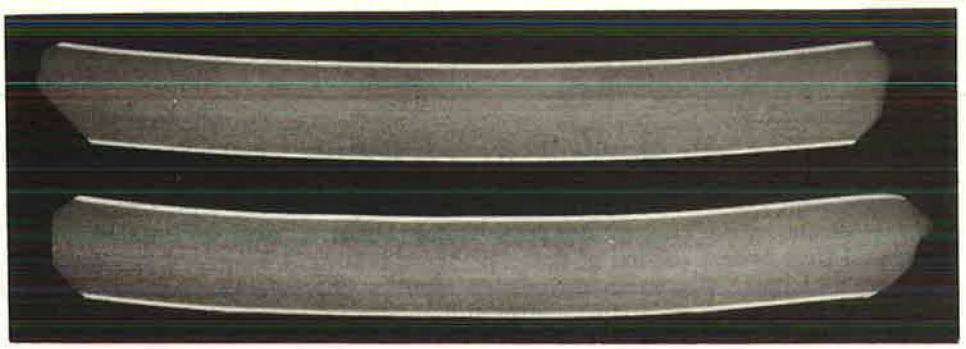
The final rating assigned to a culvert installation represents the worst condition observed on the soil side and the water side for any coupon from that culvert.

Figure 2 shows 5x metallographic mounts illustrating various ratings. Figure 3 further illustrates the condition of a B/C coupon. In Figure 2, the following is noted:

1. The cladding shows clearly as a light layer. The cladding is 5 percent of the total thickness on each side—e.g., 0.003-in. and 0.008-in. for 0.060-in and 0.164-in. thickness metal, respectively.
2. The sequence of B, B/C, and C photographs shows progression of attack on the cladding and the protection that the cladding is giving the core. Figure 3 shows the progression at 100x.
3. Only after the cladding has been expended over large areas does a significant attack of the core appear, usually in small isolated areas in the center of clad-wasted areas (D). Such attack is limited to a negligible percentage of the total culvert cross section.

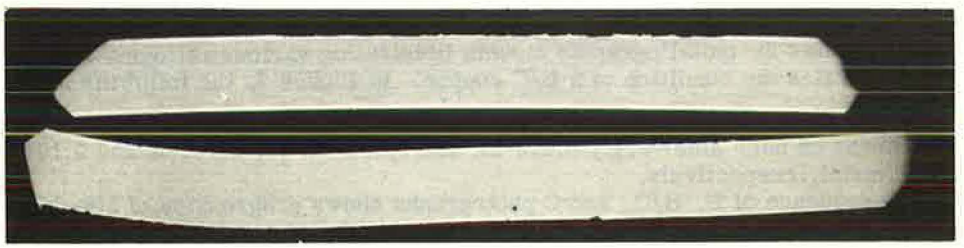
DISCUSSION OF RESULTS

Figures 4 through 7 show the number of culverts in each rating as a function of water pH, water resistivity, soil pH, and minimum soil resistivity. Each bar chart



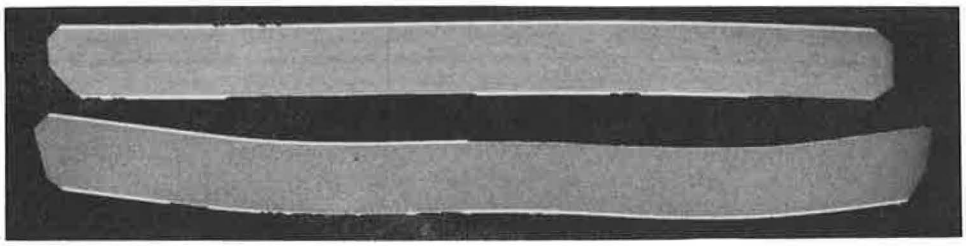
Rating A—No corrosion (Note: Cladding each side 5 percent of thickness).

Rating B—Up to 5 percent of surface attacked.

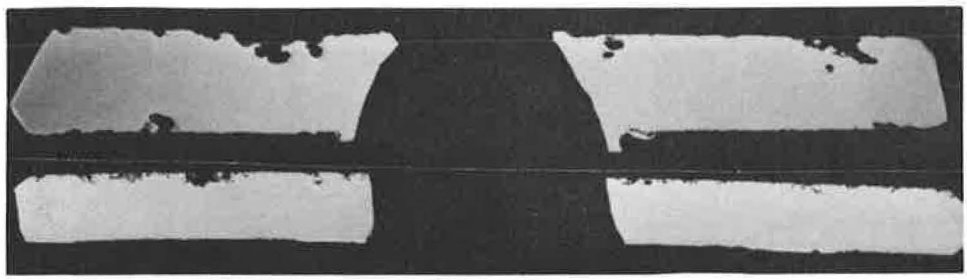


Rating B/C—5 to 50 percent of surface attacked on worst square foot (Note: Corrosion is only half depth on cladding).

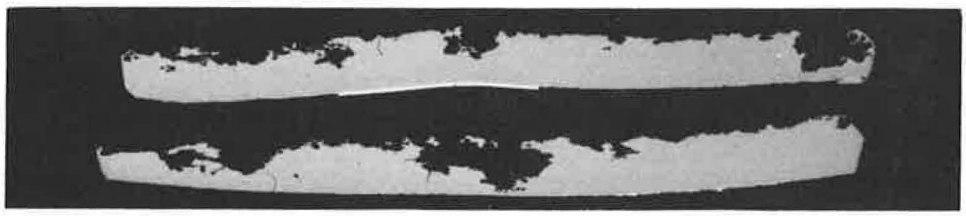
Figure 2. 5x sections showing examples of corrosion ratings.



Rating C—Over 50 percent of surface corroded on worst square foot
(Note: Corrosion confined to cladding).

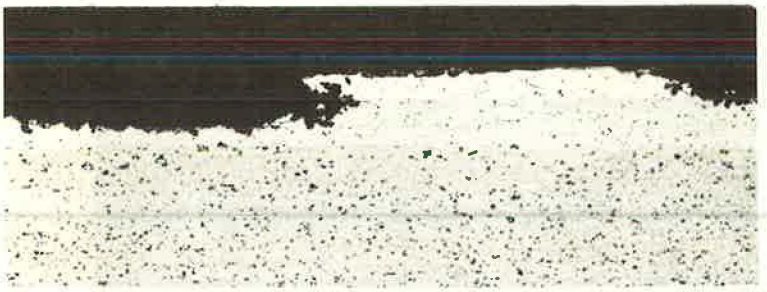


Rating D—Attack of core.



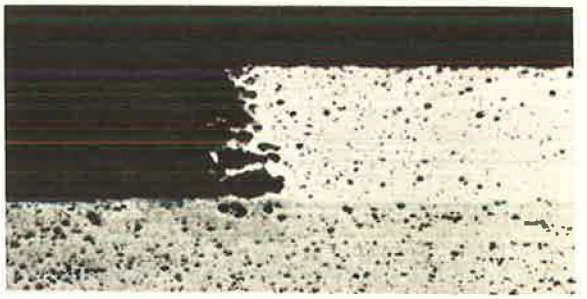
Rating E—Perforation of core.

Figure 2. (continued).



Attack limited to partial cladding thickness (100x).

Attack to full cladding thickness.



General surface appearance (5x) of a B/C-rated coupon.

Figure 3. Nature of cladding corrosion. Evaluation of coupon shows varying degrees of attack, progression of corrosion, and effectiveness of cladding.

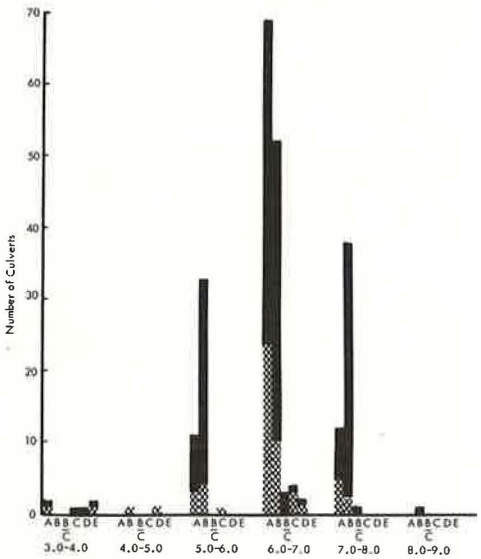


Figure 4. Culvert performance rating as influenced by water pH (cross-hatched bar represents culverts 6 years old and older).

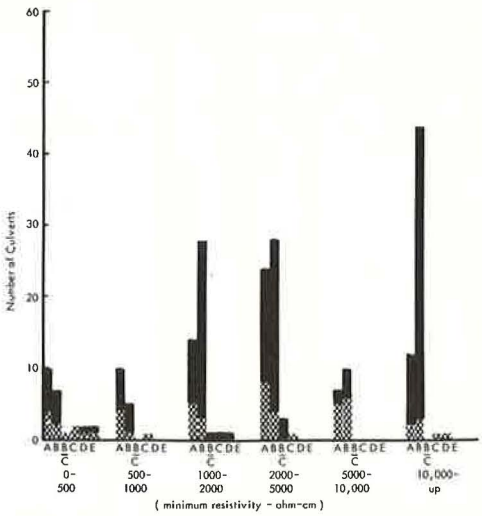


Figure 5. Culvert performance rating as influenced by water resistivity (cross-hatched bar represents culverts 6 years old and older).

designates the number of sites with 6 years or more of service, as well as the total number of sites within a category.

Most aggressive corrosion occurs at a pH below 4.0. As shown in Figure 4, exceptions to the low pH limit can occur where organic acids are responsible for the acidity of the water. The poorer ratings are attributed to sulfuric acid-containing runoff (12, 13) or to chloride-contaminated clays and mucks. Corrosive sites are characterized in Table 5. Limited data available in the pH range of 4.0 to 5.0 neither confirm nor refute the lower pH limit of 4.0, which was based on the response of aluminum to chemical environments. The Aluminum Association plans to seek additional field installations within the 4.0 to 5.0 pH range to better define this lower limit.

TABLE 5

EVIRONMENTAL DATA ON SITES PRODUCING D AND E RATINGS

Sample No.	Location	Water		Soil		Time in Service	Rating
		pH	Resistivity	pH	Min. Resistivity		
67-042	North of Maine Prairie Road, Salano, Calif.	6.9	1700	7.7	1330	5.0	D
67-180	Sweetwater Bridge, National City, Calif.	6.5	35	7.7	10.1	5.8	D
68-415	Severin Road, Port Charlotte, Fla.	6.2	35	6.7	—	6.0	E
68-449	Highway 17, Brunswick, Ga.	6.8	97	7.6	165	7.0	D
68-001	California 17, Santa Cruz County, Calif.	3.1	1440	5.4	1345	5.5	E
68-458	County Road No. 4, Meigs County, Ohio	4.5	45310	4.1	3524	8.0	D
68-461	County Road No. 33, Steudal, Pike County, Ind.	3.4	185	4.8	810	6.0	E
68-471	West of Coe, Pike County, Ind.	2.2	115	2.9	230	5.0	D

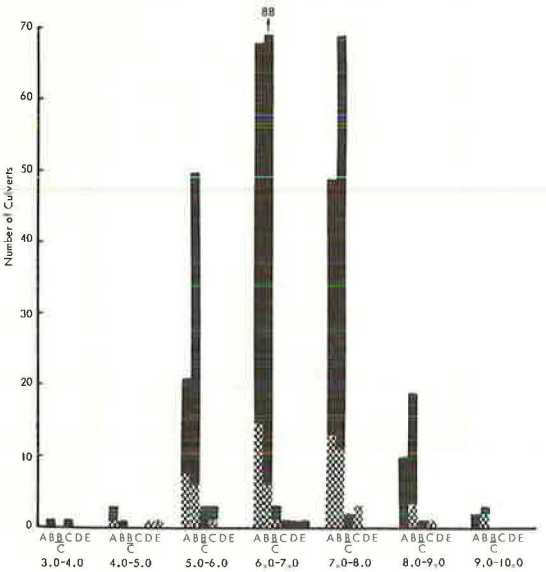


Figure 6. Culvert performance rating as influenced by soil pH (cross-hatched bar represents culverts 6 years old and older).

The data indicate that aluminum is not significantly attacked when the pH is greater than 4 and definitely will be attacked by mineral acids at pH less than 4.

Figure 5 shows lower ratings concentrated in the lowest resistivity range. Those sites responsible for the poorer ratings are listed in Table 5. Considering that low pH or muck conditions are present at these sites, the data indicate that water resistivity is not a factor affecting corrosion of aluminum culvert.

Soil pH is analogous to water pH with relation to its influence on corrosion (Fig. 6). Again the same sites listed in Table 5 are responsible for the D and E ratings throughout the pH ranges. The data support the use of uncoated aluminum culvert within a soil pH range of 4 to 9.

The influence of minimum soil resistivity is shown in Figure 7. Those sites characterized by highly acid runoff or by chloride-contaminated heavy soils (Table 5) caused lower ratings in most minimum resistivity ranges. It is interesting to note the performance of culverts in backfills with minimum resistivities below 1000 ohm-cm. Those represented by A and B ratings are saltwater-saturated granular soils, and are performing very well. Those represented by the C rating are in heavier, salt-saturated soils with some evidence of attack. Generally the attack follows the characteristics of concentration cell corrosion. The poorer ratings at the lower end are once again the acid sites or those with clay muck. The data indicate that a low-resistivity heavy soil such as clay or muck may be corrosive, but granular soils with low resistivity, and all soils with a minimum resistivity greater than 500 ohm-cm, appear to have little effect.

Field observations revealed that aluminum was subject to various degrees of staining. The degree and color of stain are known to be influenced by water chemistry (5, 14). These stains do not contribute to corrosion nor are they an indication of corrosion. The rating system provided for logging of stain as an indicator of surface appearance only.

Concentration cell corrosion has been noted when a combination of low resistivity and dense soil is encountered. The classic example is clay muck and saltwater. In this instance the poor circulation and discontinuous nature of the back-

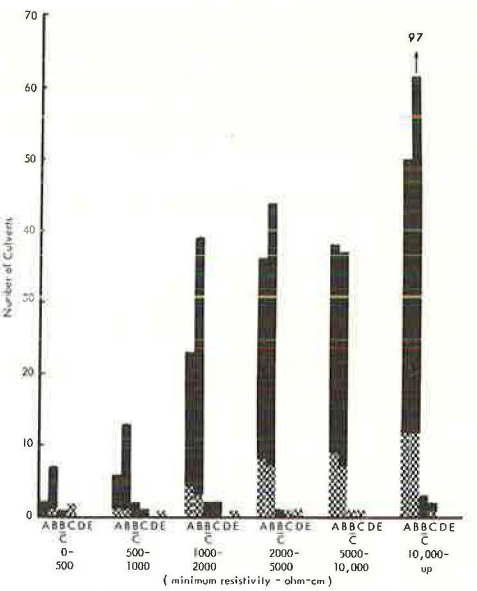


Figure 7. Culvert performance rating as influenced by soil minimum resistivity (cross-hatched bar represents culverts 6 years old and older).

fill does cause concentration cell corrosion, accelerating wastage of metal. Complete bedding and backfill of select granular material is recommended.

The field inspection revealed no selective attack in joints.

PREDICTION OF SERVICE LIFE

The prediction of culvert service life is a difficult, complex, and controversial undertaking. In the past, performance of aluminum culvert was based on one or a combination of the following: (a) service history generally less than 3 years (1, 2, 3), and (b) small sample size with detailed environmental data (2) or relatively large sample size with limited environmental data (4). This study represents the most comprehensive culvert survey undertaken to date, both as to number of culverts studied and detail on each culvert.

Researchers have not arrived at any agreement on a definition of culvert life. Haviland et al (3) suggest that point in time at which the culvert reaches a safety factor of one. Nordlin and Stratfull (1) suggest life to first perforation. It is felt that life to perforation is considered as a basis of comparison rather than an end of culvert usefulness. It must be apparent that culverts have been widely trepanned (as in the present study) to obtain specimens for examination.

For aluminum culvert, cladding and core must be analyzed separately in order to arrive at a meaningful service life figure. It is possible to estimate extent of cladding loss vs time based on coupon examination, polarization techniques, or an occasional relocated pipe. In the present study, which is based on examination of as many as five plugs from over 500 culverts, the greatest bulk of culverts showed no attack or so little attack that the cladding was not penetrated. In cases where cladding was penetrated, and therefore fulfilling its function of sacrificial protection to the core metal, less than 5 percent of the cladding was expended.

The average age of all culverts inspected in this study is 4.7 years. On this basis, the life of the cladding component is 94 years. However, this figure does not take into account the possibility that the limit of cladding effectiveness may, due to nonuniform attack, be reached before all the cladding is expended. If a 50 percent factor is assumed, and in the experience of the authors this is certainly conservative, a cladding life of 47 years is obtained. At this point in time 95 percent of the culvert wall thickness would remain—90 percent if one assumed simultaneous attack on both surfaces.

The second segment contributing to total surface life is the core material. Since core attack was not observed in 98 percent of the installations examined, it is impossible to determine pitting or weight loss rates from this study. However, valuable information may be obtained from burial studies conducted by the National Bureau of Standards, British Non-Ferrous Metals Research Association, ALCOA and ALCAN (15). These studies include the evaluation of alloy 3003, which possesses corrosion behavior very similar to alloy 3004, the core material specified for aluminum culvert. The data indicate an average pitting rate of less than 2 mils/year after a burial period of 10 years. Therefore, based on 16-gage material and again assuming that attack takes place simultaneously from both sides, a service period of 27 years may be anticipated for core material alone before initial perforation occurs. It is interesting to note that comparison of pitting rates between 5- and 10-year burial periods shows a 33 percent reduction for the longer service. This would indicate that a straight-line pitting rate may not be appropriately applied to the aluminum core alloy.

The combined effectiveness of cladding and core material results in an expected service period of 74 years before the first perforation is reached.

Application of weight loss data results in longer average service life. Ten-year burial figures show an average loss of 0.62 percent per year. If present-day design criteria are applied, a safety factor of two must be used, since buckling is controlled by this value. Applying the weight loss rate results in an 81-year period before half the core material is expended.

Again, combining the effectiveness of cladding and core material results in an expected service life of 128 years before structural integrity of the pipe wall is impaired.

CONCLUSIONS

Aluminum alloy culvert can be used where minimum soil resistivity is above 500 ohm-cm, and where pH of water and soil falls within the range of 4 to 9. Strong mineral acids, principally sulfuric, do attack uncoated aluminum culvert when the pH is less than 4.0.

The need for continuing evaluations is well recognized. The tedious portion of conducting such a survey—that of physically locating installations of particular interest—has been accomplished. Periodic inspections will report on performance of pipe in threshold environments, thereby more clearly defining upper and lower limits of water and soil parameters. Space limitations in this report precluded the inclusion of detailed data pertaining to each site. The Aluminum Association will be pleased to make this information available to any State Highway Department or federal agency upon written request.

REFERENCES

1. Nordlin, Eric F., and Stratfull, R. F. A Preliminary Study of Aluminum as a Culvert Material. Highway Research Record 95, p. 1-70, 1965.
2. Berg, Vernon E. Culvert Performance Evaluation. Washington State Highway Commission.
3. Haviland, John E., Bellair, Peter J., and Morrell, Vincent D. Durability of Corrugated Metal Culverts. Highway Research Record 242, p. 41-66, 1968.
4. Lowe, T. A., and Koepf, A. H. Corrosion Performance of Aluminum Culvert. Highway Research Record 56, p. 98-115, 1964.
5. Godard, Hugh P., Hepson, W. B., Bothwell, M. R., and Kane, Robert L. The Corrosion of Light Metals. John Wiley and Sons, 1967, Chapters 1 and 2.
6. Van Horn, Kent R. Aluminum, Vol. 1, p. 209-238, 257-276, 1967.
7. Symposium on Atmospheric Corrosion of Non-Ferrous Metals. ASTM Spec. Tech. Publ. 175, p. 21-44, 1955.
8. Koepf, A. H. The Mechanisms of Abrasion of Aluminum Alloy Culvert, Related Field Experiences and a Method to Predict Culvert Performances. 1968.
9. Schwerdtfeger, W. T. A Study of Polarization Techniques of the Corrosion Rates of Aluminum and Steel Underground for Sixteen Months. Jour. of Research, National Bureau of Standards, Vol. 65C, No. 4, Oct.-Dec. 1961.
10. Lindberg, R. I. Method of Estimating Corrosion of Highway Culverts by Means of Polarization Curves. Highway Research Record 204, p. 1-10, 1967.
11. Beaton, J. L., and Stratfull, R. F. Field Test for Estimating Service Life of Corrugated Metal Pipe Culverts. HRB Proc., Vol. 41, p. 255-272, 1962.
12. American Standard Recommended Practice for Drainage of Coal Mines. Bureau of Mines Bull. 570 (M6.1-1955, UDC622.5).
13. Braley, S. A. Acid Drainage From Coal Mines. Trans. AIME (Mining Branch), Vol. 190, p. 703-707, 1951.
14. Juniere, P., and Sigwalt, M. Aluminum. Chemical Publishing Co., New York, p. 28-30.
15. Godard, Hugh P. Discussion of Ref. 1, Highway Research Record 95, p. 33-39, 1965.