CORROSION PERFORMANCE OF ALUMINUM CULVERTS
SECOND PROGRESS REPORT

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ABSTRACT: To permit a more thorough evaluation of the corrosion performance of aluminum as a culvert material, 14 Upper Peninsula test culverts (10 aluminum, 4 galvanized steel) have been re-inspected and their environmental conditions more completely defined (Research Report R-569, October 1965). The degree of corrosion and probable service life of these culverts were studied by: visual observation; chemical analysis of the natural and backfill soils and the water traversing the culverts; soil resistivity measurements; polarization voltage measurements; and metallurgical examination. Resulting data revealed evidence of minor corrosion or mild corrosive conditions at nearly all culvert sites. Corrosion is largely confined to small amounts of white corrosion product or superficial pitting. Only small amounts of corrosion inducing chemicals were found in the soils and water surrounding most culverts. Four culverts show slightly more serious corrosion and/or corrosive conditions. It was concluded that: (1) none of the test culverts display severe corrosion or corrosive conditions, and (2) aluminum appears to be performing satisfactorily as a culvert material with respect to corrosion. It was recommended that: (1) a visual inspection of culvert inverts be performed every three years, (2) a visual inspection of the culvert exverts be performed every six years, and (3) a second soil resistivity survey and a second sampling of the soil and water be considered.

KEY WORDS: culvert materials, aluminum alloy, corrosion, corrosive environments, soil chemical properties, resistivity surveys, metallography.

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INTRODUCTION

This is the second in a series of reports, which are being filed after every inspection of aluminum culvert installations in the Upper Peninsula.

Progress Report No. 1 (R-569, March 1966) reports the history, background, and physical characteristics of certain aluminum culvert installations in Michigan. The first report briefly discusses corrosion theory, selection of test culverts, and preliminary appraisal of the corrosion performance of the test culverts based on data from the first inspection. A brief summary of Progress Report No. 1 follows:

The installation of 27 aluminum culverts (fabricated from Alclad 3004-H34 sheets) on relocated US 2 in Gogebic County (Project F 27023B, C3) was completed during the summer of 1965. Alclad aluminum sheet has a sandwich-type construction in which an aluminum-alloy core is covered with a thin surface layer of pure aluminum or an aluminum alloy of different composition than the core. The thin surface layer is anodic to the core alloy thus providing similar electrolytic protection to the core as galvanizing does to steel.

Six of the 27 culverts were selected during the first inspection to serve as test samples. Four galvanized steel culverts from the same project and an adjacent project (F 27023D, C4) were selected as comparison references within the same environment. In addition to the State culverts, four county road installations of aluminum culverts in Gogebic and Ontonagon Counties were chosen to obtain information on the corrosion performance of aluminum in various other environments. The 14 test culverts were visually inspected and the natural and backfill soils and water checked for pH. The results from the inspection and pH data revealed no serious corrosion or apparent corrosive environment for either type of culvert. The report recommended that a second field inspection be conducted, resample the soils and waters for a more complete chemical analysis, and selection of culvert locations for soil resistivity measurements.

In view of the findings of the first inspection, subsequent review of published data (1, 2), and contacts with aluminum culvert manufacturers; a more comprehensive study--designed to define the culvert environmental conditions--was considered necessary before corrosion performance could be realistically evaluated. Although this study was confined to the present Upper Peninsula installations, it is believed that some correlation with other areas would be possible if the scope of the project is later broadened to include Lower Peninsula culverts. The following operations were proposed to obtain information for evaluating the corrosion performance of the culverts.

1. Inspect the culvert inverts at appropriate intervals to determine the frequency and depth of pits due to corrosion.

2. Sample the natural and backfill soils and the water traversing the culverts; determine their pH and analyze for substances known to influence the corrosion of aluminum. Take samples after the spring thaw, and in late summer.

3. Inspect the soil surface side of the test culverts about every four years for a minimum of 12 years.

4. Conduct soil resistivity measurements during more than one season of the year.

5. Measure polarization voltages as a possible method for predicting corrosion rates in weight-loss/unit-area/year.

6. Cut samples from the test culverts for laboratory metallurgical analysis.

The second inspection, conducted during the week of August 14, 1967, included all of the above tests except No. 3, examination of soil surface side of the culverts, and No. 4, soil resistivity measurements. Soil resistivity measurements were conducted the week of August 7, 1967. Examination of soil surface side of the culverts will be included during the next scheduled inspection trip.

The procedures used (with accompanying theoretical background where applicable), results, and a discussion of the results are reported below.

VISUAL INSPECTION

The location, properties, and environmental site conditions of each test culvert are given in Table 1. The sites on US 2 generally exhibit poor drainage conditions and ponded water was noted in many culverts. The county installations displayed much better drainage patterns. Inspection of the culverts was hampered by high water levels, sand and silt in the inverts, and overgrowth vegetation (Fig. 1). Examination of the invert (water side) surface was generally limited to the area above the existing water level and to the area near the ends. When water levels were low enough to permit cleaning the bottom of the invert, a thorough inspection was conducted. Corrosion conditions at each culvert site are described in the following notes.

Galvanized Steel Culverts, US 2

Sta. 96+00. The visible area of the invert was in excellent condition. The only detectable corrosion was confined to some white and red corrosion products on several rivet heads.

Sta. 549+50. A small amount of white and red corrosion on rivet heads and at horizontal plate joints was noted at both ends. Several random spots of incipient white corrosion up to 1/2 in. diam were noted on the first ten corrugations from the south end; maximum pit depth appeared to be less than 0.5 mil. The bottom of the invert at the south end showed moderate soil staining, but no evidence of corrosion.

Sta. 622+00. Many spots of white corrosion up to about 1/4 in. diam were noted (Fig. 2). These spots covered about a 5-in. arc in the upper part of the invert, starting from a point about 2 ft from the north end and extending about 15 ft south. The maximum spot density was about 8 to 10 per sq in. with a maximum pit depth of about 1 mil. A small amount of white and red corrosion on rivet heads and at horizontal plate joints was also noted. The bottom of the invert was badly soil stained, but no pits or perforations were detected.

Sta. 643+00. A small amount of white and red corrosion on rivet heads and at horizontal plate joints was evident. Several random spots of white corrosion up to 1/4 in. diam were observed near both ends, but the coating was not seriously impaired. The bottom of the invert was badly soil stained, but not visibly attacked.

TABLE 1
PHYSICAL CHARACTERISTICS
(as of August 7, 1967)

	Corrugated Pipe Type	Location	Dimensions			Embedment Depth, ft	Years of Exposure	Natural Soil Series	Stream Characteristics		
			Length, ft	Diameter, in.	Gage				Depth, Deepest end, in.	High-Water Line, in.	Abrasiveness
F27023D, C4	Steel	Sta. 643+00	140	24	14	14.3	2.7	Adolph	4	16	Very slowly flowing. 4-in. sand and silt.
	Steel	Sta. 549+50	140	24	14	12.5	2.7	Adolph	1	12	Stagnant. 3-in sand and silt.
	Steel	Sta. 622+00	104	24	16	6.5	2.7	Adolph	1	12	Stagnant. 2-in sand and silt.
F27023B C3	Steel	Sta. 96+00	88	36	14	5.3	2.1	Peat	19	21	Stagnant.
	Aluminum	Sta. 114+50 Rt	56	18	16	5.0	2.1	Skanee	1	4	Slowly flowing. 1-in sand and silt.
	Aluminum	Sta. 121+75	72	24	14	5.7	3.3	Adolph	8	10	Stagnant. 3-in sand and silt.
	Aluminum	Sta. 181+10	116	36	8	10.8	3.6	Peat	10	15	Slowly flowing. 2-in sand and silt.
	Aluminum	Sta. 330+00	80	24	14	6.2	3.1	Peat	3	11	Stagnant. 3-in sand and silt.
	Aluminum	Sta. 420+35	120	30	14	9.0	3.0	Peat	1	21	Stagnant. 9-in sand and silt.
	Aluminum	Sta. 458+50	100	36	8	16.0	3.5	Skanee	3	20	Stagnant. 6-in sand and silt.
COUNTY	Aluminum	Bessemer	44	30	14	4.0	3.8	Adolph	1-1/2	not visible	Flowing about 1 ft/sec; invert fairly clean
	Aluminum	Bruce Crossing	36	84* 60	8	4.0	3.8	Roselawn	15	20	Slowly flowing. Small amount mud and silt. Many large stones
	Aluminum	Ewen	41	84* 60	8	4.0	3.0	Ontonagon	15	18	Very slowly flowing. 2 to 3-in clay and silt
	Aluminum	Wood Spur	36	24	14	2.5	3.8	Ontonagon	6	10	Stagnant. Small amount of silt.

* Arched culverts.

North end, Sta. 181+10.

North end, Bruce Crossing.

South end, Sta. 96+00.

Figure 1. Typical culvert site conditions.

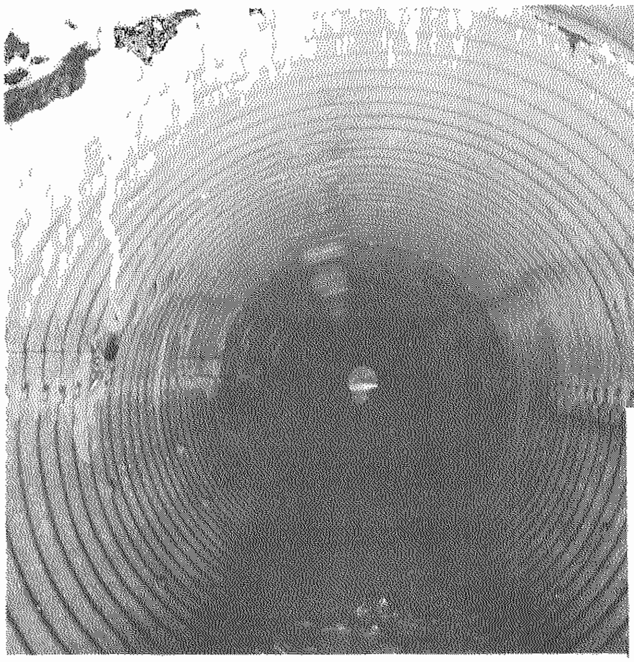

Figure 2. Galvanized steel culvert, Sta. 622+00. Upper left portion shows area of white corrosion.

Figure 3. Aluminum culvert, Sta. 181+10. White staining or etching evident at the horizontal plate joint.

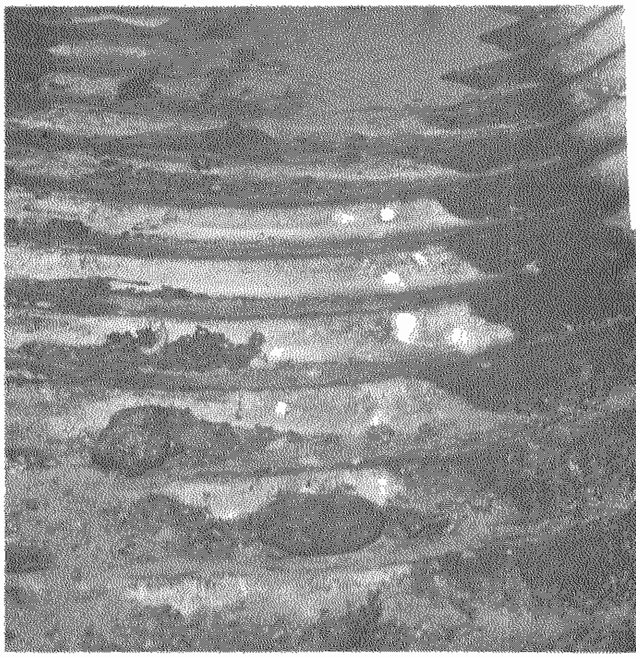

Figure 4. Aluminum culvert, Sta. 181+10. White spots near center are pitted areas that were beneath tightly adhering soil nodules. Pits apparently penetrated to the core alloy.

Aluminum Culverts, US 2

Sta. 114+50. Several areas of white corrosion near the west end were noted. The maximum pit size was about 1/4 in. diam with a maximum frequency of 2 to 3 per sq in.; maximum pit depth was about 1 mil. The east end invert showed no attack.

Sta. 121+75. Several white spots up to about 1/4 in. diam were observed along the high water line at both ends. A small amount of white stain or etch and brown soil staining at several plate joints was also noted. Maximum pit depth was about 1 mil.

Sta. 181+10. Considerable soil staining was evident at many horizontal plate joints. Superficial white staining or etching was also apparent at many of the soil stained joints. A gelatinous corrosion product was visible and the etching was more severe than in other areas at the fourth joint from the south end (Fig. 3). The cladding was not penetrated. Several tightly adhering incrustations or nodules of soil up to about 1/4 in. diam were observed in the bottom of the invert at the south end. Beneath each nodule was a pit that appeared to penetrate the cladding to the core metal, although the core metal was not attacked (Fig. 4). Several leaks at both horizontal and vertical plate joints were observed near the middle of the culvert.

Sta. 330+00. A small number of minor corrosion spots up to 1/4 in. diam with a maximum frequency of 3 to 4 per sq in. were observed at the former air-water interface about 5 in. above present water level. Some soil staining was noted at horizontal plate joints.

Sta. 420+35. A few areas of superficial corrosion up to 1/4 in. diam with a maximum frequency of 5 to 6 per sq in. were noted near the south end. Some soil staining at horizontal plate joints could be seen from the north end.

Sta. 458+50. Numerous white spots were visible along former high water line at the north end. The spots were spaced about 1/4 to 1 in. apart with a maximum diameter of about 1/4 in. The maximum pit penetration was about 1 mil. These spots were noted during the first inspection and do not appear to have increased in size or penetration. The culvert was badly soil stained throughout the bottom half of the invert.

Aluminum Culverts - County

Bessemer. The entire invert was covered with many spots of white stain or etch up to about 1/4 in. diam with a maximum frequency of 3 to 4 per sq in. Three or four feet of exposed exvert of this culvert were covered with many white blotches up to 1 in. diam with a maximum frequency of 8 to 10 per sq ft (Fig. 5). The corrosion attack on both invert and exvert appears to be of the same type and to be superficial. The maximum depth of penetration was estimated to be 0.5 mil.

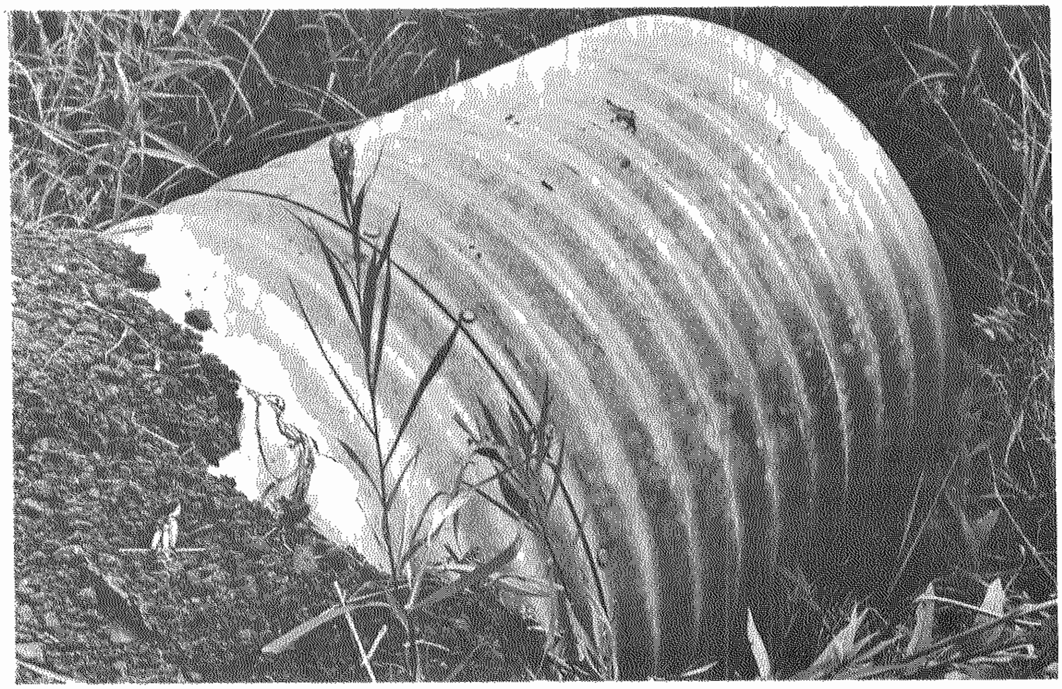

Figure 5. Aluminum culvert, Bessemer (exvert). Spotted or blotchy appearance typifies the superficial corrosion referred to as white stain or etch.

Wood Spur. The invert was badly soil stained below the high water line. A number of corrosion spots up to about 1/4 in. diam were spaced about 1/2 to 1 in. apart along the high water line. A small amount of incipient white staining or etching in spots up to 1/4 in. diam, with a maximum frequency of 3 to 4 per sq in. was noted near the east end. The maximum pit depth was about 1 mil. The culvert was deformed about 4 in. out of round.

Bruce Crossing. Superficial white surface stain or etch spots were prevalent over about 50 percent of the invert area. Most spots were 1/16 to 1/8 in. diam. A few spots approached 1/4 in. diam with a maximum frequency of about 10 per sq in. This culvert was also deformed several inches near the center, probably due to heavy loads and insufficient fill height.

Ewen. A number of small random surface stain spots, mostly 1/8 to 1/4 in. diam were noted. The maximum spot frequency was about 2 to 3 per sq in. The high water level precluded inspecting the invert bottom where pits that appeared to have perforated the cladding were noted during the first inspection.

The visual inspection of the test culverts revealed no serious corrosion of the galvanized or aluminum culverts. Corrosion of the galvanized steel culverts was generally confined to rivet heads, plate joints, and random spots of minor white rust. Station 622+00 exhibited the most severe attack with many spots of white corrosion in the upper invert. Corrosion of the aluminum culverts was generally confined to small spots of corrosion at, or near, former water-air interfaces and to random spots or blotches of white stain or etch. The aluminum culvert at Station 181+10 displayed the most severe corrosion. Several pits up to 1/4 in. diam in the bottom of the invert appeared to penetrate the cladding to the core alloy. Many culverts of both types had reddish-brown soil stains at plate joints and in the bottom of the invert.

CHEMICAL ANALYSIS

Soil chemistry is believed to be a factor in the corrosivity of soils to metals. Certain chemical elements in solution such as copper, iron, calcium, nickel, cobalt, and the anions (negatively charged particles) sulfate and chloride are believed to accelerate the corrosion of aluminum. Reported data do not define amounts of these materials above which corrosion is known to occur. Accelerated corrosion of aluminum has been reported in water containing 0.09 ppm of copper, 0.08 ppm cobalt, and 0.03 ppm nickel (2). It is further reported that aluminum, when protected by its natural oxide film, is relatively inert to corrosion within a pH range of 4 to 9 (1).

Two series of soil and water samples were analyzed for materials reported to accelerate corrosion of aluminum. The first series was taken in early May 1967 to define the culvert environments immediately after spring thaw when the culverts are subjected to cool temperatures, high humidity, high soil moisture content, and large volumes of run-off water containing varying amounts of de-icing salts. The second series of samples were taken at the time of the inspection during mid-August 1967 to define the culvert environments during the normal hot, dry period of late summer.

TABLE 2
CHEMICAL DATA

Station No. or Location	Natural Soil											Backfill Soil											Water								
	pH			Chloride, ppm		Calcium, ppm		Iron, ppm		Moisture, percent		pH			Chloride, ppm		Calcium, ppm		Iron, ppm		Moisture, percent		pH			Chloride, ppm		Calcium, ppm		Iron, ppm	
	Oct 1965	May 1967	Aug 1967	May 1967	Aug 1967	May 1967	Aug 1967	May 1967	Aug 1967	May 1967	Aug 1967	Oct 1965	May 1967	Aug 1967	May 1967	Aug 1967	May 1967	Aug 1967	May 1967	Aug 1967	May 1967	Aug 1967	Oct 1965	May 1967	Aug 1967	May 1967	Aug 1967	May 1967	Aug 1967	May 1967	Aug 1967
96+00	7.2	6.35	7.08	0	18	83	106	0.8	0.6	46.8	22.0	8.4	6.81	6.92	8	8	64	39	0.8	0.2	6.3	2.5	8.0	7.40	7.29	496	340	206	176	0.0	0.0
114+50Rt	5.9	4.29	5.94	0	25	34	59	9.9	2.9	30.9	21.8	8.5	7.27	7.03	5	6	9	54	0.2	0.4	5.4	3.3	6.7	7.00	7.11	43	66	18	41	0.8	1.0
121+75	6.8	5.48	6.48	10	30	46	55	6.3	5.8	55.4	37.0	---	6.89	7.12	9	4	28	35	1.2	0	10.6	3.5	6.3	6.68	7.48	7	123	6	95	0.2	0.0
181+10	6.2	---	6.87	---	11	---	51	---	7.8	---	14.3	8.1	---	6.85	---	45	---	100	---	1.2	---	23.4	8.2	---	7.61	---	30	---	51	---	0.0
330+00	4.9	4.85	4.83	0	125	38	110	7.7	3.1	28.8	97.0	7.6	6.93	6.78	0	0	26	51	0.5	1.1	7.9	11.2	7.6	6.02	7.30	0	216	5	135	0.2	1.5
420+35	5.1	4.06	4.02	0	22	37	53	19.2	12.6	52.6	29.9	8.5	5.61	6.29	18	42	42	25	4.2	3.1	26.2	25.6	7.0	6.65	6.71	110	610	48	299	1.9	35
458+50	6.2	3.92	5.43	18	13	153	16	7.8	2.0	57.7	21.7	8.2	6.81	7.14	0	7	24	35	1.6	0	12.1	7.6	6.2	5.92	6.79	7	280	5	221	0.6	0.2
549+50	5.4	4.11	4.14	0	104	14	42	3.3	28.9	27.0	29.7	5.8	5.20	6.05	12	6	15	15	0.5	0.7	11.3	10.2	6.2	6.15	6.69	14	302	6	100	1.5	1.7
622+00	5.1	3.72	3.98	14	72	4	48	23.3	40.0	37.1	44.2	6.6	5.40	6.13	0	17	19	2	1.2	1.0	3.9	3.7	5.6	5.28	6.78	25	47	7	52	0.8	4.6
643+00	5.2	3.69	3.40	119	1834	76	160	80.1	67.5	99.5	221.	7.1	5.34	5.76	6	0	22	4	1.2	0.5	20.8	4.8	5.4	5.37	6.00	18	22	5	5	0.6	4.1
Bessemer	6.0	5.28	6.61	26	83	3	33	1.9	1.3	31.8	26.8	6.9	6.41	6.79	0	33	45	61	1.0	6.9	6.3	18.3	7.4	7.39	7.58	18	43	21	47	0.6	0.7
Woodspur	6.4	6.19	5.86	0	10	125	129	0.5	6.5	57.4	34.1	6.7	5.82	6.02	0	37	68	91	3.2	6.9	29.7	15.0	8.0	7.19	7.45	71	210	31	93	0.6	0.0
Ewen	6.5	7.40	7.20	9	14	96	153	0.1	2.6	45.0	18.2	8.0	7.50	7.21	29	9	122	27	0	1.1	19.7	14.1	7.4	7.08	7.09	20	35	13	16	1.7	0.4
Bruce Crossing	4.7	4.90	5.90	20	33	40	88	4.2	0.4	42.8	44.5	8.2	7.12	7.15	0	6	36	19	0	0	9.0	4.5	7.0	6.80	7.10	0	25	7	21	1.1	1.2

TABLE 3
SOIL RESISTIVITY VALUES

Depth in Feet	Resistivity in OHM-CM																									
	Station 643+00		Station 549+50		Station 622+00		Station 96+00		Station 114+50Rt		Station 121+75		Station 181+10		Station 330+00		Station 420+35		Station 458+50		Bruce Crossing		Ewen		Woodspur	
	North	South	North	South	North	South	North	South	East	West	North	South	East	West	East	West	North	South	North	South	North	South	North	South	North	South
2	113,350	88,630	46,300	81,100	104,660	83,960	40,860	64,750	77,170	142,540	63,250	65,300	55,120	52,910	63,320	72,760	59,410	53,650	52,330	56,180	83,410	62,320	11,150	10,440	5,390	37,087
4	79,090	67,140	200,000	89,260	53,600	111,700	27,440	57,530	41,480	93,400	32,960	25,640	37,750	39,260	36,730	38,050	24,580	19,400	19,990	23,850	38,620	96,710	108,830	32,150	3,560	1,990
6	40,470	38,240	5,960	46,250	26,960	42,300	25,690	39,830	16,520	39,420	18,450	16,620	27,070	28,660	23,850	20,850	9,230	8,200	7,290	7,020	18,450	41,030	22,470	28,090	3,250	3,400
8	41,610	25,570	22,790	23,480	18,230	22,720	15,880	23,390	10,020	16,230	15,130	10,890	19,720	22,030	15,740	14,320	5,800	5,760	3,080	4,820	10,470	22,000	6,290	13,470	3,490	4,050
10	22,850	18,770	11,010	14,390	12,870	14,120	10,800	13,200	8,650	9,880	12,670	9,930	16,260	14,500	10,650	10,320	4,220	4,880	2,640	4,100	5,750	10,600	2,810	5,220	4,040	5,060
12	22,160	23,730	7,910	11,170	11,180	9,340	8,180	8,510	7,610	7,030	18,960	18,050	12,720	13,170	8,140	8,360	4,390	5,600	8,300	3,800	3,630	8,160	1,490	2,230		
14	20,500	18,370	6,840	10,780			5,380	5,420					10,160	10,220			5,950	4,760	5,510	5,760	2,450	8,450	2,500	1,180		
16	17,510	23,360	6,940	6,570			4,790	4,310					8,110	7,560					2,330	7,210						
18	15,890	13,200	5,740	7,000									8,250	7,370					4,500	12,410						
20	16,440	18,970																	2,530	3,710						
22	12,830	11,140																	3,310	17,470						

However, unseasonable rains the previous week resulted in high water levels and high soil moisture at many culvert sites. Thus, conditions were not typical for the summer season. Approximately 1 kilogram each of the water traversing the culverts and of the natural and backfill soils were taken at each sampling. The moisture content of the soils was determined by the Standard Method of Laboratory Determination of Moisture Content of Soil, ASTM D-2216. By this method the moisture content of soil is expressed as the ratio of the weight of water in a given soil mass to the weight of the solid particles. The weight of water is determined by measuring the weight loss of a soil sample after drying to constant weight at 110 ± 5 C. Moisture content of the soil (w) is calculated as follows:

$$w = \frac{\text{weight of moisture}}{\text{weight of oven dry soil}} \times 100$$

The dried soil samples were extracted with distilled water for chemical analysis of the water soluble fraction. Chemical analysis of the water and the water extracts of the soils were performed, where possible, using procedures described in Standard Methods of Chemical Analysis (3). The chemical data and soil moisture content are given in Table 2. The pH measurements from the first inspection (October 1965) are included for comparison.

Examination of the chemical data reveals the presence of chemicals reported to influence corrosion at several culvert sites. The water at Sta. 96+00, 330+00, 420+35, 458+50, 549+50, and at Wood Spur contained calcium and chloride in relatively high amounts.[1] The water at Sta. 420+35 also showed an iron content of 35 ppm. The backfill soils (in which culverts are embedded) show relatively high amounts of calcium and chloride at Sta. 181+10, Wood Spur, and Ewen. Station 181+10 also showed 43 ppm of sulfate. The natural soils (not in contact with the culverts) have relatively large amounts of chloride at Sta. 330+00, 549+50, and 643+00; calcium at Sta. 96+00, 330+00, 458+50, 643+00, Wood Spur, and Ewen; iron at Sta. 420+35, 549+50, 622+00, and 643+00. Station 181+10 showed 23 ppm of sulfate. No nickel, copper, or cobalt were detected at any culvert site. The data further reveal pH values generally near neutral for the waters and backfill soils, and generally quite acid for the natural soils. The natural soils at Sta. 420+35, 458+50, 622+00 and 643+00 are especially acidic. In

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[1] After reviewing available information, arbitrary values of 50 ppm chloride, 100 ppm calcium, and 10 ppm iron were set as relatively high amounts.

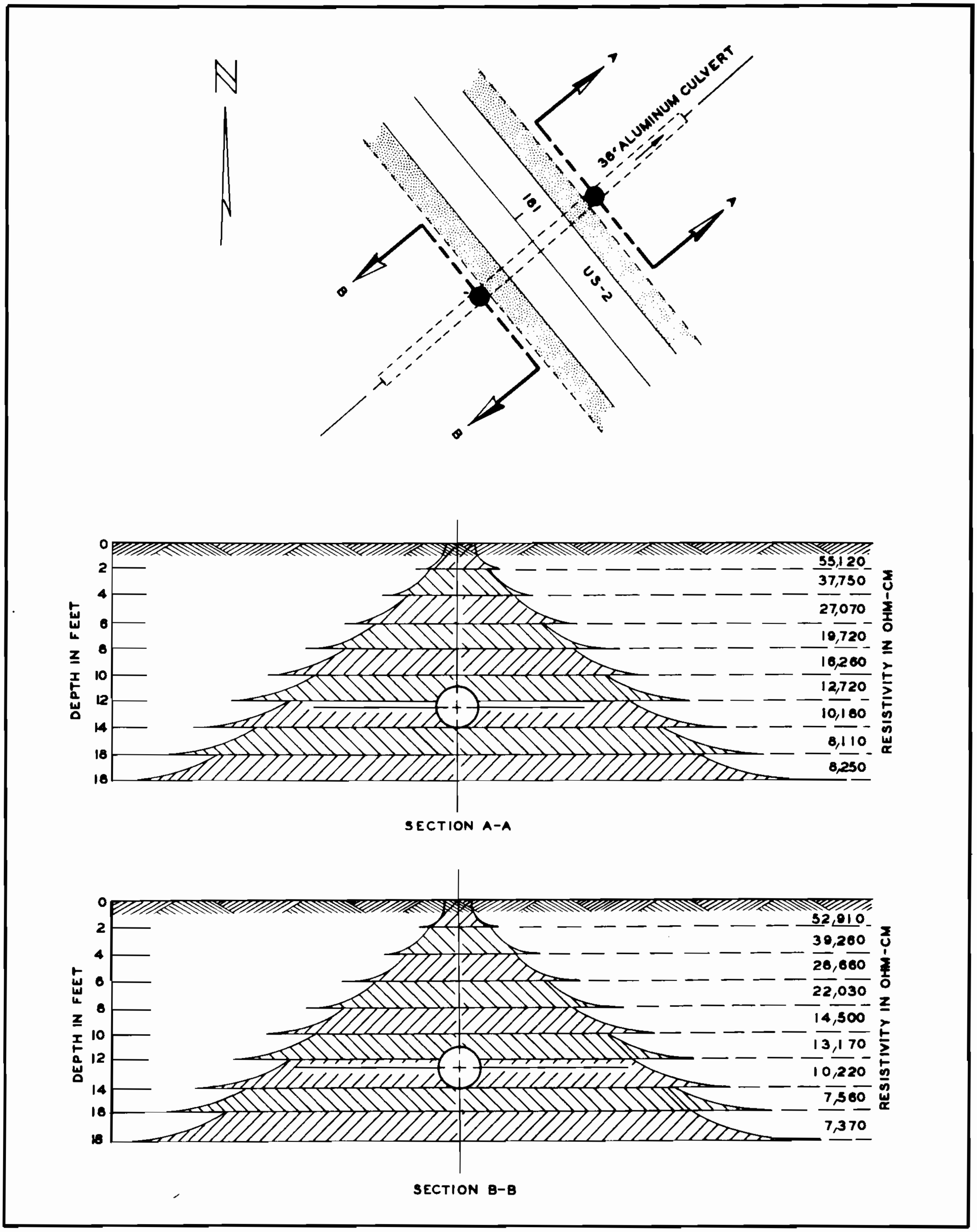


Figure 6. Aluminum culvert, Sta. 181+10. Plan shows typical relationship of the resistivity soundings to the roadway and the culvert.

general, the chemical content of the soils and water remained fairly constant or increased somewhat from the spring to summer samplings. With the exception of the Wood Spur culvert, which is backfilled with natural soil, the natural soil data should be given less weight than the water and backfill soil data, since this soil is not directly in contact with the culverts. It should receive some consideration, however, since the waters traversing the culverts are in contact with these soils and would likely extract soluble chemicals. The chemical data indicate that no serious corrosion condition exists at any of the test culvert sites. Several culverts, notably Sta. 96+00, 181+10, 458+50, 643+00, Wood Spur, and Ewen, have sufficient amounts of corrosion-inducing chemicals present in their environment to justify close observation and possible resampling of their soils and waters during subsequent inspections.

SOIL RESISTIVITY MEASUREMENTS

Since corrosion is an electrochemical phenomenon, resistivity is one of the most commonly used measurements for indicating soil corrosivity (1). The lower the soil resistivity, the higher the conductivity and, accordingly, the greater the tendency for the soil to enhance corrosion by providing a more efficient electrical path. Soil resistivity is influenced by the nature and quantity of chemicals present, and by the temperature and moisture content of the soil. The higher the temperature and moisture content, the lower the soil resistivity is likely to be. Since soil temperatures and moisture contents are expected to vary widely throughout the year, soil resistivities are subject to wide variation.

A soil resistivity survey of the test culverts, with the exception of the Bessemer culvert which has an asphalt surface layer over the backfill, was performed by the Testing Laboratory Section during the week of August 7, 1967. Further surveys at different seasons of the year were to be considered pending evaluation of the data from the first survey. The resistivity measurements employed the Wenner electrode configuration (4). Two resistivity soundings were conducted at each culvert site, just outside the roadway shoulder and directly over the culverts. Two-foot resistivity increments were used for all soundings extending from the ground surface to one to three increments below each culvert.

The typical area plan shows, schematically, the general relationship of the soundings to the roadway and to the culverts (Fig. 6). The resistivity values obtained at each site are given in Table 3.

The data show a general, but erratic, decrease in soil resistivity as depth increases. This is not surprising, since some of the conditions that influence soil resistivity (moisture, temperature, and chemical content) change with depth. The resistivity values at all except one of the culvert sites are well above a suggested threshold value of 1500 ohm-cm, below which corrosion of aluminum may occur. The county culvert at Ewen had two resistivity values below 1500 ohm-cm. One value of 1490 ohm-cm was recorded at the 10- to 12-ft increment at the north end, and the other of 1180 ohm-cm at the 12- to 14-ft increment at the south end. These conditions are not considered serious since only two measurements out of 14 were slightly below 1500 ohm-cm and were at depths 3 ft or more beneath the culvert.

Further soil resistivity surveys are not recommended at this time since the data from this survey probably represent near-minimum soil resistivity values, and accordingly, the most severe corrosion conditions expected at any time of the year.

POLARIZATION VOLTAGE MEASUREMENTS

A relatively new technique of predicting the rate of metallic corrosion, and thus service life, of buried metal materials has been investigated. The polarization curve method has been successfully used by Schwerdtfeger (5) for measuring the corrosion rate of specimens of buried aluminum and steel pipe, and by Lindberg (6) as a means of estimating the corrosion rate of aluminum and galvanized-steel highway culverts. The polarization curve method involves the application of sufficient electrical current to stop the corrosion action of the soil on a corroding specimen (culvert). The current is added in incremental amounts and recorded along with the corresponding change in soil-to-culvert potential. A plot of the change in pipe-to-soil potential vs the logarithm of the current produces a polarization curve, such as shown in Figure 7. The current at the points of abrupt change in slope or "break points" in the respective anodic and cathodic polarization curves determine anodic current (Ia) and cathodic current (Ic). The corrosion current,

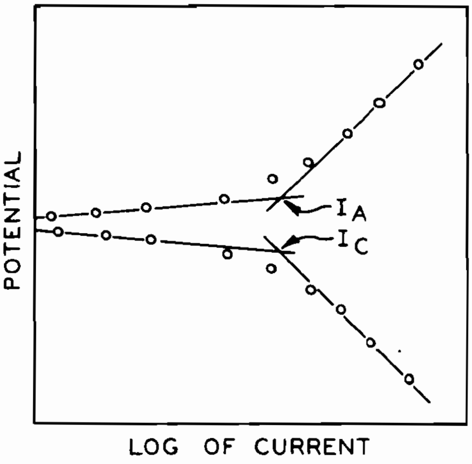


Figure 7. Typical polarization curve.

I corr., can be calculated by Pearson's equation (7) where $I\ corr. = \frac{Ia \times Ic}{Ia + Ic}$. This is the current flowing from the culvert due to corrosion, and by Faraday's Law ($m = eIt$) we can calculate the weight loss of metal represented by this current, where m is the mass of metal lost, e is the electrochemical equivalent in gm/coulomb (9.3×10^{-5} for aluminum and 3.39×10^{-4} for zinc), t is time in seconds. Thus, the polarization curve technique provides a means of predicting corrosion rate in terms of weight-loss per unit time without the impractical step of digging up the specimen after a period of time to weigh it. However, two limitations must be considered when employing this technique: 1) it only predicts the total weight loss due to corrosion, and does not take into account localized corrosion or pitting that may lead to perforation and early failure, and 2) it reflects only the corrosion conditions present at the time the measurements were taken. Measurements performed at different times during the year are likely to change, depending on temperature, moisture, and other soil conditions.

TABLE 4
COATING LOSS DATA AS COMPUTED BY
POLARIZATION VOLTAGE TECHNIQUE

Location	I corr., ma	Wt. loss, gm/yr	Wt. loss/sq ft, gm/yr	Total Wt. of Coating,(1) gm/sq ft	Percent of Total Coating Weight Loss Per Year
US 2 Sta. 181+10	3.3	9.8	.009	105	.009
US 2 Sta. 420+35	7.5	22.2	.024	48	.050
US 2 Sta. 643+00 (galv)	2.5	26.9	.031	57	.054
Ewen	11.5	34.1	.044	104	.043

(1) Weight of cladding is based on assumption that the thickness of cladding is 5 percent of total sheet thickness per side, or 10 percent of total thickness. The total weight of galvanizing is based on a coating thickness of 2 oz/sq ft or 3.4 mils total thickness.

The polarization voltage measurements were performed by Research Laboratory personnel with the assistance of R. I. Lindberg, Corrosion Engineer, Reynolds Metals Company, who supplied the equipment. Measurements were completed at only 4 of the 14 culvert sites because of instrument difficulties and time limitations. The measuring equipment included a 1-volt galvanometer - potentiometer, milliammeter, copper-copper sulfate reference electrode, 12-volt battery, auger electrode, and bridge circuit. The test procedure is described in Appendix A. The results for the four culverts are given in Table 4.

It is apparent from the data in Table 4 that the predicted metal loss for each culvert is only a few grams per year, representing a very small percentage of the total coating weight. For example, the county culvert at Ewen shows the largest weight loss of 34.1 gms/yr, and assuming this corrosion rate will be uniform we find that the coating life will be several hundred years. This prediction does not consider the effects of localized corrosion or pitting.

METALLURGICAL ANALYSIS

Nine of the 14 culverts (8 aluminum and 1 steel) were sampled for metallurgical examination. High water levels and insufficient space for operating the sampling equipment precluded sampling the five remaining culverts. The analysis was expected to determine depth of cladding penetration and condition of the base metal at points of cladding perforation. A battery-powered hole saw was used to cut 1-1/8 in. discs from the culvert areas showing the most severe corrosion (Fig. 8).

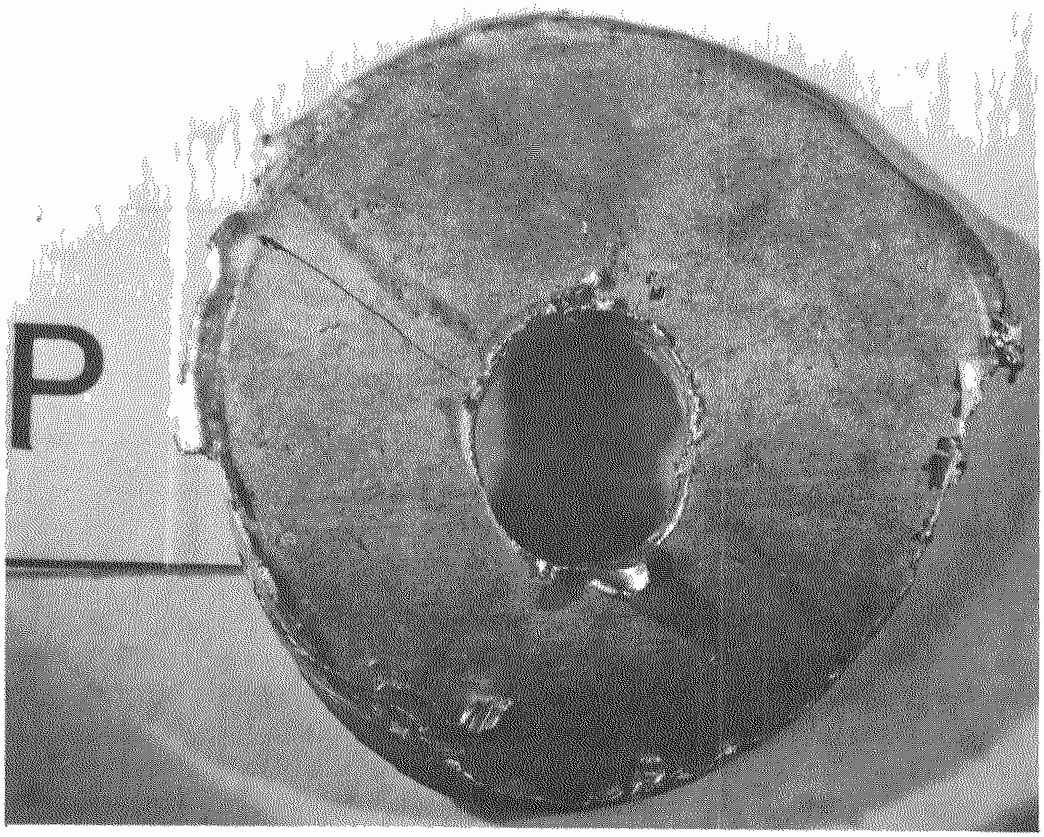


Figure 8. Typical 1-1/8 in. sample disc cut from culverts.

The Metallurgical Research Laboratory of the Reynolds Metals Co. in Richmond, Virginia, conducted the sample examination in the following manner: Specimens were cleaned in nitric acid, examined visually, and photographed at low magnification 6-10X to show general surface condition. The specimens were then cross-sectioned, mounted in plastic, metallographically polished, etched, and microscopically examined on both the inside (invert) and the outside (exvert) to observe and measure corrosion penetration. The areas of most severe attack were then photographed at 100X except for the galvanized steel culvert at Sta. 622+00 which was photographed at 250X to accommodate the thinner coating.

The following is a summary of the culvert conditions:

US 2, Sta. 114+00. General condition on both sides good. The deepest pit was on the inside and had penetrated about 90 percent of the cladding thickness (Fig. 9).

US 2, Sta. 181+10. General condition on both sides fair. Pits on both the invert and exvert had penetrated the cladding, exposing the core alloy (Fig. 10). No damage to core metal observed.

US 2, Sta. 420+35. General condition good. At least two pits on the inside had penetrated 80 percent of cladding thickness (Fig. 11).

US 2, Sta. 458+00. General condition good. No significant penetration of the cladding.

Bessemer. General condition good. One pit on the outside was observed to have perforated the cladding, but no damage to the core was detected (Fig. 12).

Bruce Crossing. General condition very good. No significant penetration of the cladding.

Ewen. General condition good. No significant cladding penetration in the area sampled. Due to the high water level, it was not possible to sample the area where pitting was noted during the previous inspections.

Wood Spur. General condition good. Pits which had penetrated 70-80 percent of the cladding were observed on both the inside and outside surfaces. Two adjacent pits on the outside are shown in Figure 13.

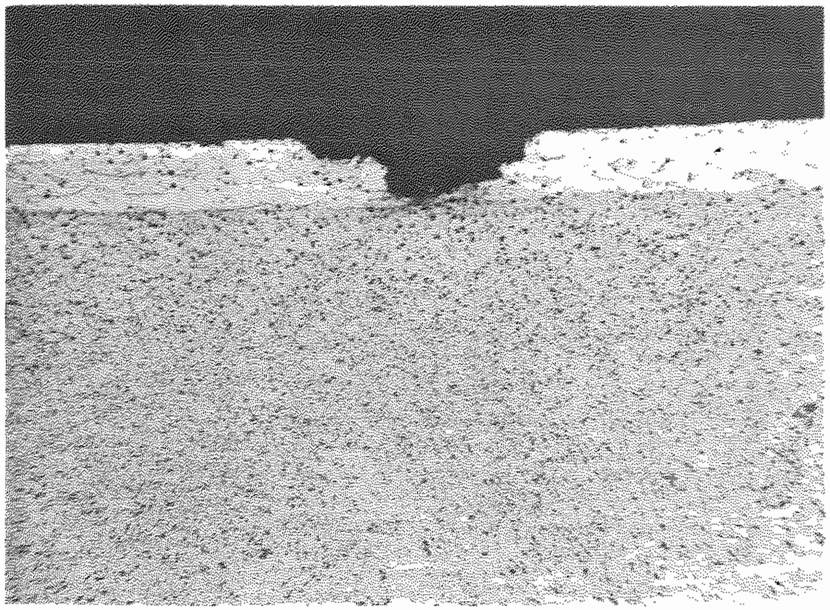
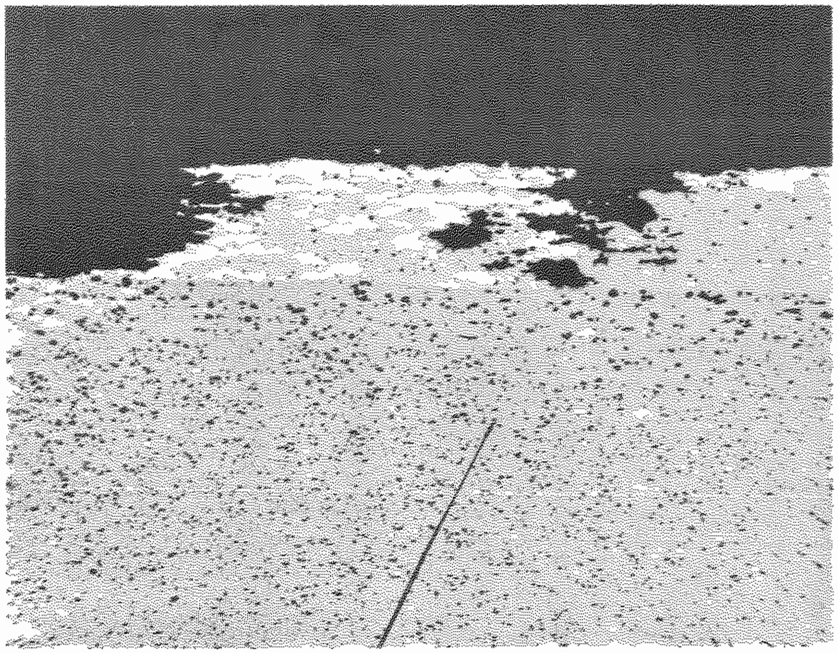


Figure 9. Photomicrograph (100X) of a cross-section showing depth of corrosion penetration (Sta. 114+00, invert).



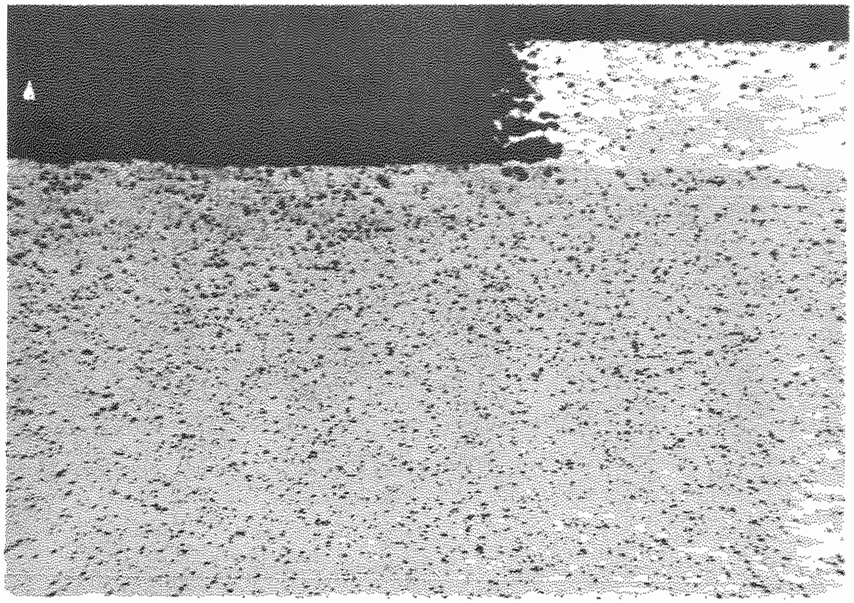


Figure 10. Photomicrographs (100X) of cross sections depicting perforation of cladding (Sta. 181+10).

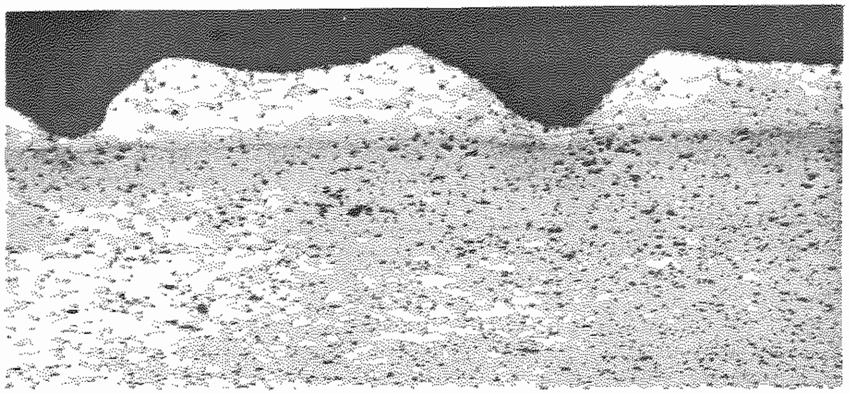


Figure 11. Photomicrograph (100X) showing two corrosion pits that have penetrated about 80 percent of the cladding (Sta. 420+35).

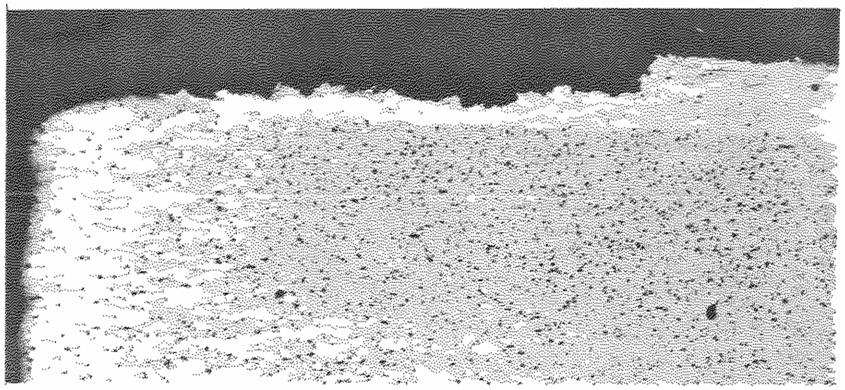


Figure 12. Photomicrograph (100X) showing depth of penetration at the most severely etched area (Bessemer).

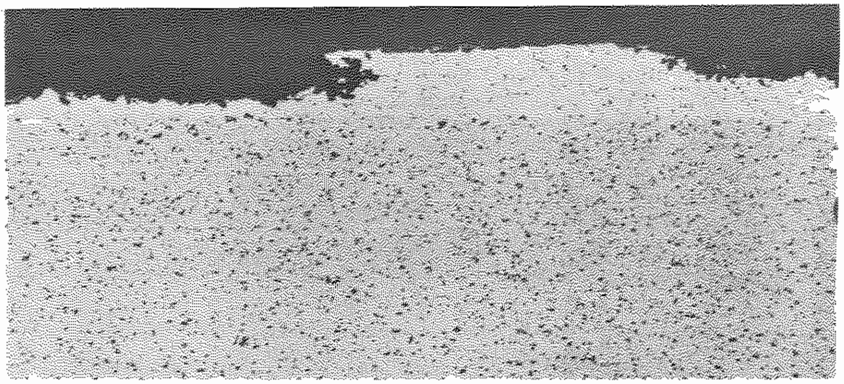


Figure 13. Photomicrograph (100X) depicting cladding penetration of two adjacent outside corrosion pits (Wood Spur).

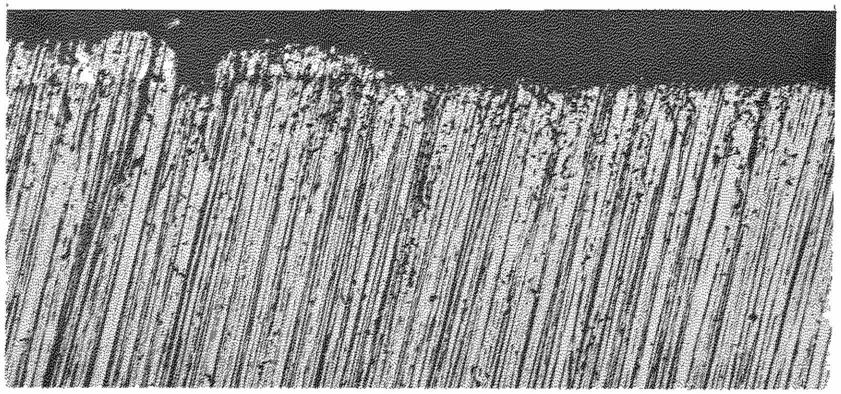


Figure 14. Photomicrograph (250X) of galvanized steel at Sta. 622+00. Corrosion has perforated galvanizing to the base metal in the white-rusted area in the upper part of the invert. Base metal appears unaffected.

US 2, Sta. 622+90 (galvanized steel). General condition fair. Several pits on the inside perforated the coating and exposed the base metal (Fig. 14). No damage to the base metal was observed.

Corrosion effects observed by metallographic examination did not reveal serious corrosion damage to any of the culverts examined. The culverts on US 2 at Sta. 181+10 and 622+00, and at Bessemer, warrant further attention, perhaps in the form of resampling at a later date because the cladding has been perforated in several areas.

CONCLUSIONS

1. None of the test culverts (either aluminum or galvanized steel) display corrosion of sufficient severity to indicate that perforation of the culvert is likely to occur in the forseeable future.

2. The environments of the test culverts are not seriously corrosive in nature.

3. Based on present knowledge, it appears that aluminum is performing satisfactorily as a culvert material with respect to corrosion resistance in Upper Peninsula environments.

RECOMMENDATIONS FOR FUTURE EVALUATION

1. Perform visual inspections of test culvert inverts every three years, giving special attention to the culverts at US 2, Sta. 181+10, and at Bessemer and Ewen. The next inspection would occur in the summer of 1970.

2. Inspect an area of the soil-surface (exvert) side of the test culverts every six years. Scheduled for the summer of 1970.

3. Consider a second soil resistivity survey and a resampling of the soils and waters and of the culverts if subsequent visual inspections indicate a change in corrosion rate or corrosive conditions.

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5. Schwerdtfeger, W. J., A Study by Polarization Techniques of the Corrosion Rates of Aluminum and Steel Underground for Sixteen Months. Journal of Research, National Bureau of Standards, Vol. 65c, No. 4, October-December 1961.

6. Lindberg, R. I., Method of Estimating Corrosion of Highway Culverts by Means of Polarization Curves. Highway Research Record No. 204, pp. 1-7.

7. Pearson, J. M., Transactions of the Electrochemical Society, Vol. 81, p. 485, 1942.

APPENDIX A

The procedure for obtaining polarization voltage measurements was as follows:

1. Make necessary wiring connections as shown in the circuit diagram (Fig. 15).

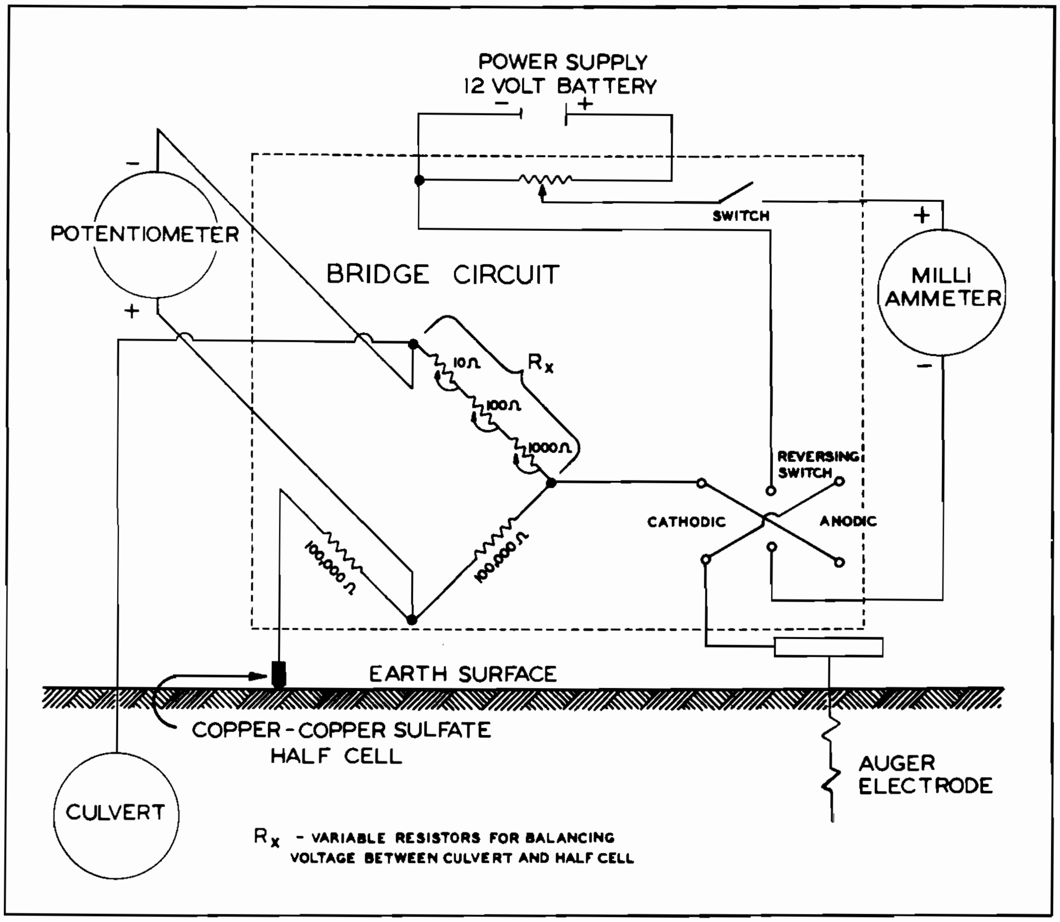

Figure 15. Circuit diagram for polarization voltage measurements.

2. Balance out any small amount of current due to galvanic effects between the culvert and auger electrode by applying resistance with the variable rheostat in the bridge circuit.

3. Close the switch on the bridge circuit (Fig. 16), and adjust resistance to the power supply until a small current (about 0.1 ma) flows between the auger electrode and the culvert. Balance the galvanometer and read the pipe to soil potential.

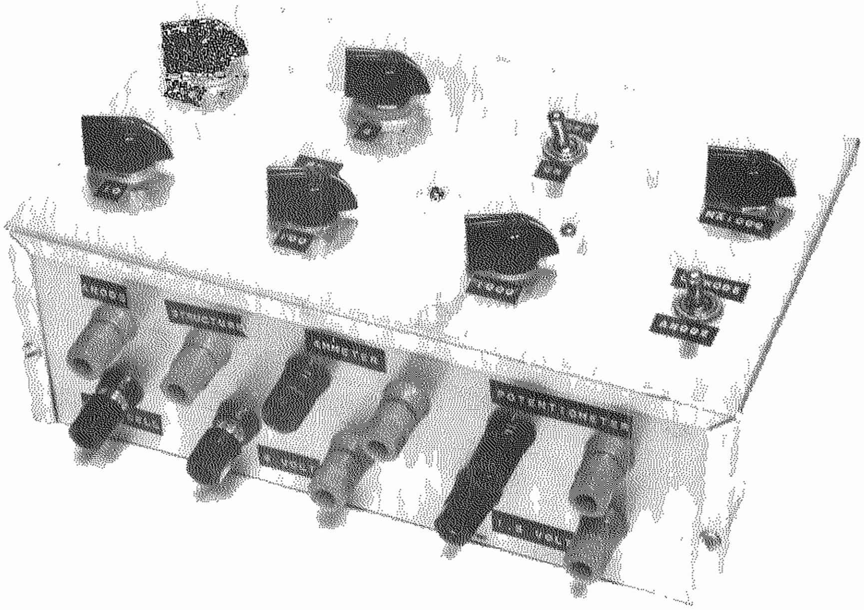

Figure 16. Bridge circuit used in polarization voltage measurements.

4. Plot applied current vs half of the pipe to soil potential $\frac{E}{2}$ on semi-log paper (Fig. 17). Add another increment of current (0.1 ma), balance galvanometer, read pipe to soil potential and again plot the point. Continue in this manner until an obvious break in the curve occurs.

5. Reverse the polarity with the reversing switch and repeat steps 3 and 4. From the above procedure anodic (Ia) and cathodic (Ic) currents were

determined for each culvert (Fig. 17) as well as corrosion current I corr. and rate of metal loss, m. A sample calculation of I corr. and the weight loss per year for the aluminum culvert on US 2, Station 181+10 follows:

From the polarization curve Ia = 6.3 ma, Ic = 7.0 ma

$$\text{I corr.} = \frac{\text{Ia x Ic}}{\text{Ia + Ic}} = \frac{6.3 \times 7.0}{6.3 + 7.0} = 3.3 \text{ ma}$$

Using Faraday's Law $m = e\,I\,t$; where $t = 31.8 \times 10^{6}$ sec/year, $e = 9.3 \times 10^{-5}$ gm/coulomb, $I = 3.3 \times 10^{-3}$ amp, then $m = (9.3 \times 10^{-5})(3.3 \times 10^{-3})(31.8 \times 10^{6}) = 9.8$ gm/yr.

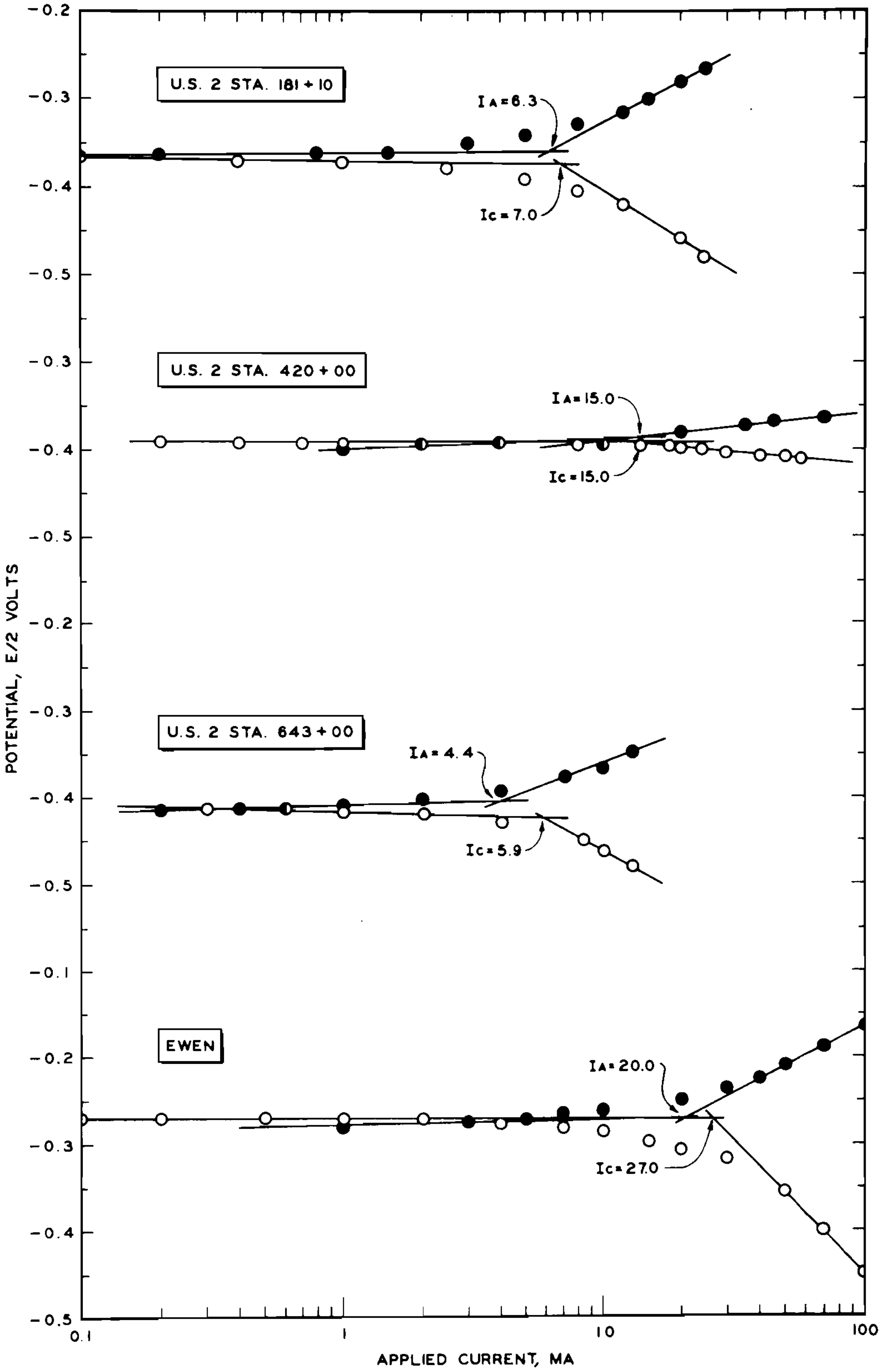

Figure 17. Polarization curves for culverts indicated.