EVALUATION OF DRAINAGE PIPE BY FIELD EXPERIMENTATION AND SUPPLEMENTAL LABORATORY EXPERIMENTATION

Interim Report No. 3

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SUMMARY

The Louisiana Department of Transportation and Development reacts to a major problem when it attempts to shape and control drainage patterns along its right-of-ways. The Department's design engineers meet this challenge through proper section design and appropriate application of drainage structures.

Perhaps the most common structure used by these design engineers is the drainage pipe--primarily concrete and metal. This study is an investigation of the durability properties of metal drainage pipe in Louisiana. Durability of such pipe is as important as design strength because of the harsh environments which promote corrosion.

In August 1973, ten test locations and ten types of culverts were selected. A pair of each of the test culverts was installed at each location. In 1975, another type of pipe, in addition to the ten original ones, was installed at each of the ten sites (one pair per site). In 1977, an additional test site with acidic soil (pH=4.4) was selected and a series of test culverts including five types of the original ones and three other similar types were installed at this site.

This interim report relates field and laboratory observations concerning the condition of the test pipes after six years of in-service exposure. It was found that the asbestos-bonded asphalt-coated, galvanized steel pipe was performing better than the other ten original types of culverts in resisting corrosion. All of the coating on the various test culverts are showing signs of distress at the highly corrosive test sites.

Aluminum alloy culverts have developed significant pitting in environments with pH less than 5 as well as environment with resistivity less than 1000 ohm-cm after six years of service.

INTRODUCTION

The state of Louisiana annually receives approximately 60 inches (152 cm.) of rainfall. The LA. DOTD Road Design Engineer assigns a cross-slope and texture to the highways to rid them of this deluge of water. The Hydraulics Engineer often employs drainage pipe to remove the ensuing runoff from the highway right-of-way.

The Hydraulics Engineer can generally choose either reinforced concrete pipe or corrugated metal pipe in his designs. Concrete pipe is very durable (1)* and with stable bedding conditions can normally serve effectively for the life of a highway.

The Department also recognizes that metal pipe has its place in the field of hydraulics and maintains an interest in innovations in metal pipe. Metal pipe is relatively lightweight, an advantage that gains significance as the size of pipe increases. Metal pipe is relatively flexible, an advantage that could preclude failure under certain heavy loads. The major drawback with metal pipe is its tendency to corrode in the presence of moisture, oxygen, and salt. Additional information is needed on the rates at which galvanized steel and aluminum (with the various types of coatings recently introduced) will corrode.

The purpose of this study is to investigate the corrosion properties of metal drainage structures through a controlled field experiment and limited laboratory work.

*Underlined numbers in parentheses refer to Bibliography.

SCOPE

In this study the evaluation of corrosion in 11 types of metal drainage pipe is limited to 11 field installations representing a cross section of soil and water conditions found in Louisiana. The types of corrugated culvert under evaluation include six which are presently authorized for use by Department specifications and five which are under evaluation as new products. The potential corrosiveness at the installation sites ranges from the highly corrosive environment found in brackish waters near the Gulf of Mexico to the fairly noncorrosive soils of north-central Louisiana. The indicators of corrosion potential are pH and electrical resistivity of both soil and effluent.

The evaluation is comprised of field observations, including a panel rating, and laboratory analysis of pipe samples taken in the field.

METHOD OF PROCEDURE

Site Selection

An earlier drainage pipe study (1) served to evaluate existing drainage structures in the seven general soil areas found in Louisiana. Resistivity and pH tests were conducted on soil samples from these areas to predict years-to-perforation of the culvert materials under evaluation. These test results, along with data from routine soils testing for preliminary subgrade surveys, provided the basis for selection of the sites used in the present study.

The following experimental design was developed to include soil and water conditions found in the northern, central, and southern sections of the state.

A. Normal conditions for North and Central Louisiana
   1. Resistivity > 2000 and pH 5.0-6.0
   2. Resistivity > 2000 and pH 7.0-8.0

B. Normal conditions for South Louisiana
   1. Resistivity 500-2000 and pH 5.0-6.0
   2. Resistivity 500-2000 and pH 7.0-8.0

C. Extreme soil conditions
   1. Areas of (high) resistivity > 2000 and pH 8.0-9.0
   2. Areas of (low) resistivity < 2000 and pH 8.0-9.0
   3. Areas of (low) pH and resistivity > 2000.

The following factorial design indicates test sites that the researchers selected to satisfy the requirements of the field experiment.

	Minimum Resistivity, ohm-cm	
Soil pH	500-2000	Greater than 2000
4.0 - 5.0		Site No. 11
5.0 - 6.0	Site No. 1	Site No. 8
7.0 - 8.0	Site No. 2 Site No. 3	Site No. 5
8.0 - 9.0	Site No. 9 Site No. 6 Site No. 7	

A soil with pH ranging from 8.0 - 9.0 and electrical resistivity greater than 2000 ohm-cm could not be located. However, two additional sites (7 and 10) were selected to evaluate the pipes' performances in brackish water. These two sites are in drainage canals where the water exhibits electrical resistivity values less than 500 ohm-cm.

Table 1 on page 5 presents current characteristics of the soil and effluent at the 11 test sites. Figure 1 on page 6 presents the locations of the test sites. Site number 6 is a ditch installation located directly across the road from the canal at site number 7.

In 1977 the researchers added test site No. 11 with soil exhibiting high corrosion potential to the field program. Soil at the site selected has an electrical resistivity value of 2133 ohm-cm and a pH value of 4.4. A soil with these properties rarely occurs in Louisiana. However, the investigators consider that such an environment will add depth to the study and may aid in development of a field test to evaluate durability of drainage pipe.

Materials Tested

Eleven varieties of coated and uncoated galvanized steel and aluminum culvert were selected for evaluation. All sections of the corrugated

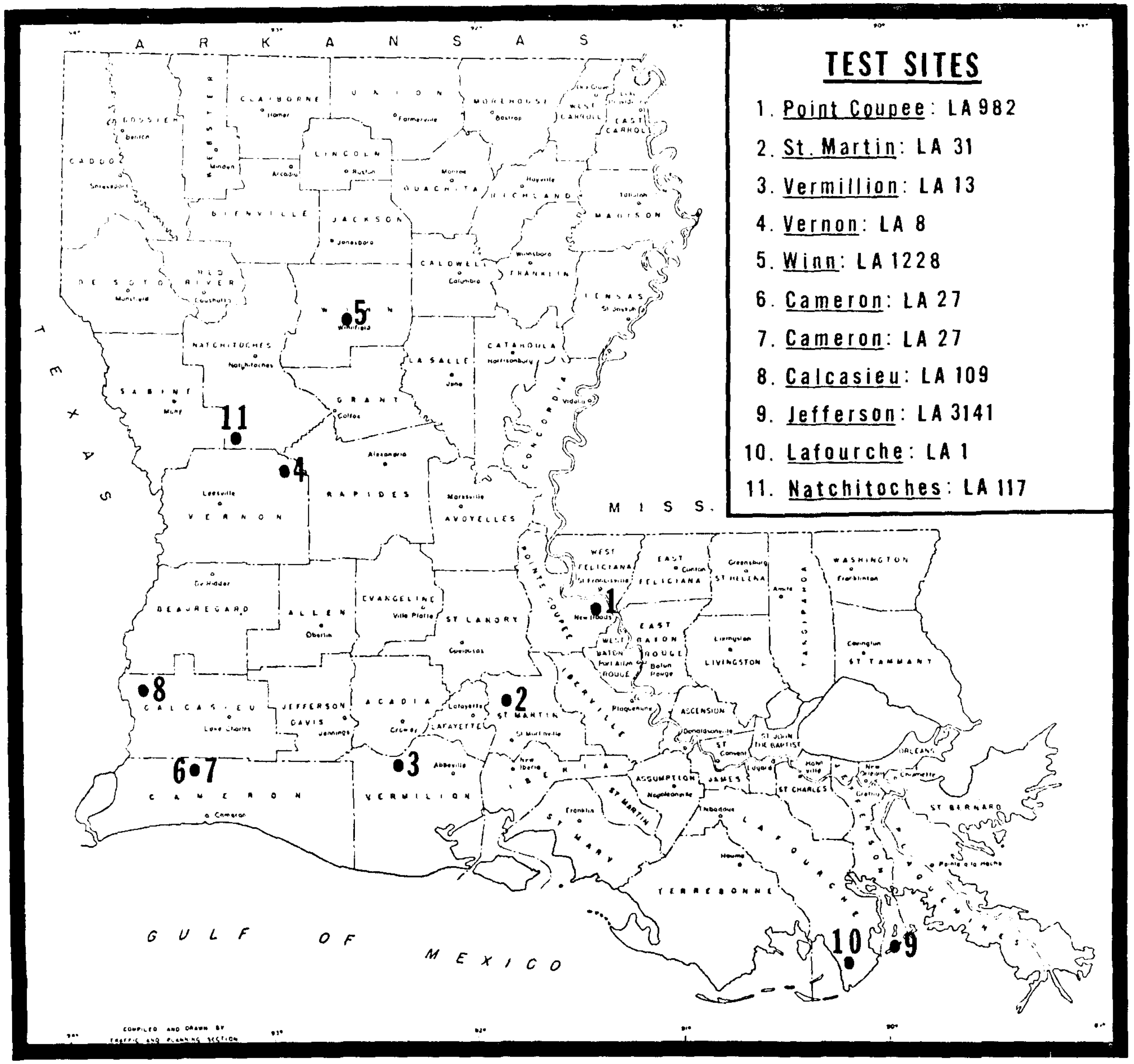
TABLE 1

SOIL AND EFFLUENT CHARACTERISTICS AT TEST SITES

Location Number	Soil Type	Soil Electrical Resistivity, ohm-cm.	Soil pH	Effluent Electrical Resistivity, ohm-cm.	Effluent pH
1[b]	Clay	1038	6.4	11750	6.4
2[b]	Silty Clay	812	7.5	4280	7.3
3[b]	Silty Clay	1268	6.9	5460	7.0
4[a]	Silty Sand	11323	5.3	20667	5.6
5[a]	Sand	3479	6.6	2333	6.6
6[c]	Sandy Clay	314	8.2	135	7.0
7[c]	Sandy Silt	456	8.1	133	7.1
8[a]	Silty Clay	3437	5.5	16200	6.8
9[c]	Sand	971	8.4	338	7.7
10[c]	Silty Clay	254	8.2	121	7.3
11[c]	Sandy Loam	2133	4.4	4400	7.4

Test results shown represent the 1980 sampling.

a - mild
b - corrosive
c - very corrosive



Location of Test Sites
FIGURE 1

culvert were 4 feet (1.2 m.) long and 18 inches (46 cm.) in diameter, with the exception of the aluminum plate arch, which is approximately 4.5 feet square (1.4 m. sq.). Six of these types of pipes are commonly known and are listed below:

1. Uncoated, 16-gauge (0.15 cm.) galvanized steel (AASHTO M36).
2. Asphalt-coated, 16-gauge (0.15 cm.) galvanized steel (AASHTO M190).
3. Asbestos-bonded, asphalt-coated, 14-gauge (0.19 cm.) galvanized steel (La. DOTD Standard Specifications for Roads and Bridges, 1977 Subsection 1007.05)
4. Uncoated, 16-gauge (0.15 cm.) aluminum pipe (AASHTO M196).
5. Asphalt-coated, 16-gauge (0.15 cm.) aluminum pipe AASHTO M190, Type A).
6. Structural aluminum plate arch (AASHTO M196).

The remaining five types of pipes (new products) selected for evaluation are as follows:

7. Sixteen-gauge (0.15 cm.) galvanized steel with a 12-mil (0.31 mm.), U.S. Steel Nexon, coal-tar-based laminate applied to interior and 0.3 mil (0.008 mm.), modified epoxy coating on the reverse side (AASHTO M246).
8. Sixteen-gauge (0.15 cm.) galvanized steel with a 20-mil, (0.51 mm.) U.S. Steel Nexon, coal-tar-based laminate applied to interior or exterior with a 0.3 mil (0.008 mm.), modified epoxy coating on the reverse side (AASHTO M246).
9. Sixteen-gauge galvanized steel with a 10-mil (0.25 mm.) interior and 3-mil (0.08 mm.) exterior, Inland Steel, polyethylene coating.
10. Sixteen-gauge (0.15 cm.) galvanized steel with a 12-mil (0.31 mm.) interior and 5-mil (0.13 mm.) exterior, Inland Steel Polyethylene coating.
11. Sixteen-gauge (0.15 cm.) galvanized steel pipe with 10-mil (0.25 mm.) interior and 3-mil (0.08 mm.) exterior, Wheeling Steel, polymeric coating (AASHTO M246).

At site 11, pipes 1,2,3,4 and 6 were installed. The additional three types of pipes (new products) selected for evaluation are as follows:

7a. Sixteen-gauge (0.15 cm.) galvanized steel with a 10-mil (0.25 mm.), U.S. Steel Nexon, coal-tar-based laminate applied to interior and exterior.

8a. Sixteen-gauge (0.15 cm.) galvanized steel with an 8-mil (0.20 mm.) interior and 4-mil (0.10 mm.) exterior, Inland Steel, polyethylene coating.

9a. Sixteen-gauge (0.15 cm.) galvanized steel pipe with 10-mil (0.25 mm.) interior and 3-mil (0.08 mm.) exterior, Wheeling Steel, polymeric coating (AASHTO M246).

Field Installation

During the month of August, 1973, research personnel, with the assistance of district maintenance forces, successfully installed 20 sections of culvert in each of ten selected locations. Two sections of each type culvert were buried in all locations, one section to be removed periodically for evaluation and reinstallation, and the other to remain undisturbed for the duration of the ten-year study. Immediately prior to installation a survey of the condition of each pipe was conducted to make note of any possible damage to the various protective coatings which may have occurred while in transit or during the loading-unloading process. On the whole, damage of this nature was minor. Several of the coatings incurred minor scrapes where binding chains came into contact with the pipe exteriors. As the installation was conducted in the summer months, high temperatures caused the asphalt to soften. Some asphalt was, therefore, removed in handling. Conditions such as these were photographed before installation and have been taken into consideration to make the distinction between these and any actual signs of coating deterioration.

A "Grade-All" was used to remove all grass and debris from the ditches for approximately 200 feet (61 m.) to facilitate the installation. Next, the top two feet (0.6 m.) of in-place soil was removed and the pipes were lowered into the ditch by hand and spaced approximately six feet apart. The removed soil was then used to cover the individual pipe sections to provide a minimum cover of one foot (0.3 m.).

At the two water locations, the drainage pipes were installed along the side of drainage canals which parallel state highways running through the coastal marshes. The pipe sections were installed perpendicular to the roadway, half being covered with soil and half extending out into the brackish water. Two typical field installations can be observed in Figures 2 and 3 on page 11. Soil and water samples were obtained at the time of installation and are now being taken annually to detect any changes in the potential corrosiveness at the test sites.

Using the above-described installation procedures, in 1975 research and maintenance personnel installed an eleventh type of test pipe at ten test sites, one pair per site. And in 1977 the series of test culverts were installed at an eleventh test site with an acidic soil (Table 1, page 5). The culverts at test site No. 11 were inspected in March, 1979 after two years of in-service exposure.

Field Inspection

During the months of March and April, 1979, the third field inspection was conducted, representing six years of exposure. One of each type of pipe was removed for inspection, using a "Grade-All" and a padded, two-inch (5 cm.) pipe with a chain running through the center. After being hooked by chain to the "Grade-All" bucket, test culverts were slowly lifted and removed. The apparatus, illustrated in Figure 4, Appendix C page 49, helped insure a relatively nondestructive removal by providing uniform support along the length of each culvert. Upon removal, the four-foot (1.2 m.) sections were washed clean, removing as much of the soil as possible without contributing to the removal of the coatings as shown in Figure 5, Appendix C. As was mentioned in Interim Report No. 2, the asphalt-coated galvanized steel and asphalt-coated aluminum sections were the only two types of culvert noticeably affected by the removal process and to a lesser extent by the washing process. Some of the asphalt remained in the soil, thus indicating more loss of bond over the six-year period. Even if these pipes had not been disturbed, it is questionable whether the coating could have prevented seepage of water onto the metal surfaces. The answer to this question may be resolved in the final inspection when the pipe samples left undisturbed for ten years are removed and evaluated.

After the pipes were cleaned, photographs were taken at several different angles to document the condition of each. Next, a panel con-

Typ[illegible] Installation (Site 3)
FIGURE 2

Typi[illegible] Installation (Site 10)
FIGURE 3

sisting of two highway engineers and three highway engineering technicians visually rated the pipes using the evaluation form, Figure 10 in Appendix C, page 52. The criteria for defining the condition of a pipe were as follows:

1. Excellent condition - If, under visual observation, there are no signs of deterioration.
2. Good condition - If, under visual observation, there are very slight signs of deterioration and pitting.
3. Fair condition - If, under visual observation, there are moderate signs of deterioration and pitting.
4. Poor condition - If, under visual observation, there are extreme signs of deterioration and pitting.
5. Very poor condition - If, under visual observation, there are signs of complete deterioration, and the pipe is no longer useful as a drainage tool.

The pipes were then sampled for laboratory analysis. The sampling shown in Figure 6, Appendix C, page 50, consisted of cutting a three-inch (8 cm.) band off the end of each section removed. To provide protection between yearly evaluations, a film of asphalt was brushed on the metal edge exposed during the cutting process. Upon completion of the field evaluation the pipes were returned to the ditch, oriented in their original positions, and covered with in-place soil.

Laboratory Analysis of Soil, Water and Unexposed Culverts

Soil and water samples were initially collected from each installation site on a semi-annual basis. The investigators have changed to sampling annually, since the results from the semi-annual samples show very little change in the pH and resistivity. These samples have been tested for pH in accordance with La. DOTD:TR 430-67 and for resistivity in accordance with La. DOTD:TR 429-77. The two laboratory procedures require the use of a pH meter and a resistivity meter as the basis of measurement. The soil samples were identified by laboratory technicians in accordance with La. DOTD:TR 423-71.

Initially, the culvert testing program dealt with determination of the physical characteristics of the various metals and their protective coatings as manufactured. The amount of zinc coating, expressed in oz./ft.^{2}, was determined by measured weight loss as the zinc coating was dissolved in an acid solution. Thicknesses of the bituminous, asbestos, and various organic coatings were measured with a micrometer. The composition of steel and aluminum used in the culverts was determined by X-ray fluorescence, a process which provides a quantitative analysis of each element present in the metal alloys. Composition and thickness data are presented in Appendix B, pages 37 and 38 of this report.

The durability of the culvert materials as manufactured has been evaluated in the laboratory by two primary methods, the Salt Fog Exposure and the Weather-Ometer Exposure tests. The Salt Fog Exposure (La. DOTD:TR 1011-74) consists of a closed salt spray cabinet equipped with a cyclic temperature control. This test was originally designed to test zinc-rich paint systems. The Weather-Ometer Exposure (La. DOTD:TR 611-75) consists of a carbon arc Weather-Ometer with automatic humidity controls. The evaluation of Salt Fog and Weather-Ometer Exposure results are subjective and are normally reported as satisfactory or unsatisfactory for the specified number of hours exposed. Initial durability test results are presented in Appendix B, pages 39 and 40.

Laboratory Analysis of Field-Exposed Samples of Culvert

As related previously, the researchers sawed a circumferential sample 3 inches (8 cm.) wide from a given end of each culvert inspected in the field.

The culvert samples were brought to the Materials Laboratory and cut into short segments for easier handling. The samples were washed with soap and warm water in order to further remove soil.

The asphalt-coated samples were stripped of their coating by soaking in a bath of chlorothane. After this coating was removed, the samples were again washed with soap and warm water.

The aluminum culvert samples were cleaned of corrosion deposits in accordance with Section 5.2 of ASTM Designation G1. This cleaning enabled better examination of the depth of pitting and thickness loss.

Aluminum

The field samples of aluminum culvert were examined under a microscope for pitting and general thickness loss. The greatest depth of corrosion in each square inch of culvert sample was measured and recorded.

These maximum-depth-of-corrosion values were categorized into one of the following ranges:

0.0 - 0.2 mm
0.2 - 0.5 mm
0.5 - 0.8 mm
0.8 - 1.1 mm

The percentage of square-inch units of sample area associated with each maximum-depth category was multiplied by the average depth for the category. Summation of the products for the four categories yielded an average maximum thickness loss, in millimeters, for the sample.

Average maximum thickness loss was compared with original sample thickness in the following equation to provide a numerical rating from 0 to 5 for the aluminum culvert:

$$R_{A1} = 5 \left(\frac{T_{L1} + T_{L2}}{T_0}\right)$$

where,

R_{A1} = Rating of field sample of aluminum culvert sample

T_{L1} = Average maximum thickness loss of interior wall, millimeters

T_{L2} = Average maximum thickness loss of exterior wall, millimeters

T_0 = Original thickness, millimeter (interior plus exterior walls)

This scheme of rating the aluminum culvert samples translates into the following scale:

Average Maximum Thickness Loss Per Square Inch (Expressed as Percentage of Original Wall Thickness)	Rating	
Negligible	0	
		Excellent
20%	1	
		Good
40%	2	
		Fair
60%	3	
		Poor
80%	4	
		Very Poor
100%	5	

Steel

The field samples of steel pipe culvert were examined to determine the percent of rusted surface area. The percentage values were used in the following equation to provide a rating of 0 to 5 for the steel culvert samples:

$$R_S = \frac{A_R}{20\%}$$

where,

R_S = Rating of field sample of steel culvert

A_R = Percent of square-inch sections of surface containing rust

This scheme of rating the steel pipe culvert samples translates into the following scale:

Percentage of Surface Area Containing Rust	Rating
Negligible	0 Excellent
20%	1 Good
40%	2 Fair
60%	3 Poor
80%	4 Very Poor
100%	5

This rating was given to both the interior and exterior walls of the culvert samples. An average of the ratings of both walls is reported as a final value. The scale of rating was developed to relate to the field panel ratings of 1 to 5 characterizing entire steel test pipes.

Coatings

The coatings, as field-exposed for two to six years, were examined to determine the percentage of surface area experiencing removal, blistering, and separation from the pipes (delamination). These percentages were used in the following equation to provide a rating of 0 to 5 for the coatings:

$$R_C = \frac{A_C}{20\%}$$

where,

R_C = Rating of field-exposed coating

A_C = Percentage of surface area which experienced coating failure

This scheme of rating the coatings translates into the following scale:

Percentage of Surface Area Which Experienced Coating Failure	Rating
Negligible	0 Excellent
20%	1 Good
40%	2 Fair
60%	3 Poor
80%	4 Very Poor
100%	5

The ratings for the coatings represent one wall or an average of the interior and the exterior walls, depending on whether or not the coating had been applied to both sides of the culvert.

A summary note is in order concerning the different rating schemes used for the aluminum and steel culverts. A rating of 5 for the aluminum culverts would indicate that the average maximum thickness loss per square inch is 100% of the original wall thickness. A rating of 5 for the steel pipes would indicate that every square inch of surface area contains rust. Ratings for all the culverts reflect the average condition of the interior and exterior walls. Perforation originating from either wall would be equally harmful.

The aluminum culverts are composed of a structural aluminum alloy core covered on both sides by an aluminum alloy cladding. The cladding is designed to oxidize in a lateral fashion and form a protective covering for the core. Hence, depth of corrosion per unit area was selected as the rating index for the aluminum culverts. Percentage of square-inch units of area containing rust was selected as the index of corrosion resistance for the steel pipes.

DISCUSSION OF RESULTS

The culvert providing the best performance after six years of field exposure is the asbestos-bonded, asphalt-coated, galvanized steel pipe. The basis of field performance was the ability of the culverts to resist metallic corrosion. An index of corrosion resistance was assigned by a panel inspecting the entire culvert in the field and by an engineer examining a sample of the test culvert in the laboratory.

The field ratings of the test pipes are summarized in Table 2 on page 20. The 10 original test sites have been grouped into three categories by degree of corrosion potential. These categories are "mile" (pH = 5.8, R = 6,000), "corrosive" (pH = 6.9, R = 1,000), and "very corrosive" (pH = 8.3, R = 200). The "mild" sites (No.s 4, 5, and 8) are mildly acidic, the "corrosive" sites (No.s 1, 2, and 3) are approximately neutral in pH, and the "very corrosive" sites (No.s 6, 7, 9, and 10) are slightly alkaline. It is believed that electrical resistivity is the primary factor influencing corrosion of the aluminum-alloy and galvanized-steel culverts in this study.

Field ratings for individual test sites are listed in Tables 5 and 6, Appendix A, pages 31 and 32. The ratings are the collective opinions of a panel of five highway engineering employees who examined the culverts and assigned a numerical rating ranging from one (excellent) to five (very poor) to each culvert. Neither the two highway engineers nor the three engineering technicians comprising the panel are corrosion experts. However, it is felt that the technical backgrounds of these individuals qualify them to identify signs of corrosion such as rust on steel and pitting on aluminum and to assign valid ratings to the test culverts.

TABLE 2

SUMMARY OF FIELD PANEL RATINGS OF TEST PIPE - SIX YEARS OF EXPOSURE

		Field Environment		
Pipe No.	Type Pipe	Mild pH=5.8, R=6000	Corrosive pH=6.9, R=1000	Very Corrosive pH=8.3, R=200
1	Uncoated Galvanized Steel	2.1	2.4	4.7
2	Aspahlt-Coated Galvanized Steel	1.5	1.9	3.6
3	Asbestos-Bonded Asphalt-Coated Galvanized Steel	1.1	2.0	1.7
4	Uncoated Aluminum	1.8	1.9	2.9
5	Asphalt-Coated Aluminum	1.6	1.9	2.4
6	Structural Plate Arch	2.0	2.0	3.1
7	12-Mil Coal - Tar - Based Polymer Coated Galvanized Steel	1.9	1.9	3.4
8	20-Mil Coal - Tar - Based Polymer Coated Galvanized Steel	1.9	1.9	4.0
9	10-Mil Polyethylene Coated Galvanized Steel	1.7	2.0	2.6
10	12-Mil Polyethylene Coated Galvanized Steel	1.5	1.9	3.1

The laboratory ratings for each individual test site are summarized in Tables 7 and 8, Appendix A, pages 33 and 34. These ratings result from a chemical engineer examining each square-inch unit of area of samples from the test culverts in the laboratory and assigning a numerical rating ranging from zero (excellent) to five (very poor) to each sample. In many instances field samples submitted for lab evaluation did not include perforations or coating blisters which occured on the test culverts. For this reason the field panel ratings are considered more indicative of the overall performance of each culvert.

The protective coatings applied to a number of the culverts experienced various types and degrees of failure. The asphalt coatings have cracked and separated from the metal significantly, leaving much of these culverts unprotected. The polymeric coatings have exhibited separation from the steel and blistering and, therefore, can not be relied on to seal moisture and air from the culvert metal. The thick asbestos-bituminous coating is the most durable of the coatings being evaluated. Table 3 on page 23 lists test culverts experiencing perforation and further illustrates this point.

The aluminum culverts displayed two types of deterioration. Pitting of the surface was noticed on samples from most test sites. The other type of deterioration was a uniform loss of metal thickness for a given local area of the culvert. The aluminum alloy structural plate has exhibited a greater degree of pitting, thickness loss, etc., than the cladded aluminum culvert, as would be expected. For example, in Table 3 on page 23 the structural plate has developed minor edge perforations and surface pitting after six years exposure at Site No. 2. This site contains a silty clay with an electrical resistivity of 812. Pitting of the cladded aluminum culvert is very minor at this site.

The galvanized steel culverts, both coated and uncoated, are experiencing the fastest rates of corrosion in the low resistivity sites. In this environment only the asbestos-bituminous coating has protected the culverts for six years, as previously indicated in Table 3 on page 23. Soil-side corrosion of the uncoated galvanized steel culverts indicates that the nature of the soil as well as the nature of the effluent should be considered in specifying and designing metal culvert for durability.

The field panel rating of culverts at the 11th test site are listed in Table 4 on page 24, representing two years of service. The sandy loam at this test site contains a pH of 4.4 and a resistivity of 2100. This site was selected primarily to determine the corrosive effects of soil pH in the 4 to 5 range on the test culverts. The aluminum culvert and aluminum structural plate were found to have a significant degree of pitting, considering the relatively short two year exposure to the acidic soil. In particular, the structural plate contained pit depths of approximately 60% of the 12 gauge thickness. The soil at this test site which is 60% sand, 30% silt, and 10% clay has deprived the aluminum of oxygen thereby preventing the oxidation-healing process and allowing the acid to dissolve the alloy. The galvanized steel culvert was found to be in excellent condition with no evidence of rusting, thickness loss, etc.

A detailed review of the field and laboratory rating for each type of the test pipes at all the test sites may be found in Appendix C, page 41.

TABLE 3

METAL CULVERT PERFORATION - SIX YEARS OF EXPOSURE

Pipe No.	Type Pipe	Field Environment pH=5.8, R=6000	Corrosive pH=6.9, R=1000	Very Corrosive pH=8.3, R=200	Site No.
1	Uncoated Galvanized Steel	None	None	Perforated	6,7 & 10
2	Asphalt-Coated Galvanized Steel	None	None	Perforated	7 & 10
3	Asbestos-Bonded Asphalt-Coated Galvanized Steel	None	None	(*) None	
4	Uncoated Aluminum	None	None	Perforated	6
5	Asphalt-Coated Aluminun	None	None	(**) None	
6	Structural Aluminum Plate Arch	None	(***) Edge Perforations	Perforated	9 & 10
7	12-Mil Coal - Tar - Based Polymer Coated Galvanized Steel	None	None	Perforated	7
8	20-Mil Coal - Tar - Based Polymer Coated Galvanized Steel	None	None	Perforated	7
9	10-Mil Polyethylene Coated Galvanized Steel	None	None	Perforated	7
10	12-Mil Polyethylene Coated Galvanized Steel	None	None	Perforated	6

(*) Minor rusting where coating removed.
(**) Heavy Pitting and general thickness loss.
(***) Site No. 2.

PANEL RATING OF TEST PIPE

Site Number Eleven
(pH = 4.4, R = 2133)
Two Years Service

TABLE 4

Pipe No.	Type Pipe	Metal Corrosion	Coating Deterioration
1	Uncoated Galvanized Steel	1.2	---
2	Asphalt-Coated Galvanized Steel	1.0	1.0
3	Asbestos-Bonded Asphalt-Coated Galvanized Steel	1.0	1.0
4	Uncoated Aluminum	2.4	---
6	Structural Aluminum Plate Arch	3.2	---
7a	10-Mil Coal-Tar-Based Polymer Coated Galvanized Steel	1.9	1.6
8a	8-Mil Polyethylene Coated Galvanized Steel	1.7	1.6
9a	10-Mil Polymeric Coated Galvanized Steel	1.4	1.4

CONCLUSIONS

Six years of field exposure have provided much information concerning the performance of various types of test culverts. The following conclusions have been reached at this time:

1. The type of culvert providing the best resistance to corrosion after six years of field exposure is the asbestos-bonded, asphalt-coated, galvanized steel pipe. It stands out in its ability to resist corrosion in the low-electrical-resistivity environments.

2. A number of the test culverts have corroded significantly after six years of field exposure in harsh environments. Eight of the individual test culverts have experienced perforation. These eight are as follows: a galvanized steel culvert, an uncoated aluminum culvert, an aluminum plate arch, an asphalt-coated galvanized steel culvert, a U.S. Steel Nexon 12-mil-coated galvanized steel culvert, a U.S. Steel Nexon 20-mil-coated galvanized steel culvert, an Inland Steel 10-mil coated galvanized steel culvert, and an Inland Steel 12-mil coated galvanized culvert.

3. The coated and uncoated pipes are experiencing the greatest amounts of corrosion at sites 6, 7, 9 and 10. The electrical resistivity of the effluent at these four sites is less than 350 ohm-cm.

4. Within six years, aluminum alloy culverts have developed significant pitting in environments with pH less than 5.0 as well as in environments with resistivity less than 1000. Service life of these culverts may be greatly reduced when either pH or resistivity falls into one of these categories.

5. Bituminous coating is susceptible to removal during transport and installation (especially in hot weather) and to cracking as it ages. Polymeric coatings cannot be relied on to seal moisture and air from metal culverts. Factors such as delaminations at the culvert edge and blistering undermine their ability to seal adequately in the environments where they are most needed.

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APPENDIX A

PANEL AND LABORATORY RATING OF TEST PIPE

PANEL RATING OF TEST PIPE

TABLE 5

Pipe No.	Type Pipe	Years Exposed	Mild >1500 ohm-cm Site 4	Site 5	Site 8	Corrosive 500-1500 ohm-cm Site 1	Site 2	Site 3	Site 6	Very Corrosive <500 ohm-cm Site 7	Site 9	Site 10
1	Uncoated	2	1.9	1.3	1.7	1.4	1.2	1.2	2.9	3.7	1.5	2.9
	Galvanized	4	2.0	2.0	2.4	1.4	1.2	2.2	2.8	5.0	4.0	5.0
	Steel	6	2.4	1.8	2.2	2.2	2.0	3.0	4.4	5.0	4.5	5.0
2	Asphalt-Coated	2	1.2	1.2	1.2	1.8	1.4	1.2	1.4	2.1	1.3	2.0
	Galvanized	4	1.2	1.6	1.8	1.4	1.8	1.8	2.2	4.4	2.0	3.2
	Steel	6	1.4	1.4	1.6	1.8	2.0	2.0	2.0	4.6	3.2	4.5
3	Asbestos-Bonded	2	1.2	1.2	1.2	1.8	1.2	1.2	1.2	1.4	1.3	1.5
	Asphalt-Coated	4	1.0	1.2	1.2	2.0	1.6	1.2	1.2	1.4	1.2	1.5
	Galvanized Steel	6	1.0	1.0	1.4	2.2	2.0	1.8	1.2	1.4	2.0	2.0
4	Uncoated	2	1.5	1.6	1.4	1.2	1.8	1.3	3.2	3.2	2.7	3.1
	Aluminum	4	1.4	2.0	2.0	1.0	1.8	1.6	2.2	2.6	3.0	2.5
		6	1.6	2.0	1.8	1.4	2.0	2.4	4.2	2.4	2.8	2.5
5	Asphalt-Coated	2	1.2	1.2	1.2	1.6	1.2	1.5	2.0	2.3	1.8	2.8
	Aluminum	4	1.2	1.4	1.6	1.2	1.6	1.6	2.2	2.8	2.2	2.5
		6	1.4	1.4	1.8	1.6	2.0	2.0	2.6	2.0	2.5	2.5
6	Structural Aluminum	2	1.3	1.4	1.5	1.5	1.4	1.2	3.3	3.0	2.7	2.6
	Plate	4	1.0	1.8	1.8	1.0	1.2	1.2	2.8	2.8	3.2	3.2
	Arch	6	2.0	2.2	1.8	2.0	2.0	2.0	2.6	2.6	3.8	3.5
7	12-Mil Coal-	2	1.2	1.2	1.2	2.0	1.2	1.2	2.0	2.4	1.5	3.1
	Tar-Based	4	2.0	1.8	2.2	1.0	1.4	1.4	2.6	3.0	2.8	3.8
	Polymer Coated	6	2.0	1.8	2.0	1.6	2.0	2.0	3.0	4.4	2.5	3.8
	Galvanized Steel											
8	20-Mil Coal-	2	1.2	1.2	1.2	1.7	1.2	1.2	1.8	2.6	1.2	3.1
	Tar-Based	4	1.6	1.8	2.0	1.2	2.0	1.8	2.4	4.0	2.5	3.5
	Polymer Coated	6	2.0	1.8	2.0	1.8	2.0	2.0	3.2	4.0	4.0	4.5
	Galvanized Steel											
9	10-Mil	2	1.5	1.0	1.2	1.3	1.2	1.0	1.5	1.4	1.7	1.5
	Polyethylene	4	2.0	1.8	1.8	1.8	2.0	1.6	2.2	2.4	3.0	2.2
	Coated Galvanized	6	2.0	1.2	1.8	1.8	2.2	2.0	2.4	3.2	2.2	a
	Steel											
10	12-Mil	2	1.4	1.0	1.2	1.2	1.0	1.0	1.5	1.4	1.4	1.5
	Polyethylene	4	2.0	2.0	1.4	2.0	1.8	1.8	4.4	2.2	2.2	2.0
	Coated Galvanized	6	2.0	1.0	1.6	1.8	2.0	2.0	4.0	2.4	2.8	a
	Steel											
11	10-Mil	2	1.0	1.0	1.0	1.0	1.0	1.0	2.2	1.8	2.0	2.0
	Polymeric	4	1.2	1.0	1.0	1.0	1.2	1.2	1.6	2.0	1.8	1.8
	Coated Galvanized											
	Steel											

a - Test Pipe Missing

PANEL RATING OF TEST PIPE COATING

TABLE 6

			Mild >1500 ohm-cm			Corrosive 500-1500 ohm-cm			Very Corrosive <500 ohm-cm			
Pipe No.	Type Pipe	Years Exposed	Site 4	Site 5	Site 8	Site 1	Site 2	Site 3	Site 6	Site 7	Site 9	Site 10
2	Asphalt-Coated	2	1.5	1.8	2.7	2.3	3.2	2.6	1.5	2.6	1.9	1.9
	Galvanized	4	2.4	1.6	3.4	2.9	3.7	3.1	3.5	4.5	2.9	4.0
	Steel	6	2.1	2.2	3.2	4.4	4.3	4.0	3.3	4.5	3.4	4.6
3	Asbestos-Bonded	2	0.9	1.0	2.4	0.7	2.6	2.4	2.2	1.6	1.1	1.9
	Asphalt-Coated	4	2.0	1.6	1.7	1.9	2.7	1.8	1.3	1.8	1.5	1.6
	Galvanized Steel	6	1.3	1.3	2.6	3.5	3.0	2.4	1.4	1.8	2.9	2.8
5	Asphalt-Coated	2	1.6	1.4	2.7	2.3	3.2	0.0	3.0	3.2	2.4	3.4
	Aluminum	4	2.5	2.3	3.0	3.7	4.0	3.4	3.6	3.6	3.5	4.5
		6	2.5	2.5	3.9	4.1	4.5	3.5	4.2	4.5	4.4	4.6
7	12-Mil Coal-	2	1.6	1.0	2.1	1.8	2.0	1.6	2.8	3.0	1.8	2.9
	Tar-Based	4	2.4	2.7	2.9	1.4	1.6	1.4	3.8	3.2	3.1	3.6
	Polymer Coated	6	2.0	2.0	1.8	1.3	2.6	2.5	4.1	4.1	2.2	3.9
	Galvanized Steel											
8	20-Mil Coal	2	1.7	1.7	2.1	1.5	1.6	1.5	2.8	3.1	2.2	2.9
	Tar-Based	4	1.7	2.4	2.1	1.5	3.4	1.6	3.1	3.3	3.1	3.8
	Polymer Coated	6	2.2	2.9	2.0	1.5	2.6	3.0	3.1	4.6	3.9	3.9
	Galvanized Steel											
9	10-Mil	2	0.8	0.3	1.2	0.2	0.8	0.3	2.3	2.5	1.9	2.3
	Polyethylene	4	2.8	2.2	1.5	1.8	2.2	1.4	2.8	2.5	3.4	3.4
	Coated Galvanized	6	2.3	1.3	2.0	1.0	1.5	2.2	3.1	3.9	3.2	a
	Steel											
10	12-Mil	2	0.8	0.3	1.0	0.2	0.6	0.6	2.4	2.5	1.8	1.9
	Polyethylene	4	2.5	2.1	1.4	1.7	2.2	1.7	4.5	2.4	2.9	2.8
	Coated Galvanized	6	1.8	1.0	1.6	1.2	1.3	1.8	3.8	3.1	3.5	a
	Steel											
11	10-Mil	2	1.0	1.0	1.5	1.0	1.0	1.0	3.1	2.3	2.6	2.4
	Polymeric	4	1.2	1.0	1.0	1.0	1.2	1.3	2.9	3.8	3.0	3.8
	Coated Galvanized											
	Steel											

a - Test Pipe Missing

LABORATORY RATING OF TEST PIPE

TABLE 7

Pipe No.	Type Pipe	Years Exposed	Mild >1500 ohm-cm Site 4	Site 5	Site 8	Corrosive 500-1500 ohm-cm Site 1	Site 2	Site 3	Very Corrosive <500 ohm-cm Site 6	Site 7	Site 9	Site 10
1	Uncoated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	3.0	3.0	1.0	3.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	4.8	5.0	1.0	4.7
		6	0.6	0.0	1.3	0.0	0.0	1.4	5.0	5.0	1.8	5.0
2	Asphalt-Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.0	0.0
		6	0.0	0.0	0.8	0.0	1.0	0.0	3.2	3.1	0.0	2.8
3	Asbestos-Bonded Asphalt-Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	1.5
4	Uncoated Aluminum	2	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.5	0.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0	0.7	0.5
		6	0.0	0.0	0.0	0.0	0.0	0.0	0.9	1.1	0.7	0.8
5	Asphalt-Coated Aluminum	2	0.0	0.0	0.0	0.0	0.0	0.0	1.7	1.0	1.5	1.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5	0.5
		6	0.0	0.0	0.0	0.0	0.7	0.0	0.4	0.3	0.4	0.0
6	Structural Plate Arch	2	0.0	0.0	0.0	0.0	0.0	0.0	2.0	0.5	0.5	0.5
		4	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.4	0.8	0.5
		6	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5	0.9	0.8
7	12-Mil Coal-Tar-Based Polymer Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	1.5	0.5	0.0	2.5
		4	0.0	0.0	0.0	0.0	0.0	0.0	2.5	1.5	0.0	2.5
		6	0.4	0.0	0.0	0.0	0.0	0.5	2.5	2.7	0.3	2.6
8	20-Mil Coal-Tar-Based Polymer Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.5	0.0	2.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	2.0	2.0	0.0	2.5
		6	0.0	0.0	0.4	0.0	0.0	0.0	1.9	3.3	0.4	3.5
9	10-Mil Polyethylene Coated Galvanized	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		6	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	a
10	12-Mil Polyethylene Coated Galvanized	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		6	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	a
11	10-Mil Polymeric Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

a - Test Pipe Missing

LABORATORY RATING OF TEST PIPE COATINGS

TABLE 8

			Mild >1500 ohm-cm			Corrosive 500-1500 ohm-cm			Very Corrosive <500 ohm-cm			
Pipe No.	Type Pipe	Years Exposed	Site 4	Site 5	Site 8	Site 1	Site 2	Site 3	Site 6	Site 7	Site 9	Site 10
2	Asphalt-Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5
		4	0.0	0.0	1.4	1.3	2.0	1.3	2.0	2.4	1.4	2.3
		6	0.6	0.2	2.0	2.7	2.3	1.5	2.3	2.5	1.2	3.5
3	Asbestos-Bonded Asphalt-Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.0	0.5
		4	0.0	0.0	0.0	1.3	2.0	1.3	2.0	2.4	1.4	2.3
		6	0.3	0.0	0.0	2.7	2.3	1.5	2.3	2.5	1.2	2.5
5	Asphalt-Coated Aluminum	2	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.0	1.5	1.0
		4	0.0	0.6	1.3	2.2	2.5	2.5	1.6	2.0	3.6	4.4
		6	0.0	0.8	2.2	2.8	3.0	3.0	3.2	1.9	2.6	3.8
7	12-Mil Coal-Tar-Based Polymer Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	0.5	1.0	1.0	1.5
		4	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.7	0.5	0.9
		6	1.0	0.0	0.8	0.0	0.4	0.5	3.3	2.9	1.7	2.6
8	20-Mil Coal-Tar-Based Polymer Coated Galvanized Steel	2	0.0	0.0	0.5	0.0	0.5	0.5	0.5	3.5	3.0	3.5
		4	0.0	0.0	0.5	0.0	1.3	0.0	0.0	3.0	3.0	1.6
		6	1.1	0.8	2.6	0.6	0.4	0.6	1.7	3.9	2.0	4.2
9	10-Mil Polyethylene Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.3	2.0	2.0
		4	0.0	0.0	0.0	0.0	0.0	0.0	1.1	1.0	1.6	2.3
		6	0.0	0.3	0.0	0.0	0.0	0.0	1.5	1.0	0.5	a
10	12-Mil Polyethylene Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	2.0	1.5	1.3	2.3
		4	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.5	1.0	1.1
		6	0.4	0.0	0.0	0.0	0.0	0.0	0.6	0.6	0.4	a
11	10-Mil Polymeric Coated Galvanized Steel	2	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.8	0.6	2.3
		4	0.0	0.0	0.0	0-0	0.0	0.0	0.7	1.0	0.0	1.3

a - Test Pipe Missing

APPENDIX B

LABORATORY ANALYSIS OF TEST PIPE

ANALYSIS OF METAL PIPE BY X-RAY FLUORESCENCE

TABLE 9

Test Culverts	Elements								
	Zn	Cu	Ni	Ti	Ca	K	Mn	Mg	Si
Glavanized	tr	0.215	tr	tr*					0.8
A.C.G.P.	tr	0.20	tr	tr*					1.21
A.B.A.C.P.	tr	0.215	tr	tr*					1.98
Nexon (12-mils)	tr	0.215	tr	tr*	tr	tr	0.36		1.82
Nexon (20-mils)	tr	0.25	tr	tr*			0.4		1.48
Inland (12/5-mils)	tr	0.195	tr	tr*					1.2
Inland (10/3-mils)	0.065	0.175	tr	tr*			0.06		0.96
Wheeling (10/3-mils)	tr	0.26	<0.04	tr			0.4		0.18
A.C.A.P.	high,-1%	0.04						<0.1	
Aluminum Pipe	high,-1%	0.035						0.1	
Aluminum Arch	0.045	0.075						2.5	

NOTE: All values recorded are percent of material present.
A.C.G.P. = Asphalt-coated, galvanized steel pipe
A.B.A.C.G.P. = Asbestos-bonded asphalt-coated galvanized steel pipe
A.C.A.P. = Asphalt-coated aluminum pipe

tr = Trace, <0.01%
tr* = Trace, Extremely small, <0.001%
Ca & K = Amount unknown due to lack of standards; may be <0.1%

PIPE AND COATING THICKNESSES, AS MEASURED

TABLE 10

Type of Pipe	Gauge	Zinc Coating oz./ft.^{2}	Asphalt Coating oz./ft.^{2}(mils)	Other Coating mils
Galvanized Pipe	16	2.40	---	---
A.C.G.P.	16	3.03	3.03 (102)	---
A.B.A.C.G.P.	14	2.39	13.30 (200)	---
U.S.S. Nexon	16	2.77	---	16 (12*)
U.S.S. Nexon	16	2.70	---	12 (20*)
Inland Steel	16	2.52	---	Interior 10 (10*) Exterior 3 (3*)
Inland Steel	16	2.38	---	Interior 10 (12*) Exterior 5 (5*)
Aluminum Pipe	16	---	---	---
A.C.A.P.	16	---	2.55 (50)	---
Aluminum Plate	12	---	---	---
ıeeling Steel	16	2.64	---	Interior 10 (10*) Exterior 3 (3*)

* Nominal total thickness of "other coating."

Note: A.C.G.P. = Asphalt-coated, galvanized steel pipe
A.B.A.C.G.P. = Asbestos-bonded, asphalt-coated, galvanized steel pipe
A.C.A.P. = Asphalt-coated, aluminum pipe

CONDITION OF SAMPLES AFTER ONE MONTH
IN SALT FOG CHAMBER

TABLE 11

	Sample Type	Sample Condition
1	Galvanized Steel	Completely Corroded
2	A.C.G.P.	Slight Blistering Near Scribe and Edges
3.	A.B.A.C.G.P.	No Significant Effects
4	Nexon (12-mils)	Blistering Near Scribe and Edges
5	Nexon (20-mils)	Blistering Near Scribe and Edges
6	Inland (10/3-mils)	Blistering Near Scribe and Edges
7	Inland (12/5-mils)	Blistering Near Scribe and Edges
8	Aluminum Pipe	Cladding Pitted
9	A.C.A.P.	Very Slight Blistering Along the Edge
10	Aluminum Plate	Cladding Pitted
11	Wheeling (10/3-mils)	Blistering Along Surface

Note: A.C.G.P. = Asphalt-coated, galvanized steel pipe
A.B.A.C.G.P. = Asbestos-bonded, asphalt-coated, galvanized steel pipe
A.C.A.P. = Asphalt-coated, aluminum pipe

CONDITION OF SAMPLES AFTER 1500 HOURS
IN WEATHER-OMETER

TABLE 12

	Sample Type	Sample Condition
1	Galvanized Steel	No Significant Effects
2	A.C.G.P.	Asphalt Coating Cracked to Metal
3	A.B.A.C.G.P.	Asphalt Coating Cracked, Not to Metal
4	Nexon (12-mils)	No Significant Effect, Slight Discoloration
5	Nexon (20-mils)	No Significant Effect, Slight Discoloration
6	Inland (10/3-mils)	Complete Delamination of Coating
7	Inland (12/5-mils)	Complete Delamination of Coating
8	Aluminum Pipe	No Significant Effects
9	A.C.A.P.	Asphalt Coating Cracked to Metal
10	Aluminum Plate	No Significant Effects
11	Wheeling Steel (10/3-mils)	No Significant Effects

Note: A.C.G.P. = Asphalt-coated, galvanized steel pipe
A.B.A.C.G.P. = Asbestos-bonded, asphalt-coated, galvanized steel pipe
A.C.A.P. = Asphalt-coated, aluminum pipe

APPENDIX C

EVALUATION OF INDIVIDUAL TYPES OF CULVERTS AND FIELD EVALUATION FORM

Evaluation of Individual Types of Culverts

The ten original sites chosen for pipe installation were divided into three categories in terms of their soil corrosiveness as follows:

a) site 4, 5 and 8 are considered to be mildly corrosive.

b) site 1, 2 and 3 are considered to be corrosive.

c) site 6, 7, 9, and 10 are considered to be very corrosive.

Figure 8 of this appendix is a general view of the pipes ready for inspection at site 7 near the Gulf of Mexico.

Pipe No. 1 - Galvanized Steel Pipe

At sites 1, 2, 3, 4, 5 and 8 the galvanized steel pipes had minor corrosion of rivets, seams and the bottom of the pipes plus minor pittings.

At sites 6, 7, 9, and 10 the soil and effluent both exhibited low electrical resistivity values of less than 1000 ohm-cm. The galvanized steel pipe was completely rusted at these four sites with perforation of the metal at sites 6, 7 & 10. Figure 9 of this appendix shows this type of culvert after four years of in-service field exposure.

Pipe No. 2 - Asphalt-Coated Galvanized Steel Pipe

At sites 4 & 5, the pipes had minor removal of coating. The pipe at the remaining sites were reported by the panel to have moderate to heavy removal of the outer and inner coating plus rusty rivets. At two of the test sites (7 & 10) the panel noted perforation of the pipe.

Pipe No. 3 - Asbestos-Bonded Asphalt-Coated Galvanized Steel Pipe

This pipe is consistently performing very well in regard to corrosion resistance after six years in the field.

At sites 1, 2 and 10 the panel noted minor corrosion of the rivets and seams. Also, at site 10 the panel noted minor asphalt removal and edge corrosion.

Pipe No. 4 - Corrugated Aluminum Pipe

The supplier advised that in order to minimize corrosion of aluminum culvert the following conditions should be met: (1) soil and water pH should range between 4.0 and 9.0, (2) soil and water should have electrical resistivity values greater than 500 ohm-cm., unless the effluent is seawater and the surrounding soil is clean granular material, and (3) no dissimilar metals should be in contact with the aluminum.

At most of the sites which met the above pH and resistivity criteria, the aluminum pipes have performed very well. After 2 years of field exposure, the aluminum pipes exhibited staining, pitting, or localized thickness loss at sites where the soils and/or the effluent possessed electrical resistivity values near or below the 500 ohm-cm. (site #6, very corrosive area)

After four years of field exposure the test pipes at site numbers 1, 2, 3, and 4 were exhibiting the best resistance to corrosion. Test pipes at the other six original sites were experiencing pitting and/or thickness loss.

After 6 years of field exposure aluminum pipe at site number 1 is exhibiting the best resistance to corrosion. The pipes at sites 2, 3, 4, 5, 8, and 9 are exhibiting minor pitting while at site no. 6 the aluminum pipe is showing heavy pitting and perforations. The pipes at sites 3, 5, 7 and 10 are showing thickness loss.

Pipe No. 5 - Asphalt Coated Corrugated Aluminum Pipe

The asphalt coating was extensively removed from these test pipes at all test sites, except for sites 4 and 5. Only a minor portion of the coating was removed at these two sites. The panel made note of minor pitting and thickness loss at sites 2, 3, 6, 7, 9, and 10.

Pipe No. 6 - Aluminum Plate Arch

The panel noted that oxidation of this type of pipe was noticeable at all ten sites. At sites 1 through 8, the aluminum plate arches exhibited moderate pitting and thickness loss. At sites 6, 7, 9, and 10, the pipes were in the worst condition. At these four sites the panel observed severe pitting and thickness loss as indicated in figure 10 of this appendix. The pipes at sites 2, 9, and 10 also showed perforation of the metal. Sites 6, 7, 9, and 10 are located near the Gulf of Mexico and the electrical resistivity values of soil and effluent are low.

Pipe No. 7 - U.S. Steel Nexon (12-Mil Coating)

This galvanized steel pipe can be ordered from the fabricator with the thermoplastic, coal-tar-based laminate on either the inside or the outside. A 0.3 mil (0.008 mm.) organic coating is also applied to the reverse side. All of the U. S. Steel Nexon test pipes originally had the 12-mil coating on the interior except those pipes placed at site number 6.

At sites 1, 4, 5, 8, and 9 the pipes exhibited moderate corrosion of rivets, removal of the outer coating and separation of the inner coating.

The test pipes at sites 2 and 3 exhibited extreme removal of the outer coating. Also at site 3 the test pipe showed separation of the inner coating from the metal.

At site 6 (12-mils outside coating) the pipe exhibited heavy blistering of the outer coating, and complete removal of the inner coating, plus some corrosion of the riverts.

At site 7, the pipe lies in brackish water with a low electrical resistivity of 133 ohm-cm. At this site the inside coating was separated and blistered, the outer coating was removed from the metal and the pipe was perforated.

Site number 10 is located at the brackish water with a low electrical resistivity of 121 ohm-cm. The inside coating was blistered and separated, while the outer coating was removed from the metal.

Pipe No. 8 - U.S. Steel Nexon (20-Mil Coating)

The thermoplastic, coal-tar-based laminate can be ordered on the interior or on the exterior of this galvanized steel pipe. A 0.3-mil, (0.008-mm.) organic coating is applied to the reverse side. All of the U.S. Steel test pipes originally had the 20-mil coating on the inside except the ones at site number 6.

At sites 1 through 8 the test pipe showed minor corrosion of rivets, removal of outer coating and separation of inner coating from the metal.

The pipe at test site 6 (20-mils outside coating) showed minor blistering of the outer coating and extreme blistering of the inside coating.

At sites 7, 9, and 10 the pipe had extreme removal of outside coating and separation of the inner coating from the metal. At site 7, the pipe also showed perforation of the pipe.

Pipe No. 9 - Inland Steel (10-Mil Coating)

The panel noted that the rivets and seams on these pipes were corroding at all sites.

At sites 2, 3, 4, 5, and 6 the pipe showed moderate blistering and removal of the outer coating.

Sites 5, 6, 7, 8, and 9 the panel noted the separation of the outer and inner coatings. At sites 7 and 9 the pipes showed extreme blistering of the outer and inner coating. Also at site 7 the pipe was perforated.

The Inland Steel pipe was missing at site 10.

Pipe No. 10 - Inland Steel (12-mil Coating)

At all sites (except for site 5) the rivets and seams were corroding.

At sites 2 and 7 the pipes had some coating loss, while at sites 1, 3, 4, 6, 7, 8, and 9 the pipes showed minor blistering and separation of the coating. At site 6, the pipe also showed extreme separation of the outer and inner coating plus perforation.

The Inland Steel Pipe was missing at site 10.

Pipe No. 11 - Wheeling Steel (12-mil Coating)

This type of test pipe is resisting corrosion very well at sites 1, 2, 3, 4, 5 and 8 after only four years in the field. At sites 6, 7, 9, and 10 the panel noted moderate to extreme blistering, separation of the outer and inner coatings and rusty rivets.

At sites 6, 7, 9 and 10 the soil and effluent have low electrical resistivity values.

Site Eleven (First Evaluation- Two Years of In-Service Exposure)

Evaluation of Individual Types of Pipes

Pipe No. 1 - Galvanized Steel Pipe

No signs of corrosion.

Pipe No. 2 - Asphalt-Coated Galvanized Steel Pipe

No signs of corrosion.

Pipe No. 3 - Asbestos-Bonded Asphalt-Coated Galvanized Steel Pipe

No signs of corrosion.

Pipe No. 4 - Corrugated Aluminum Pipe

Pitting and minor thickness loss.

Pipe No. 6 - Aluminum Plate Arch

Extreme pitting and minor thickness loss.

Pipe No. 7a - U.S. Steel Nexon (10-Mil Coating Interior & Exterior)

Minor pitting on the outer and inner coating.

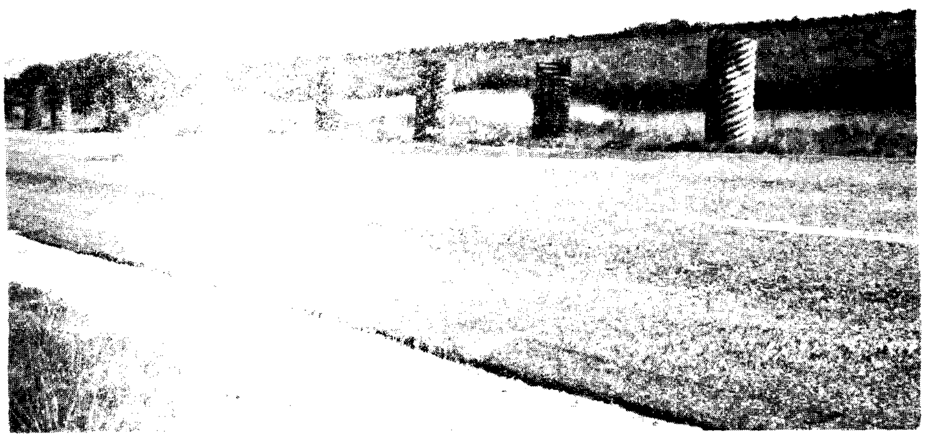
Pipe No. 8a - Inland Steel (8-Mil Interior and 4-Mil Exterior Coating)

Minor pitting of the outer and inner coating.

Pipe No. 9a - Wheeling Steel (10-Mil Interior and 3-Mil Exterior Coating)

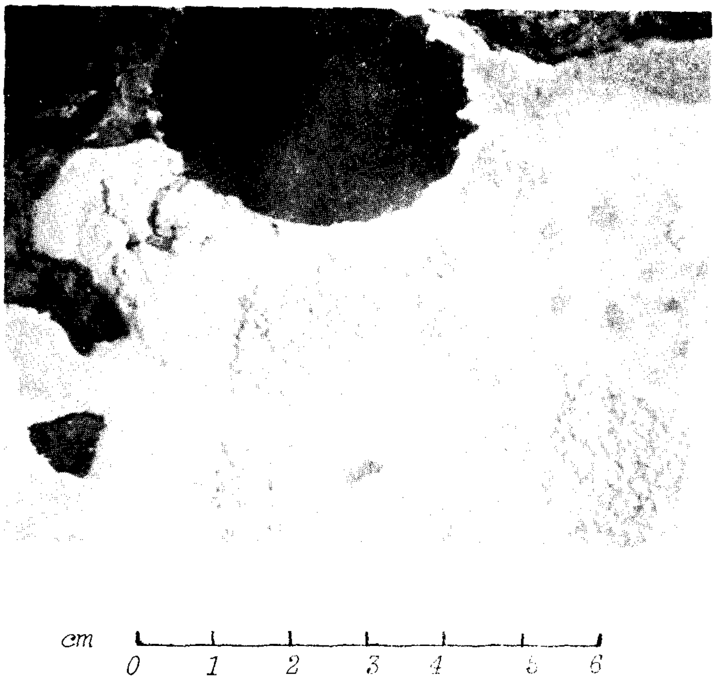
Minor corrosion of rivets and blistering of inside coating.

... Laboratory Testing



... Pipes at Site 7

Galvanized Steel Culvert at Site No. 7 after Four Years
FIGURE 8



Note: 1 cm = 0.39 in.

Aluminum Plate Arch After Six Years
FIGURE 9

Date: ______________________ Evaluation No.: ______________________

Location No.: ______________________ Evaluated By: ______________________

Pipe No.	Condition of Pipe					Condition of Coating							
	Excellent	Good	Fair	Poor	Very Poor	Blistering		Removed		Other		Good	
						I	O	I	O	I	O	I	O

(1) Excellent condition - If, under visual observation, there are no signs of deterioration.
(2) Good condition - If, under visual observation, there are very slight signs of deterioration and pitting.
(3) Fair condition - If, under visual observation, there are moderate signs of deterioration and pitting.
(4) Poor condition - If, under visual observation, there are extreme signs of deterioration and pitting.
(5) Very poor condition - If, under visual observation, there are signs of complete deterioration, and the pipe is no longer useful as a drainage tool.

Type of Fluid Flowing: ______________________

Other Comments: ______________________

O = Outside Coating
I = Inside Coating

Sample Field Evaluation Form
FIGURE 10