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ALUATION OF HIGHWAY CULVERT COATING PERFORMANCE

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FOREWORD

This report presents the results of an evaluation study and recommends improvements in current practices and procedures on protective coatings for highway culverts. This evaluation consisted of conducting field investigations in nine States and a comprehensive literature review on the following types of coatings: asphalt, asbestos bonded asphalt, asphalt paving, coal tar laminate, polyethylene, PVC, vinyl plasticsol, aluminized, aluminum-zinc, and epoxy coated concrete.

Additional coatings and methods of protection are suggested which may be superior to existing coatings, but have not been sufficiently evaluated to justify additional cost. An evaluation program is presented for potential improvement in existing culvert specifications and recommendations. This report will be of primary interest to supervisors and engineers responsible for the design, construction, and maintenance of culverts and pipes used in highway and road drainage systems.

This report is being distributed under FHWA Bulletin with sufficient copies of the report to provide a minimum of three copies to each regional office, three copies to each division, and five copies to each State highway department. Direct distribution is being made to the division offices.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

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16. Abstract

The objective of this study was to evaluate the performance of coatings for highway culverts and to recommend methods of improving culvert service life through improved coating systems and other means. A literature search was conducted through a review of technical literature and interviews with cognizant state officials throughout the United States. The literature search revealed durability problems with the most commonly used materials and coatings. Corrosion and erosion of interior surfaces appear to be the most serious durability problems in most states. Field investigations conducted in nine states confirmed the findings of the literature search. Most coatings exhibit durability problems under conditions of abrasive bed load and extreme corrosivity. Coating types examined at various test sites and actual drainage installations include: asphalt, asbestos bonded asphalt, asphalt paving, coal tar laminate, polyethylene, PVC, vinyl plastisol, aluminized, aluminum - zinc and epoxy coated concrete. The best overall coating appears to be asphalt coated and paved asbestos bonded galvanized steel, although significant deterioration is probable with this coating under certain conditions. Organic coatings applied to local areas where needed might be more cost effective than present complete coating methods. Other coatings and methods of protection are suggested which might be superior to existing coatings. Many of these alternative methods are more costly than existing coatings and their benefits are not defined yet. Durability evaluations are needed to deterimine if their use is justified. A review of existing State culvert specifications and recommendations for improvement are included. An evaluation program is presented.

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OBJECTIVE

The objective of this study was to evaluate the performance of coatings for highway culverts and to recommend methods of improving culvert service life through improved coating systems and other means. A literature search was con-ducted through a review of technical literature and interviews with cognizant state officials throughout the United States. The literature search revealed durability problems with the most commonly used materials and coatings. Corrosion and erosion of interior surfaces appear to be the most serious durability problems in most states. Field investigations conducted in nine states confirmed the findings of the literature search. Most coatings exhibit durability problems under conditions of abrasive bed load and extreme corrosivity. Coating types examined at various test sites and actual drainage installations include: asphalt, asbestos bonded asphalt, asphalt paving, coal tar laminate, polyethylene, PVC, vinyl plastisol, aluminized, aluminum - zinc and epoxy coated concrete. The best overall coating appears to be asphalt coated and paved asbestos bonded galvanized steel, although significant deterioration is probable with this coating under certain conditions. Other coatings and methods of protection are suggested which might be superior to existing coatings. Many of these alternative methods are more costly than existing coatings and their benefits are not defined yet. Durability evaluations are needed to determine if their use is justified. A review of existing state culvert specifications and recommendations for improvement are included. An evaluation program is presented.

PREFACE

This study is part of a continuing effort to improve the performance of highway culverts, and in doing so, lower the cost of highway maintenance.

We wish to thank all of those individuals in the various State highway departments for their cooperation in giving the experiences of their States with regard to culvert performance and for supplying specifications and technical data. The cooperation and assistance of those States in which we performed the field inspections is most appreciated. We also thank those coating fabricators and coating suppliers that we contacted for their cooperation.

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SUMMARY

One of the primary methods of extending highway culvert life is to apply a protective coating. The purpose of this study is to evaluate the performance of the coatings used and to determine if better performance can be achieved through the use of other methods or coatings. The study included a literature review of the existing state of the art, a field survey of coated culverts in nine states, a review of methods to improve existing coatings, a review of alternative coating systems and methods of protection and a review of existing specifications.

Protective coatings used by the States include barrier coatings and sacrificial metallic coatings or a combination of both. Most coatings and materials used present durability drawbacks in many situations, thus requiring the use of more costly materials or higher maintenance cost through a lower life expectancy. Many states, either individually or through the Federal Highway Administration, have conducted surveys to establish coating and material performance under extreme and typical conditions. Coatings evaluated by the states include asphalt, asbestos bonded asphalt, various polymerics, epoxies, zinc coating, aluminum coated steel and aluminum-zinc coated steel. Materials investigated include steel, clad aluminum, stainless steel and concrete. Fiberglass and polyethylene are being evaluated in a few cases.

Most states have criteria to determine which coating and material to use in a given exposure situation. One criteria is California Method 643, which utilizes pH and resistivity to establish a life expectancy basis. Because of the wide range of conditions throughout the country, this method is not universally applicable.

Field inspections at 82 locations in 9 states indicate that most coatings are effective in situations where runoff does not include abrasive debris and the water does not contain a high percentage of soluble salts, particularly chlorides. All organic coatings inspected are subject to impact and abrasion deterioration and most will deteriorate under wet alkali or salt conditions. Low pH conditions do not seem to deteriorate the coating as much as attacking the metal substrate at coating defects, causing disbondment. The best all around existing coating system is asbestos bonded asphalt coated and paved galvanized steel.

The most commonly used coating, asphalt, suffers from poor adhesion under immersion conditions, low impact

strength at low temperatures and water penetration leading to removal from the substrate. Less than adequate surface preparation prior to coating and ill-defined application techniques impair this coating's performance. Possible improvements to this coating include the use of organic additives to improve adhesion and blending with other components such as inorganic fibers or organic polymers to improve mechanical properties.

Certain methods might be useful for protecting culverts in erosive conditions instead of organic coatings. Such methods include the use of stilling basins, energy dissipators and reinforced paving.

Alternative coating systems might prove beneficial for protecting culverts. Coating systems include urethanes, epoxies, neoprene, fusion-bonded coatings, ceramics and metallized coatings. While these coatings are more costly than any current culvert coating, they have the advantage that they can be applied only where needed, such as on the invert. Additional study is desirable to identify the most cost effective coatings.

Several primers and wash primers were evaluated in laboratory screening tests to determine if improvements in the adhesion of asphalt and other coatings to galvanized steel can be obtained. The tests show that some adhesion improvement is possible but that further work is needed to establish the cost effectiveness of primers under culvert exposure conditions.

State specifications could benefit from some additions regarding procedures for protecting coated pipe. Suggested additions are included in this report. AASHTO specifications, notably M190, M243 and M246, are used by most states to specify culvert coatings. Recommendations are made for additions to these specifications.

INTRODUCTION

Culvert life expectancy is determined by material durability and structural durability. Material durability refers to the ability of rigid or flexible drainage pipe to resist deterioration due to the natural processes of corrosion, abrasion and erosion. Structural durability is the ability of rigid or flexible drainage pipe to carry the static and dynamic stresses and strains imposed by the earth and traffic without deterioration. Total durability is a function of both of these interdependent factors and both are essential to satisfactory performance and service life of any drainage pipe. This study is concerned with material durability.

Erosion by runoff debris can gradually abrade the pipe material. Corrosion can deteriorate the pipe material on both internal and external surfaces. Appendix A presents a brief description of the corrosion process. Several methods can be used to combat corrosion and abrasion. These include: coatings, linings, cathodic protection, increased metal thickness and alternate materials selection.

Coatings used on culverts can be divided into two major categories, that is, metallic and barrier. Metallic coatings are either intended to present a corrosion and abrasion resistant surface to the environment and/or provide protection to the base metal by acting as the anode in a galvanic cell (cathodic protection). Not all metallic coatings offer sacrificial protection to the base metal. For example, chromium coatings are cathodic to steel. Sacrificial coatings such as zinc, aluminum or aluminum zinc on steel, and aluminum cladding are used on drainage pipe. Barrier coatings are used to prevent contact between the material to be protected, metal or concrete, and the environment. Organic coatings are often used effectively in conjunction with sacrificial coatings. Barrier coatings used on drainage pipe include bituminous coatings (asphalt dips, mastics), epoxies and thin film polymeric coatings. Invert protection against abrasion and corrosion can be provided by asphalt paving, clay, cement or fiberglass linings. Other types of coatings such as passivating conversion coatings and inhibited coatings are not used on drainage pipe.

Cathodic protection is a method whereby direct current is applied to a corroding metal to make the entire surface a cathode. The direct current is applied by using sacrificial anodes or impressing current from an external rectifier through anodes to the protected surface. Cathodic protection is most usable on the external surfaces of drainage pipe and will not prevent abrasion or corrosion of non-immersed areas. Cathodic protection is seldom used on drainage pipe.

Increasing metal thickness to compensate for expected corrosion and erosion losses is a method of increasing the life expectancy of culverts. The degree of expected corrosion and/or erosion must be known for the site involved. Severe corrosion or erosion limit the applicability of this method making other methods more cost effective for a particular situation.

Materials known to be durable in severe environments can be used in place of coatings or other measures. These materials include: aluminum, concrete, vitrified clay, stainless steel, polymers and fiberglass.

The purpose of this study is to evaluate the effectiveness of various protective coating systems in controlling the deterioration of drainage pipe. This project included seven tasks as follows:

1. Literature review
2. Field investigations
3. Performance review of asphalt coatings
4. Evaluation of coating need and alternatives
5. Coatings other than asphalts
6. Improving coating bond to galvanized steel
7. Specification review

This report summarizes the findings of these tasks and presents conclusions and recommendations for future action.

DISCUSSION

Literature Review

Table I presents a summary of the literature review findings and Appendix B summarizes the interviews and technical literature.

Contact with knowledgeable individuals in each of the fifty states provided information on culvert materials and performance. Appendix C lists the references used throughout the study. Additional sources utilized were the National Association of Corrosion Engineers (NACE) abstracts, National Technical Information Service (NTIS), American Association of Highway and Transportation Officials (AASHTO), American Concrete Pipe Association (ACPA), American Corrugated Steel Pipe Institute (ACSPI), American Society for Testing and Materials (ASTM) and American Iron and Steel Institute (AISI).

Most states use essentially the same drainage pipe materials. Culverts are fabricated from galvanized steel, clad aluminum and various types of concrete. Additional materials for under-drains and culverts include vitrified clay, bituminized fiber, asbestos cement, polyvinylchloride (PVC) and acrylonitrite-butadiene-styrene (ABS). Coatings used to protect metallic culverts also are similar from state to state. Bituminous coatings to include asphalt dipped and asbestos bonded asphalt are the most common. Polymeric coatings are beginning to be used more frequently with U.S. Steel Company Nexon coal tar laminate having the longest service history of the polymers. Other polymeric coatings being tested are Inland Steel Company Black Klad, Wheeling Steel Company Plasticote, Bethlehem Steel Company Beth-Cu-Loy PC and Republic Steel Company Polycote. Metallic coatings (excluding zinc) such as aluminum and aluminum-zinc on steel are being evaluated in several states. Epoxy coatings are used to protect concrete in acidic areas in some states.

Coating deterioration, particularly with asphalt, is common. Asphalt dipped pipe is subject to asphalt disbondment both in abrasive and non-abrasive conditions. Reasons cited for poor asphalt performance include water penetration, either through the coating or through coating defects, alternate freezing and thawing, mechanical abrasion, poor or variable asphalt quality and inadequate application techniques.

Asphalt application techniques are similar from fabricator to fabricator. Asphalt is usually applied to galvanized steel by immersing the completed culvert pipe into an open liquid asphalt bath for a period of time. Most states use AASHTO Specification M190 to govern coating thickness and quality. AASHTO M190 does not specify either pipe cleaning procedures or application procedures. Pipe is immersed in asphalt at a temperature of about 400°F (204°C) for a time thought to be sufficient to attain asphalt adhesion. Immersion times, although critical, are not uniform and mostly depend on experience, or in a few cases, are the result of testing programs. There does not seem to be quantitative procedure for shop testing asphalt adhesion. Although two studies reported improvement in asphalt adhesion to zinc by chemically pre-treating the surface[38,43], there is no commonly used pre-treatment of the zinc surface other than occasional removal of soil and drying. Asbestos bonding improves asphalt adherence and is usually used where severe applications are expected. There is evidence to suggest that certain chemicals in water runoff can corrode the zinc substrate and loosen asbestos fibers[9]. An effective barrier coating should increase culvert life even if the underlying metal is corroded by limiting the surface area of metal exposed to the corrodent. There are indications from some states that asphalt quality varies resulting in field performance differences. This is discussed more fully in the section on Asphalt.

Polymer coatings reportedly suffer from poor adhesion in corrosive environments at areas where the coating to metal interface is exposed such as at section joints. Another problem appears to be the abrasion resistance of the relatively thin film coatings. Lack of adhesion between coal tar laminate coating and asphalt paving was also reported, however, other sources indicate better adhesion of asphalt to polymeric coatings than to galvanized steel. This investigator has seen proprietary data showing an order of magnitude increase in adhesion between asphalt and a vinyl plastisol coating over that between asphalt to galvanized steel and asphalt to asbestos bonding using the reverse impact test method.

External corrosion in most areas does not seem to be as much of a problem as interior corrosion and erosion. In areas where external corrosion is a problem, non-metallic and metallic coatings are used with varying degrees of success. Concrete is usually used in severely corrosive areas. Most concrete is installed uncoated. Cathodic protection (excluding sacrificial coatings) is not used to protect exterior culvert surfaces and is not applicable to interior surfaces unless the culvert is immersed in water. Attempts to use cathodic protection appear to have been limited to uncoated galvanized culverts. This would be costly to do and somewhat impractical to protect a sacrificial finish. Cathodic protection is best applied to coated surfaces to minimize protective current requirements and reduce costs. Metal surfaces intended for cathodic protection need not be coated with a sacrificial metal. Further discussion of cathodic protection is presented in the section on Alternate Methods.

Field Investigation

Professional Services Group investigators conducted a field survey in nine states to supplement the literature survey. States were selected from which the maximum amount of information could be obtained and on the basis of exposure condition types, culvert and coating materials used and existence of test sites where information could be gathered for a large number of coatings under similar exposure conditions. The states selected for the field study were: California, Colorado, Kentucky, Louisiana, New York, Ohio, Oregon, Pennsylvania and Utah.

Culvert test sites were selected after discussions with state Department of Transportation engineers. We made an effort to include as many types of coatings and service conditions in the study as possible. The preponderance of asphalt coated culverts inspected reflect the fact that asphalt is still the major coating material used. We selected test sites to include a broad range of exposure conditions so as not to bias the results with extremes of service exposures. Culvert locations were selected so as to minimize chances of finding high water levels as this would prevent inspection of the interior. Generally, the minimum size culvert examined was 76.2 cm (30 in.) to allow inspection of the interior. Smaller sizes were examined when necessary. A total of 108 culverts were inspected at 82 highway and test sites. Table II presents a breakdown of the inspection by state and coating type.

A. Procedures

Information obtained at each site included:

1. General

   Location, type, size, construction material, coatings, installation date, maintenance history and prior inspection information.

2. Environmental

Measurements were taken to establish the service conditions at the culvert tested. These included: soil and water pH, soil and water resistivity, sulfides in the soil, sulfates and chlorides in the soil and water, alkalinity and hardness of the water (if present). Resistivity, pH and sulfide tests were performed in the field. Chloride, sulfate, alkalinity and hardness tests were performed in the laboratory using portable test kits (Hach). Minimum resistivity measurements were performed on soil samples by saturating the soil with deionized water and measuring the resistivity in a soil box. Field resistivity readings were taken using the Wenner 4 pin method with spacings at 5, 10 and sometimes 15 feet, depending on pipe depth. All pH readings were made with a portable analog pH meter. Sulfides were measured using a specific ion electrode, however, sulfides were not detected at any location tested. Tests were not replicated unless a question arose as to validity of a particular measurement. Questions of this nature were satisfactorily resolved in replicate tests. Measurement precision is as follows: chloride (±10%), sulfate (±35 mg/l), alkalinity (±17 mg/l), hardness (±17 mg/l), resistivity (±1%), pH (± .1 pH unit).

Approximate flow rates through culverts were measured where water was present by timing the passage of a floating ball through the culvert. These flow rates, being taken at times of low flow, do not necessarily represent maximum flow conditions.

3. Culvert Pipe Condition

This was done visually and by the use of an ultrasonic thickness instrument, micrometer and pit depth gauge. Detailed corrosion loss measurements were not taken since the primary purpose of the inspection was to evaluate the coating.

Exterior surfaces were examined by cutting 5 cm (2 in.) diameter samples from the invert. Samples were examined in detail in the laboratory. Three samples were usually taken approximately 10° from the invert at least 3.05 m

(10 ft.) apart. The first sample was cut at least 30.5 m (10 ft.) from the inlet or outlet. We originally planned to remove more samples but sample condition was uniform and we felt that no additional benefit would be gained by cutting more samples. We used a high speed steel hole saw and a 12 volt D.C. battery powered drill. Holes were repaired using an expandable rubber stopper (See Figures 1 & 2). Samples were not removed from all culverts because of high water level, small size or the lack of an exterior coating. Soil samples for pH and resistivity measurements were removed from the sample holes where applicable.

Electrochemical potential and polarization data[20,40] were obtained on most culverts to supplement the samples. Polarization tests utilized the E-log I and polarization resistance methods to measure corrosion current for comparison between locations. Test instrument accuracy is ±.2 percent full scale or better. Polarization data can be used as a means of evaluating the relative coating condition and the protective current needed if cathodic protection were to be used. Polarization data is currently being used to evaluate corrosivity in at least three states (Arizona, Utah, Michigan) and the method was suggested as a means of evaluating coated pipe[52].

Polarization measurements can not, however, be used to determine absolute corrosion rates. This is because test current flows only to areas such as edges, rivets and coating defects which allow the electrolyte to reach the pipe surface. Unless the magnitude of these areas are known by some means, the corrosion current density can not be calculated and an accurate corrosion rate can not be determined. A method which averages the corrosion current over the entire surface area, which might be valid for an uncoated culvert, yields a low and misleading corrosion rate. The corrosion rate of an exposed metal surface on a coated pipe is likely to be greater than the corrosion rate of a similar uncoated culvert because galvanic corrosion currents, such as caused by oxygen differential cells are concentrated on a small area. Resistance and capacitance measurements are better methods of evaluating coating performance. They have proven utility in laboratory tests[84] but have not been established as being useful tests in field applications.

A pipe corrosion condition rating was assigned to each culvert based on the condition of the interior exposed metal, if any. The rating system is defined in Table IV.

4. Coating Condition

Interior coatings were examined for coating disbondment, adhesion, blistering, erosion, checking and cracking. A coating condition rating was assigned as defined in Table IV. Coating thickness was measured on the flat portion of the corrugations in several random areas with a nondestructive magnetic-eddy current gauge. Adhesion tests were qualitative in nature made by prying off the coating in several areas. Quantitative adhesion data was not obtained as a reliable test is not available in our opinion.

Random interior culvert surfaces were inspected for coating defects which would expose the culvert metal to water by using a low voltage (67.5 volt) coating fault detector.

Table III lists the culvert sites inspected and provides information on culvert size, age, type of coating and location. Table IV contains a summary of the field data for the sites listed in Table III.

B. Results-General

All of the coatings inspected appear to perform similarly under similar exposure conditions. The data presented in Table IV establishes the environmental conditions affecting the culvert and its coating. Comparisons between environmental data and culvert condition do not show strong cause and effect behavior. Relationships examined are as follows:

1. Corrosion Condition <u>vs</u>:

		dipped asphalt	coal tar laminate
a.	water pH	r = .07	r = .34
b.	water resistivity	r = .07	r = .51

c.	water sulfate content	r = -.18	r = -.34
d.	water chloride content	r = -.19	r = .57
e.	sulfate and chloride	r = .18	r = -.67
f.	pH and resistivity	r = .01	r = .20

2. Coating Condition <u>vs</u>:

a.	water pH	r = -.18	r = .06
b.	water resistivity	r = -.05	r = .64
c.	water sulfate content	r = .20	r = .17
d.	water chloride content	r = -.17	r = .51

Figure 3 illustrates the linear regression curve of coating condition of coal tar laminate coatings versus water pH. Each of the correlation coefficients were tested against the hypothesis that no dependency exists using the following relationship:

$$Z_\alpha = \frac{\sqrt{n-3}}{2} \ln \frac{(1 + r)}{(1 - r)} \qquad \text{(ref. 56)}$$

Where Z = standardized random variable for a normal distribution

n = number of sample points

r = correlation coefficient (a measure of the closeness of the correlation, ±1 = perfect dependency)

α = 95% confidence level

No significant relationships were found between these variables at a 95 percent significance level.

We also attempted to establish a correlation between environmental data and Corrosion Condition using the following relationships: power function ($Y = Ax^n$), exponential function ($Y = A^{nx}$) and polynomial function ($Y = A+Bx+Cx^2+Dx^3+\ldots$). The data tested in this analysis was obtained at coal tar laminate coated culvert sites and include pH, resistivity, sulfate, chloride and equivalent weights (of sulfate and chloride). The analysis utilized a computer program using least squares curve fitting techniques. We did not establish a reasonable relationship between any of the variables tested. This analysis confirms the results of the linear regression analyses so that testing of additional data was not considered worthwhile.

The ability of water to form a protective scale can influence the corrosion rate of metal. Two measures of a water's ability to scale or not to scale are the Langelier Index and the Ryznar Index[57]. Briefly, the Langelier Index is defined as the algebraic difference between the actual pH and the pH at which a water is saturated with $CaCO_3$. Positive Index values represent waters with scaling tendencies and negative values represent nonscaling. The Ryznar Index is empirical and is defined as 2 x pH at which $CaCO_3$ saturation occurs minus the actual pH. Values above 7 represent scaling waters and values below 6 indicate corrosive tendencies. Although not on the original test plan, we felt that it might be beneficial to determine if there was a relationship between the scaling tendency and corrosion condition. We chose the Ryznar Index as it presents a continuous scale which can be used to estimate magnitude and is relatively fast to calculate. Additional data needed to calculate this index is the hardness and methyl orange alkalinity which were gathered starting with test site 23 of Tables III and IV. The Ryznar Index is calculated as follows:

$$pH_s = \log \frac{K_s}{K_2} - \log (Ca{+}{+}) - \log (alk) \quad \text{(ref. 58)}$$

Where: K_2 is the second dissociation constant for carbonic acid

K_s is the activity product of calcium carbonate

Ca++ is expressed in mg/1 Ca

alk (alkalinity) is expressed in mg/1 $CaCO_3$

Figure 4 presents the resulting correlation. Corrosion condition appears to correlate with the Ryznar Index at a significance level of 95% but not at a 99.5% level. However, the general trend indicates that the more corroded culverts are found at greater Ryznar Index values. This would not be the predicted relationship since the greater Pyznar Index values are associated with the lower corrosion tendency. A similar relationship was also found to exist between the Ryznar Index and coating rating. Again, this data is significant at the 95% level but not at a 99.5% level (See Figure 5). The scatter in this data is too wide and the number of data points too small to draw firm conclusions, but perhaps the method deserves further investigation for use as a design tool.

Coating condition appears to be significantly related to corrosion condition as shown on Figure 6. This appears reasonable because many of the environmental factors which lead to coating deterioration also cause corrosion of the pipe.

Significant correlations between corrosion current (all coatings) and: average soil resistivity (r = -.12), minimum soil resistivity (r = .12), soil pH (r = -.10), age (r = .24), total culvert surface area (r = .16) and pipe to soil potential (r = .18) were not found. This indicates that corrosion current is related to both the corrosivity factors and exposed surface area which can not be measured with presently known methods.

Comparison of the internal coating condition (CtgC) by the three major coating types inspected yields the following mean coating conditions (See also Table IV).

Coating	Unpaved		Paved	
	Mean CtgC	No. Culverts	Mean CtgC	No. Culverts
Asbestos Bonded Asphalt	3.4	9	4.25	8
Coal Tar Laminate	3.1	20	-	-
Asphalt	2.3	15	1.73	15

Applying statistical methods to determine the significance of the differences in means at the 95% level, we find that the only difference in coating condition occurs betweem coal tar laminate and asbestos bonded asphalt and that no differences exist at the 99.5% level. This means the three unpaved coating types would probably perform similarly under similar conditions. The effect of asphalt paving would seem to improve the performance characteristics of asbestos bonded asphalt coated pipe and reduce the performance of the asphalt coated pipe. We think the anomaly with the asphalt paving is caused by the small number of sample sites inspected and is probably not a true indication of the effect of asphalt paving.

The lack of statistical correlation and evident scatter can be traced partially to the limited number of sites that could be included in this survey. Another factor is variability of the data at a given site. It is likely that the pH, resistivity, scale forming tendencies and abrasive characteristics of the streams flowing through the culverts change considerably depending on seasonal precipitation conditions. Most test sites were examined under conditions of normal flow as evidenced by wear patterns on the culverts and in the streams. Rapid changes do occur, however, as evidenced by the doubling of water volume and velocity in a culvert in California during a light rainfall as it was being inspected. It is also apparent that the measured flow rates do not reflect the worst conditions to which the pipe is exposed.

Coating deterioration on the culverts inspected was limited to the invert section and most invert damage seemed to occur in areas of normal stream flow. Abrasion and impact loading by rocks and other debris appear to be a major cause of deterioration. Small stones appear to be as capable of causing erosion damage as large rocks based on observations made at each site. The embrittling effect of asphalt in cold weather can be a factor in impact and abrasion deterioration but is not the sole factor as similar deterioration was observed in the warm climate of southern California. Coating damage above the normal stream flow level was not observed at any of the culvert sites inspected. Coatings above normal stream flow level protect the pipe from corrosion and adhere well to the galvanized steel.

C. Results-Individual Coating Types

1. Asphalt

a. Field Applied Asphalt

Figures 7 and 8 illustrate two culverts with field applied mastic which were subject to abrasive flow conditions. Figure 9 shows a culvert with field applied mastic exposed to alkali water. Generally speaking, the field applied mastics inspected exhibited poor performance. Coating thickness measurements revealed that coatings were not uniformly applied. The average thickness being below the .127 cm (.050-inch) minimum specified by AASHTO and the states.

b. Mill Applied Asphalt

Figures 10 and 11 illustrate damage to asphalt dipped culvert pipe. The damage in Figure 10 was caused by abrasion and impact while that in Figure 11 was apparently the result of high chloride and sulfate concentrations in the water. Test samples in Louisiana show extensive damage to asphalt dipped galvanized steel when subjected to a non-abrasive environment containing chlorides and sulfates (numbers 67, 68). Figure 12 illustrates a pure abrasion failure on a 2 year old steeply sloped culvert in California. There was no water flow at the time but the maximum flow level was indicated to be one-half the 1.52 m (60-inch) diameter with rocks up to 6-inches and other debris visible. We performed a coating thickness profile on the downstream side of the corrugations and found a definite erosion loss on the invert. Mean coating thickness on the unaffected portions was .148 cm (.058-inch) whereas in the abraded portion, the thickness was .115 cm (.045-inch). The zinc had eroded away on the upstream side of the corrugations sufficiently for general corrosion of the steel to occur. Figure 13 illustrates a debris crib used at one site. Unfortunately, as Figure 14 shows, this design is unsuccessful in preventing abrasion damage. Corrosive conditions affecting the culverts shown in Figures 10, 11, 13 and 14 could not have appreciably influenced the invert coating deterioration.

Figure 15 illustrates corrosion perforation of a connecting band on an asphalt coated asphalt paved culvert otherwise performing well. The coupling bands had apparently been field coated. This culvert was in an area of low resistivity water and rapid flow rate but no abrasion. The pipe coating was in very good condition, other than at connecting bands. A few locations were visible at section joints where the paving was recently removed as evidenced by bright galvanizing. This was apparently the result of turbulence at the joints. Figures 16 and 17 show two other culverts where turbulence at section joints caused coating loss and perforation. The asphalt coating and paving was in otherwise excellent condition.

The exterior performance of asphalt dipped pipe can be considered adequate. Core samples removed from the culverts exhibited fair to good coating adhesion and the coating seems to protect the pipe surface from serious corrosion. Mild corrosion of the zinc under the asphalt was observed on three core samples, numbers 18, 58 and 60. However, polarization tests indicate that the average total corrosion current existing on the external pipe surface of asphalt coated pipe is .022 ampere. This amounts to an average metal loss of .199 kg (.44 pounds) per year for exposed steel and .179 kg (.396 pounds) per year for exposed zinc. The average total culvert area of those sites tested is 155 sq. m (1675 sq. ft), with a range of 26-613 sq. m

(282-6597 sq. ft). The metal loss could be spread out over a large area or confined to a localized area which could result in a high or low corrosion rate. Pipe to soil potential measurements indicate that the average asphalt coated culvert has lost the zinc coating on metal exposed to the environment, the average pipe to soil potential being -.710 volt to a copper sulfate reference. We did not observe pipe perforations from the soil side. The average coating thickness on exterior surfaces is .401 cm (.158-inch) based on the core samples.

We conclude that asphalt coatings applied directly to galvanized steel by conventional methods are subject to deterioration at the ends where exposed to infrared light and in the stream flow channel where abrasion and erosion taken place. Deterioration of the invert sometimes appears as removal only at section joints, removal from the upstream side of the corrugations or complete removal.

Paving does not appear to appreciably improve performance under severely abrasive conditions. That is, rocks and other debris combined with high water velocity damage coating. Both conditions must be present. Large rocks were found in culverts with low flow rates not displaying coating damage although the flow must have been at least momentarily high to carry in the debris. Rapidly moving streams in themselves will not cause coating failure unless turbulence is present at coating discontinuities such as at section joints. Unfortunately, the field data and culvert service history are not sufficient to correlate flow velocity and bedload characteristics with asphalt deterioration. This would be a useful project. Water penetration into the coating and disbondment occur in the stream flow channel. Waters and soils containing relatively large quantities of chlorides and sulfates are capable of causing deterioration of field applied asphalt mastic and asphalt dipped pipe.

Deterioration at ends exposed to sunlight takes the form of cracking, checking, peeling and eventual removal of the coating by the stream flow.

Asphalt exhibits good performance where abrasion and salts are not a factor even in low pH environments and the performance above stream level is excellent.

Some improvements in asphalt performance should be possible. These include increased adhesion to the galvanized steel and increased abrasion resistance. The section on asphalt coating performance discusses these improvements in detail.

Six States have discontinued the use of asphalt coating, they are: Hawaii, Kansas, Maryland, Missouri, Pennsylvania and Tennessee. Asphalt is no longer used because it was found to provide an insufficient increase in service life to justify the cost. Poor service life in these states was the result of abrasion and impact failure. Two of these states, Missouri and Pennsylvania are using the organic coatings (polymerics); the others are of the opinion that organic coatings are unnecessary and that substitute materials, such as concrete, can be used in corrosive situations. See also Table VII for criteria in using uncoated pipe.

2. Asphalt Coated Aluminum

Inspections included only four asphalt coated aluminum culverts (two at test sites). Figure 18 shows a three year old aluminum coated culvert which was installed with a settling basin at the inlet. Some chipping of the coating is seen on the invert. Coatings on both aluminum culverts examined in field use were in good condition with little coating deterioration and no corrosion of the aluminum. Abrasion and rapid stream flows did not appear to be factors in the two culverts examined. Asphalt exhibits a poor bond to aluminum, being easily removed by prying. Figure 19 shows a test culvert from Louisiana exposed to a moderately corrosive environment in which almost no coating remains. While the condition in Figure 19 could be the result of periodic removals during inspections, it does illustrate the poor adhesion between aluminum and asphalt when conventional application techniques are used.

The sample size examined is too small to make firm conclusions but it appears that asphalt coated aluminum is unsuitable for abrasive locations. We do not know how paved aluminum would perform but suspect it would not perform as well as asphalt paved galvanized steel.

3. Asbestos Bonded Asphalt Coated Galvanized Steel

Asbestos bonded asphalt coated galvanized steel generally exhibited better performance than plain asphalt dipped galvanized steel. This coating is still subject to the same modes of deterioration as asphalt coated pipe, that is: checking and cracking at exposed ends and abrasion of the invert.

Figure 20 shows an unpaved culvert where the coating was removed from the upstream side of the corrugations. Stream velocity was important in coating deterioration as the coating was intact where the stream velocity decreased near the outlet. Figure 21 shows the interior of a culvert exposed to waters with a high salt concentration. The asphalt has delaminated from the saturated asbestos layer at and below the water level. Layer type corrosion is occurring on the steel. In many areas, although the asphalt has been removed, the steel is not corroded, being protected by the asphalt impregnated asbestos and zinc. This observation was made at several other locations. Figure 23 illustrates the asphalt delamination in alkali soil conditions at the Utah test site but no corrosion of the steel. Figure 22 shows an asbestos bonded asphalt coated test culvert exposed to brackish water from Louisiana's Hackberry test site. No significant coating deterioration was observed although asphalt delamination was observed at the Starks test site (number 76). Some of the delamination at the test sites might be the result of periodic removal operations but could also be the result of freeze thaw cycling. Adhesion of the asphalt to the substrate varied, but the mode of failure always consisted of tearing of the asbestos layer.

Asbestos bonded asphalt coating appears to protect the exterior pipe surfaces as well as asphalt. Average pipe to soil potential is -.660 volt to copper sulfate indicating depletion of the zinc at exposed areas. Average external coating thickness (includes galvanizing and asbestos layer) is .467 cm (.184-inch) based on the core samples. There is no significant difference between average asphalt thickness and that on plain asphalt dipped pipe.

4. Coal Tar Laminate

Coal tar laminate (U.S. Steel Nexon) exhibits good performance except under abrasive stream flows and in low pH and high salt environments. Figure 24 illustrates the beginnings of abrasive damage at corrugation crests. This particular culvert is in the Genessee Expressway (I-390) in New York and was about a year old when inspected. Most of the damage occurred during construction when angular shale passed through the culvert. Figure 25 shows a more advanced stage of erosion on a six year old culvert with a strongly acidic stream flow. In addition to the abrasion damage, the coating is disbonding from the substrate, probably as a result of zinc corrosion.

A pitch resin film is laminated onto the galvanized sheet which is then formed (at some future time) into a corrugated culvert. The culverts inspected in this survey contained a defect at the lock seam which did not seem to impair performance under mildly corrosive conditions but which could seriously impair performance in adverse environments. In the lock seam forming operation, the coating is cut completely through to the base metal by the tooling at the lock seam. Similar damage was observed on polyethylene coated aluminum test samples being installed at the Hackberry, LA test site. In corrosive conditions this defect acts as a point where the zinc is attacked and disbondment occurs. Figure 26 shows an extreme example of this where the invert coating is undercut and lifted up by the stream flow and is only restrained by a pipe passing through. Figure 27 shows another extreme case where the coating has lifted up and is acting as a dam, collecting silt and other debris. In both cases, no other deterioration of the coating was observed. Figure 28 shows a seven year old culvert in an acidic stream in Ohio. This culvert was reported to have perforated about one year after installation, probably as a result of disbondment starting at the lock seam. The condition which led to this deterioration can be corrected in the manufacturing procedure.

Figure 29 shows a coal tar laminate coated test culvert exposed to brackish waters at the Louisiana Hackberry test site for six years. General blistering is occurring over the entire surface although it is more severe at uncoated cut edges and coating defects. Similar blistering and disbondment at edges and the lock seam were observed in alkali soils at two Colorado test sites (No. 45, 48) but were not observed in the alkali soil of the Utah test site (No. 39). The major difference between the Louisiana, Colorado and Utah test sites is the greater chloride content at the Colorado and Louisiana test sites (see Tables III-IV).

Coal tar laminate protects the steel from soil corrosion (except in soil with a high chloride content) based on samples removed from the culverts examined and very limited polarization tests. Pipe to soil potentials indicate that the zinc is essentially depleted from exposed metal, the average potential being -.740 volt (Copper Sulfate reference).

The yellow coating (called a modified epoxy) used on the opposite side of single side coated Nexon has little or no protective value. When exposed to water containing high salt concentrations, the coating allows corrosion attack of the metal substrate (numbers 37, 66, 72, 75, 72, Table IV). The coating is applied thinly, the maximum thickness measured was .020 cm (.008-inch), and does not act as an effective barrier coating when tested with a coating fault detector. The average soil side corrosion current of the culverts tested was .06 ampere or 1.08 pound (.49 kg) per year zinc loss. Average surface area is approximately 137 sq. m (1482 sq. ft). Pipe to soil potentials indicate that zinc was still intact at each of the culverts using this coating. The reason that the zinc remains intact on the modified epoxy coated pipe and not with the other coatings is that the thin epoxy is not an effective barrier coat. Most of the zinc is exposed to the soil so that the corrosion current is spread over the surface and not concentrated at small areas. The resulting corrosion rate does not deplete the zinc as quickly at any one point.

5. Polyethylene

Polyethylene (Inland Black Klad) coated culverts were examined at test sites in Colorado, Kentucky and Louisiana. Figure 30 illustrates a sample removed from the brackish Louisiana Hackberry test site (No. 69, 70) and shows extensive general blistering and disbondment. Minor blistering was observed at coating discontinuities at the mildly corrosive test site at Starks (No. 80, 81). No deterioration was noted at the Dillon, Colorado test site (No. 55). Performance in the acidic waters of Kentucky's Mortons Gap test site (No. 94) is satisfactory except for some disbondment at uncoated edges.

6. Polyvinyl Chloride

Polyvinyl Chloride (PVC) as manufactured by Wheeling Steel Company (Plasti-Cote) coated culverts were inspected at test sites in Colorado and Louisiana. PVC coating performance is similar to polyethylene, developing blisters over the surface in areas with high chloride content. Figure 31 shows a PVC coated test culvert removed from Louisiana's Hackberry test site (No. 71). Minor blistering at the lockseam was also found at the two Colorado test sites at Fruita and Olathe (No. 46, 49). Significant deterioration was not observed at Louisiana's Starks test site (No. 74) or the mildly corrosive test site near Dillon, Colorado (No. 54).

Abrasion was not a factor at any of the test sites inspected in Louisiana or Colorado so that we do not know how well the polyethylene or PVC coatings perform under abrasive conditions.

7. Epoxy Coated Concrete

Epoxy coatings applied to concrete culverts seem to be successful in protecting the concrete substrate. Figure 32 illustrates a culvert with a coal tar epoxy invert coating. A few areas were disbonded on this invert but the coating was otherwise in good condition. Figure 33 shows a polyamide epoxy invert coating which did not exhibit deterioration. This particular coating contains a sand filler which might improve its erosion resistance. The stream can erode the concrete and undercut the coating as in number 87 in Table IV if the paving does not cover a sufficient portion of the pipe circumference to shield the concrete during normal stream flow conditions. The coated concrete culverts examined were not exposed to abrasive flow or rapidly moving water so that performance under these conditions can not be documented here. An epoxy coated culvert exposed to rapid water movement and abrasion (number 31, Table IV) was given only a cursory examination because of rapid water flow and volume. The epoxy appeared to be intact after 3 years.

8. Others

A vinyl plastisol coating (Bethlehem Steel Beth-Cu-Loy-PC) was examined at the Genessee Expressway site in New York. Both coal tar laminate and vinyl plastisol coated culverts had been installed in sections 7A and 7B of the Genessee Expressway (I-390) near Dansville, New York. The terrain is hilly and abrasive flow exists, particularly during the period following construction. The two coatings were not necessarily installed under similar exposure conditions, however, the abrasiveness of the bedloads carried by the vinyl plastisol appears to be less severe. As previously mentioned, the coal tar laminate coating is experiencing severe abrasive damage. The vinyl plastisol, on the other hand, has not been damaged. Erosion of the vinyl plastisol has occurred, however, affecting the upstream side of the culvert crests. Evidence of this is seen in a dulling of the coating gloss and a slight thickness loss measured to be .0032 cm (.0013 in.) compared to the unaffected side. Tearing and disbondment were not observed. The vinyl plastisol material was also inspected at two test sites at a Bethlehem Steel plant in Bethlehem, Pennsylvania where polluted plant runoff flowed through galvanized steel, asphalt coated steel and the vinyl plastisol. The polymeric coating was resisting deterioration well after 4 months exposure where both the uncoated and asphalt test culverts were deteriorating.

Gunite paving was found to be unsatisfactory in acidic flows. The gunite paving that we examined appeared to have broken loose from the corrugated steel. There was no reinforcing used and this might have helped retain the paving. Figure 34 illustrates the type of deterioration observed on gunite paving.

Figure 35 shows a portion of concrete paving applied over asphalt paving which was applied over asbestos bonded asphalt dipped pipe. Although the water pH was neutral at the time of inspection, the concrete was eroded as much as 12.7 cm (5-inches) in the normal flow line. In addition, the water was flowing under the concrete in places.

Figure 36 shows a concrete paved culvert applied over asbestos bonded asphalt. The concrete is probably reinforced according to Utah specifications. No deterioration was observed, however, the culvert is exposed to only intermittent flow.

Vitreous clay lined concrete appears to perform satisfactorily, based on inspection of a single sample. In the culvert examined, there was no erosion of the vitreous clay plates and only some erosion of the mortar after 18 years. The unprotected concrete at the ends showed deterioration from the low pH water.

One aluminized steel test culvert was examined in alkali soil at the Utah test site. Figure 37 shows a typical view of that pipe. The only deterioration noted was at the spiral weld and some corrosion at the soil-air interface.

One test site containing an aluminum-zinc (Bethlehem Steel Galvalum) coated culvert and a galvanized culvert was inspected. Figure 38 shows the test installation with the Galvalum culvert on the right. Figure 39 shows a detail of the galvanized culvert and Figure 40 shows a detail of the Galvalum culvert. Both culverts are performing similarly on the interior, namely both coatings have completely deteriorated. The test installation is near a major road and it is possible that they drain a high concentration of deicing salts. The exterior of the Galvalum culvert is deteriorating more rapidly than that of the galvanized culvert based on the core samples removed from each, and pipe to soil measurements. Galvalum is practically depleted while the galvanizing is intact.

An epoxy coating (number 42, Table IV), organic zinc (number 41, Table III), and an inorganic zinc (number 40, Table III) were examined at the Utah test site. All completely deteriorated in the alkali soil. An unbonded polyethylene wrap similar to that permitted in American Water Works Association (AWWA) Specification C105-77 for ductile iron water pipe was inspected at one of the Colorado test sites and found to be unsatisfactory. Unbonded polyethylene was found to be unsatisfactory in corrosive soils in another study also[60].

9. Coating Test Sites

PSC investigators inspected test culverts in four states during the field study. Figures 41-44 illustrate the typical appearance of four of these sites and Table IV provides environmental information (numbers 39, 45, 48, 53, 64 & 74). Only one coated culvert was examined at Kentucky's Morton's Gap test site (No. 94) because the site is being abandoned and few culverts remain. A new test site with similar characteristics might be selected nearby. The primary purpose of the test sites is to expose the test coatings to the most corrosive environment in the state. None of the test sites inspected address the problem of impact and abrasion which appear to be the common modes of deterioration. Since the laboratory tests used to evaluate abrasion resistance are useful mainly for comparison of coating types but do not simulate a stream flow with an abrasive bedload, consideration should be given to establishing test sites to evaluate abrasion resistance under actual field conditions.

All of the culverts that we examined were performing their intended function, that is, permitting water flow and keeping the roadbed intact. Several culverts were perforated significantly or had lost their inverts completely but none appeared to be in danger of failure. In the case of the few coal tar laminate coatings previously discussed which delaminated extensively, eventual failure by stream blockage is possible.

Coatings appear to be effective for increasing service life under conditions free from abrasion or high salt content. Invert pavings appear to be effective except under conditions of severe abrasion. We do not have sufficient data to predict the service life of coatings, however, of those we examined the service life can be as low as two years or less under severe abrasive conditions and greater than twenty years under other conditions. Two methods can be used to evaluate service life, excluding laboratory methods which would be useful only in screening tests, that is, inspection of a large number of culverts or the establishment of test sites which would provide the major exposure classifications. Many States have conducted extensive field tests on in service culverts. One of the problems affecting this method is that the exposure history of the culvert is not always known. The establishment of an exposure site in which both exposure and coating condition can be frequently monitored would seem to provide more consistent information. The Louisiana program is an example of this type of program. A possible test program is discussed in Appendix F.

Asphalt Coating Performance

The literature review raised the question of asphalt uniformity and whether performance varies because of that lack of uniformity. Variation in performance can be caused by application technique or asphalt composition.

PSG investigators interviewed twenty-three culvert fabricators by telephone in order to ascertain if variations in application procedures exist. We also visited six fabricators. Appendix D lists the fabricators interviewed and visited. Asphalt application procedures are relatively consistent among applicators. Pipe is brought in from storage, cleaned of loose dirt (not always done), preheated at some plants and dipped in the liquid asphalt. Asphalt is supplied by refiners to conform to AASHTO Specification M190-78. The AASHTO specification is a physical property requirements specification and does not detail application procedures. Guidelines are published by the National Corrugated Steel Pipe Association (NCSPA) but there is no indication that these are generally followed.

Asphalt bath temperature varies between applicators, ranging between 182-246°C (360° and 475°F), however, individual applicators seem to maintain a temperature range of about 3.9°C (25°F) or less. Some states specify the application temperature and range and some specify pipe immersion times in their specifications.

Pipe immersion times are critical to asphalt adhesion and are established through experience at some plants or as the result of previously performed laboratory testing at others. Most plants seem to rely on operator experience in judging the proper immersion time. Two methods are used to obtain the minimum required thickness of .127 cm (.050-inch), that is by single or double dipping. Double dipping involves immersion of the pipe for a few minutes (exact time depends on metal thickness) to bring the metal up to the bath temperature so that the asphalt thoroughly wets the metal. This is said to provide the best bond between metal and asphalt. A second dip is made to achieve the minimum thickness. Some states (detailed in Table XII) specify application procedures but most do not, which essentially leaves the entire application procedure up to the fabricator.

It appears that asphalt performance might be improved by: more stringent surface preparation techniques, uniform asphalt application temperatures, uniform immersion schedules and by specifying double dipping. We do not know at this point the optimum application procedures but suggest that the guidelines published by NCSPA be used until better methods are established.

Surface preparation is critical to the adhesion of a barrier coating such as asphalt. As a minimum, the metal surface should be thoroughly cleaned of oil, grease, soil, zinc corrosion product, and completely dried. Acid or alkaline etching, phosphating, chromating or the use of a primer are used to promote adhesion of coatings and might be useful to improve asphalt performance. These possibilities are discussed in more detail in the section on Galvanizing.

All of the asphalt coated aluminum culverts examined exhibited less adhesion between the asphalt and aluminum than found between asphalt and galvanized steel. Asphalt could be easily pryed loose from the aluminum probably due to the smooth surface profile of the aluminum. Surface preparation procedures to increase the surface profile such as acid or alkaline etching, light sand blasting, anodizing, oxide coatings, phosphating or chromating could be used to improve adhesion. Comparative tests are needed to determine which would be cost effective. Asphalt coated aluminum culverts are generally not used but many state specifications allow the material. Present specifications call for essentially identical coating procedures to be used for both steel and aluminum.

The properties of asphalt vary due to the different sources of crude oil but it is not clear how these properties vary with culvert asphalt or how the variances affect asphalt performance. This is the general implication based on discussions with applicators, refiners and the literature search.

Asphalt is a complex substance produced from natural deposits, coal tar or petroleum. Culvert asphalt is produced from crude oil products by air injection (blown) at an elevated temperature. The blowing operation converts asphalt constituents to heavier oils then to asphaltic resins and then to asphaltenes. Asphaltenes briefly described are organic polycondensates containing aromatic and naphthenic rings with aliphatic side chains[62]. The effect of blowing is to increase the fusion point and decrease the specific gravity. Asphaltenes promote hardness and a high softening point while asphaltic resins promote ductility and increase the breaking point. Blown asphalts differ from residual asphalts in that residual asphalts are derived from steam distillation of semi-asphaltic or asphaltic petroleums. Blown asphalts are considered more weather resistant than residual asphalts having the same source, fusing point and volatile matter[63]. Typical constituents of blown asphalt and composition ranges are: sulfur (trace-7.5%), paraffins (0-10%), oily constituents (12.2-30.5%), saturated hydrocarbons (30-75%), minerals (0-.5%), carbenes (methylene) (0-8%), asphaltenes (17-42%) and asphaltic resins (17.8-41%)[64,67]. As seen, asphalt composition can vary greatly depending on the source of crude (Middle Eastern, Venezuelan, Mexican, Gulf Coast, California, etc.)[64,65,66,67]. Variations in composition can occur from the same source at different times.

The effects of these variations on the performance of asphalts as applied to culverts do not appear to be well understood. For example, an increase in asphaltene content would seem to improve abrasion resistance but would also lessen impact resistance. The effect of asphaltenes on adhesion and water penetration are not known. Blown petroleum asphalts are refined to meet the requirements of AASHTO M190 and in-house specifications of the refiner. Table V illustrates some typical specification limits of culvert asphalt as reported by the refiners. Table VI compares

AASHTO specifications with some compositions of blown asphalt obtained from the literature. A narrow range is seen between the asphaltene content and penetration whereas other constituents vary over wide ranges. Thus, it is possible for wide variations in asphalt characteristics to occur within AASHTO specification limits.

The acid number of asphalt could also hold an important clue into its performance behavior. The acid number is a measure of the constituents in the asphalt which have acidic characteristics such as organic acids, inorganic acids, esters, phenolic compounds, lactones, resins, heavy metal agents and additives. Acid numbers for asphalts can range between .02-5.3[64]. Two patents were issued in 1943[68] for additives used to neutralize asphaltic acids for better adhesion to steel. We do not know if significant benefit can be derived from these methods. The effects of the various components of asphalt on adhesion, abrasion and impact resistance should be investigated to determine if alterations in specification requirements are advisable.

Additives are used with asphalt to improve adhesion to various aggregates for highway paving. Superior adhesion between asphalt produced from Arkansas crude oil and steel was reported in separate correspondences between the PSG investigator and Lion Oil Company and Armco Steel. This asphalt was also reported to have an unknown proprietary additive. Additives are not used by culvert fabricators to increase the adhesion of asphalt to steel or aluminum (except as previously noted) although several manufacturers, notably Armco Steel and Republic Steel, have conducted tests to determine feasibility. Some additives might be applicable to increasing adhesion to galvanized steel. These include: branched polyalkylenepolyamines[69], fluorocarbons[70], polytheylenepolyamine and synthetic fatty acids (high thermal stability reported)[71], .5% polyamine or .25% polyamine +.25% stearic acid[72] and stabilized abietylamines (Amine D)[73], petroleum resin+1-pentene (applied to primed steel)[74] and petroleum resin+2-methyl-1,3 butadiene (applied to primed steel)[75]. Others, too numerous to list in this report, are reported in the literature to improve asphalt adhesion to aggregates. Reference 63 lists many of these additives. Of these additives, we learned of only one which was tested and found to improve adhesion significantly. Amine D, a high molecular weight amine, derived from pine resin acids, was found to improve adhesion to galvanized steel by a factor of 4 in laboratory tests when used in a concentration of about 1 percent. However, the additive presents difficulties in stability at the elevated asphalt bath temperatures as it decomposes rapidly at asphalt application temperatures according to manufacturer's data. Such problems would require extensive analysis of the asphalt to assure adequate concentration. Coating cost also increased about 10 percent. Laboratory testing is needed to screen a large number of additives to determine if any additive would be cost effective.

Water absorbs into asphalt where immersion conditions exist[76,85] and tends to cause disbondment from the zinc coating. This undoubtedly explains the great difference in performance between immersed areas and unimmersed areas. Better adhesion between the asphalt and substrate would improve coating performance. Better surface preparation techniques will improve the bond.

Asphalt coatings are also subject to abrasion forces which cause the asphalt to flow and wear down. Methods to improve abrasion resistance include increasing the asphaltene content, use of filters and blending. An increase in the asphaltene content would increase erosion resistance but would probably decrease impact resistance and weatherability. Penetration resistance is related to asphaltene content and penetration is greatly affected by exposure temperature[53]. Increasing the asphaltene content might make the coating too susceptible to impact damage during the winter months.

The use of fillers to improve erosion resistance should be investigated, particularly for use as invert paving. Possible filler materials include sand, fiberglass, asbestos or steel. One manufacturer is currently investigating the use of reinforced asphalt, using tailings from another process. No data is available yet.

A blend of asphalt and coal tar is said to improve adhesion and weathering properties. The blend is also reported to have decreased susceptibility to temperature changes and increased viscosity at elevated temperatures . Coal tar will evidently not mix well with asphalts in all proportions. The optimum concentration range for improving asphalt performance is reported to be 15-25 percent coal tar. We were not able to find comparative data. Blending coal tar and asphalt appears to be worth investigating.

Abraham presents several other methods of improving asphalt weather-resistance[63]. Since we do not know details of the manufacturing processes used in refining culvert asphalt, some of these might be used now, however, in the interest of completeness, they are, briefly:

1. Separate the light and medium lubricating oils from the asphaltenes and resins. Remove the oily constituents from the lubricating oils and reflux the residue with the asphaltenes and resins - air blow the mixture.

2. Remove resins of low molecular weight from the mixture of asphaltenes and resins.

3. Separate the oily constituents from the asphaltenes and resins. Treat the oily constituents with a selective solvent and recombine with the asphaltenes and resins.

4. Incorporate oxidation inhibitors.

Coating Need and Alternative Means of Protection

Five states (Arkansas, Nebraska, New Mexico, North Dakota and South Dakota) have never used organic coatings and four others (Hawaii, Kansas, Maryland, Tennessee) have ceased using them. Most States have criteria which allow the use of uncoated galvanized steel, aluminum and sometimes other metallic coated pipe. The criteria are usually based on pH and resistivity data and a certain design life as well as structural requirements. Other criteria sometimes used relate to the type of road and traffic volume. Table VII lists known criteria used by several states for permitting the use of corrugated pipe without organic coatings. Many of the test sites inspected fall into the ranges in the criteria which permit uncoated pipe but a coating was used possibly for abrasion protection. It is also possible that exposure conditions have significantly changed. An alternative means of protecting the invert would be economically justifiable in these cases if abrasion resistance were desired.

Protective coatings are used to extend culvert service life where either corrosive conditions exist or abrasive flow is expected, or both. The literature search and field survey have shown that asphalt type coatings are effective in controlling culvert deterioration on exterior surfaces but are not entirely satisfactory on internal surfaces. Polymer coatings can be provided on either the internal or external surface or both, depending on where increased durability is needed. Performance is questionable in abrasive or very corrosive environments. Other means of extending culvert life can be explored.

Exterior deterioration can be controlled through the use of cathodic protection either by using sacrificial or impressed current anode systems. Cathodic protection of a large uncoated culvert can involve large numbers of anodes in order to achieve corrosion control. The cost of the anodes, engineering time necessary to determine current requirements in the field and inevitable maintenance costs (mandatory on impressed current systems) can easily surpass the present cost of coating. Cathodic protection could be an economic choice in very severely corrosive environments in conjunction with a protective coating. Polarization tests on externally coated culverts during the field study indicate that an average of 3.4×10^{-4} ampere per sq. m (3.1×10^{-5} ampere per sq. ft.) is needed to protect the external culvert surface. The range is 3.23×10^{-6} to 1.81×10^{-3} ampere per sq. m (2.99×10^{-7} to 1.67×10^{-4} ampere per sq. ft.). An average of 3.4 17 pound magnesium anodes (range: 1-18) would be needed for 50 year anode life at an average material cost of $91 (range: $27-$486). The cost of engineering tests and installation would raise the total cost of cathodic protection.

Coating and external cathodic protection might be used in a cost effective manner if ungalvanized culvert material were used. Galvanizing costs $7.42 per hundredweight ($.163 per kg), the average estimated galvanizing cost of the culverts tested being $1026 (range: $64-$2619). Substantial savings might be realized in many installations, however, the total cost of a cathodic protection system could exceed the galvanizing cost particularly on small culverts. Cathodic protection can not be used to protect non-submerged surfaces and would not be effective in protecting surfaces exposed to alternating wetting and drying conditions. Anodes would be subject to damage if installed unprotected in the stream flow. An effective coating would be needed to protect internal surfaces.

Abrasive bedloads could be prevented from entering the culvert through the use of settlement basins or screening devices. Energy dissipators could be used to lessen stream velocity. Screening devices (i.e. cribs) are used in some cases but are not entirely effective as shown in Figures 13 and 14. Settlement basins might be the best alternative as they would trap abrasive debris but not affect the hydraulic efficiency of the culvert. All three methods require periodic maintenance by highway personnel which would be a disadvantage.

Reinforced invert pavings or vitrified clay tile are recommended where abrasive stream flows are encountered and could be used in place of organic coatings where corrosive conditions are not a consideration. Reinforced Portland cement or reinforced asphalt could be used although

Portland cement would probably provide the best abrasion resistance. Reinforcing should consist of wire mesh or similar steel reinforcing welded to the invert. The cost of using reinforced invert protection will probably vary greatly. Reinforced concrete would be field applied and be labor intensive. Concrete paving would also be limited to culverts large enough to allow the applicator to work efficiently. Reinforced asphalt could be shop applied using existing equipment but would require improved surface preparation. The use of fillers, such as fiberglass and metal turnings, mixed with the Portland cement and asphalt, should be investigated.

Other inorganic coatings for invert protection include metallized coatings, clad metal liners, ceramic coatings, fiberglass lining and clay lining. Mr. H. Johns of the Bureau of Reclamation is evaluating several metal and ceramic coatings for their erosion resistance in drainage applications[79]. These include stainless steel sheet (which could be provided as mill applied metallurgically bonded cladding on the steel culvert sheet), metallized stainless steel, metallized bronze, metallized high chrome stainless steel, metallized molybdenum and flame sprayed aluminum oxide. The tests are being conducted using rotating steel drums coated with the test material and containing water and silt, sand or gravel. Test results were compared to coal tar enamel. Coal tar enamel has exhibited up to seven times the abrasion resistance of asphalt according to tests similar to the Bureau of Reclamation program[80]. Of the metallic coatings tested, the stainless steel sheet and metallized stainless steel outperformed the coal tar enamel and all but the flame sprayed aluminum oxide might be expected to outperform asphalt based on abrasion resistance. There is insufficient information to estimate the useful life of these other relatively thin coatings compared to the greater thickness of asphalt pavings. Flame sprayed coatings vary greatly in cost, and are more expensive than presently used coatings on a square foot basis. However, since flame sprayed coatings can be applied only on the invert, total cost could be lower. Table VIII presents typical flame spray material costs. A possible disadvantage to flame spray coatings is that they must be applied to sandblasted steel which would require the removal of the galvanizing or the use of ungalvanized culverts sheet.

Fiberglass might also be an effective selection for invert protection. The Bureau of Reclamation tests have also included several glass reinforced resins to include polyester resins filled with Al_2SiO_3, sand and glass fiber. Both performed as well as or better than the coal tar enamel standard. Industry sources, however, claim that adhesion to galvanized steel is poor and application to corrugated metal costly. The cost range for fiberglass application is $64.80-$216 per sq. m ($6-$20 per sq. ft.) Fiberglass might be better applied to concrete culverts as invert protection.

Although the epoxy coatings appear satisfactory for protecting concrete in acidic environments, there are alternative means which might be advantageous, particularly in environments corrosive to concrete. These methods include sealants such as those being evaluated for use on bridge decks to prevent chloride penetration. Possible sealants include wax[81], methyl methacrylate, styrene, acrylonitrite and t-butyl styrene[82]. Concrete mixtures with polymer latex, epoxy resin and polyester resin could also be evaluated as invert paving in acidic or abrasive areas[79,82]. The cost of surface treatments is difficult to predict since most of the work done has been experimental in nature. One source estimates the cost of impregnating (bridge decks) to be $5.40 to $10.80 per sq. m ($0.50 to $1.00 per sq. ft.)[82]. The cost of applying a polyester resin, polymer latex or epoxy resin concrete invert paving will probably not be much different from that of current epoxy systems.

Polyethylene liners could be used to provide additional protection to metal or concrete culverts in corrosive or abrasive environments or to increase the service life of deteriorated culverts. Such liners, which are field installed, are currently used to rehabilitate sewer pipe. One application to drainage culverts is known in Michigan where galvanized steel deteriorated along I75. Polyethylene liners are available in sizes ranging between 1.9 cm (.75 in.) to 1.22 m (4 ft.). The thickness of a thin wall liner is based on the diameter with a diameter to thickness ratio of 32. The cost of using polyethylene to line corrugated metal or concrete culvert pipe is in ranges from $13.39 per sq. m ($1.24 per sq. ft.) for 15.2 cm (6 ft.) to $83.81 per sq. m ($7.76 per sq. ft.) for 1.22 m (4 ft.) diameter pipe. The best use of this material would seem to be as protection for the culvert against corrosive streams. The material also might exhibit acceptable abrasion resistance.

<u>Alternative Coatings</u>

Asphalt and several precoated polymer coatings (coal tar laminate, polyethylene, polyvinyl chloride and vinyl plastisol) are now used for culvert protection. The literature[79,83] suggests several post applied organic coatings which might provide improved performance. Two of the most abrasion resistant are polyurethane and neoprene which have abrasion resistances several times that of coal tar enamel. Table IX lists organic coatings which might be candidates as alternatives for existing systems and their approximate application costs. In preparing this list, the primary characteristics were the abrasion and impact resistance. Important characteristics for culvert coatings include water penetration, chemical resistance and adhesion as well as impact and abrasion. Comparative test data on these other properties is not available. The screening of these alternative coatings should be the subject of a laboratory program which would select suitable coatings for testing under actual field conditions.

Coal tar enamel is included in Table IX since it would be a low cost alternative to asphalt and could be applied in the same manner. Plasticized coal tar enamel has superior water absorption properties to asphalt[85] and has a higher penetration coefficient which should give it greater abrasion resistance as indicated in the literature[80]. Coal tar is, however, subject to the same adverse weathering behavior (on exposure to infrared radiation) as asphalt. Another problem is its possible carcinogenic effect which it also shares with asphalt. Coal tar enamel would almost certainly require a primer to assure adequate adhesion.

The cost figures in Table IX are seen to be considerably greater than the conventional coatings. This is because the cost figures contain a large application cost allowance for cleaning and spray application and multiple coats are needed in some cases. Costs would decrease if automated application procedures could be used. Many of these coatings have the distinct advantage of application to specific areas where they are needed, such as the invert. For example, a polyurethane elastomer could be applied to one-half the interior surface to protect the invert at a cost of about $5.14 per ft. compared to $9.57 per ft. for asphalt paving (using the pipe size example given in Table IX).

Alternative coatings can also be applied to aluminum culverts. Asphalt is the only coating now used on aluminum but at least one manufacturer, Kaiser Aluminum, is testing a polyethylene laminate manufactured by Dow Chemical Company.

Two alternatives to galvanizing are inorganic zinc and Zincrometal. Zincrometal is a trademark of the Diamond Shamrock Company but its use is licensed to many steel companies and is a mill applied process. The coating consists of 2.54 µm (.0001 in) of a proprietary zinc-chromium water based dispersion with a second coat, 10.16 µm (.0004 in) thick, of a zinc rich weldable epoxy. It is applied to automotive sheet metal prior to fabrication at the present time. The cost for coating both sides of a sheet is in the order of $110 per 908 kg (1 ton) or $5.50 per 45.4 Kg (1 cwt) compared to $7.42 per 45.4 Kg (1 cwt) for galvanizing. The manufacturer claims that it is compatible with most topcoats and is probably compatible with hot applied asphalt. Disadvantages include the lack of sacrificial protection and a limit on the thickness sheet that can be coated (up to about .203 cm/.080 in) at the present time.

Inorganic zinc is a spray applied coating which does offer sacrificial protection. This coating must be applied to a white metal sandblasted surface (Steel Structures Painting Council SP-5). The material cost would amount to $1.19 per sq. m ($0.111 per sq. ft) at a dry film thickness of .0076 cm (.003 in), sandblast would cost about $10.76 per sq. m ($0.12 per sq. ft) and application about $1.29 per sq. m ($0.12 per sq. ft) bringing the total cost to $13.24 per sq. m ($1.23 per sq. ft). The cost to coat both sides of the culvert example in Table IX would be $33.38 compared to $3.26 for hot dip galvanizing. We do not believe that benefits would be derived using inorganic zinc sufficient to justify the cost.

Fusion bonded epoxy powder coatings or polyurethane/polyester powders could offer a significant cost benefit for culverts. Fusion bonded powders exhibit good abrasion[81] and weathering resistance as well as resistance to chemicals[87,88]. A fusion bonded epoxy coating is being evaluated by Armco Steel Company for use on culverts and one is approved for potable water pipelines (AWWA Specification C213-79). This epoxy is intended for application over nongalvanized steel. Fusion bonded powders can be applied over galvanized surfaces but blistering and film continuity problems can be encountered due to trapped moisture and gases. Prebaking the steel prior powder application might alleviate the application problems. Powder coatings applied over uncoated steel could save the cost of galvanizing if proven affective in field tests. Additional protection such as paving would be needed in abrasive environments. Corrosive soils might also require additional protection such as cathodic protection as discussed in the section on Coating Need and Alternative Means of Protection. Epoxy coatings tend to chalk on outdoor weathering exposure which could be a disadvantage at the ends of the pipe.

Adhesion to Galvanized Steel

The adhesion of coatings to galvanized steel is often less than satisfactory for several reasons including: poor surface profile, silicate coatings applied at the mill to prevent white rust, zinc corrosion products and outgassing of the zinc during high temperature coating operations. The minimum surface preparation normally recommended for galvanized surfaces is cleaning and degreasing. Advanced methods include acid or alkaline cleaning, surface conversion coatings, wash primers, surface conditioners or sandblasting. Several methods can be used in combination.

The field study indicated the need to improve the adhesion of asphalt to steel, particularly in the invert area. Several studies have shown that asphalt adhesion is significantly improved when surface etching or phosphate or chromate conversion coatings are used. Surface treatment would add to the coating cost of a culvert. It is possible to limit the surface preparation to the invert area to lower the cost, but unless the culvert is installed correctly, the method would not be effective.

Typical costs are:

Acid or alkaline cleaning (mill applied)	$\$1.08/m^2$	$(\$.10/ft.^2)$
Phosphate conversion coating (mill applied)	$\$1.19/m^2$	$(\$.11/ft.^2)$
Chromate conversion coating (mill applied)	$\$1.94/m^2$	$(\$.18/ft.^2)$
Wash primers, conditioners & Primers	$\$1.49\text{-}1.73/m^2$	$(\$.14\text{-}.16/ft.^2)$
Sandblasting (SP-7)	$\$2.70/m^2$	$(\$.25/ft.^2)$
Cleaning & Degreasing	$\$2.70/m^2$	$(\$.25/ft.^2)$

Test data is not available to determine which, if any, of these surface preparation methods is cost effective in a culvert installation. The scope of this study included a screening test of various wash primers and primers which might be used to improve the adhesion of asphalt or other coatings. Two test methods were used in the screening test, they are: ASTM D2197 Scrape Adhesion test and the Elcometer pull-off test which measures the tensile bond strength of the coating to its substrate. Both tests were performed on 18 primers and wash primers and asphalts obtained from 5 sources. Primers were applied according to manufacturers instructions by brushing onto cleaned and degreased flat galvanized steel culvert sheet. Asphalt coatings were applied by dipping the panels into asphalt at 204°C (400°F) for 3 minutes. Tests temperature was approximately 21°C (70°F). Asphalt coated panels were also tested at 0°C (32°F). Three of the asphalt primers were tested with one asphalt topcoat at 21°C and 0°C.

Table X presents the adhesion data for the asphalts and primer combinations. The data presented in Tables X and XI indicate that there are only a few primers which exhibit adhesion strengths to cleaned and degreased galvanized steel greater than that of hot dipped asphalt. Some improvement in asphalt adhesion can be obtained by using one of these primers with the hot applied asphalt. An exception occurred with the PA-980 primer in which the adhesion strength actually decreased. This unexpected result was replicated and could be caused by a degradation of the primer under heat. Significant changes are observed with the other two primers exposed to hot asphalt. The significant problem of asphalt adhesion after water has absorbed into the coating was not addressed in this program. The ultimate effectiveness of a primer will depend on how well it maintains its adhesion under immersion conditions. This question should be addressed in future evaluations.

Data indicated on Table XI that the adhesive strength of the asphalt varies considerably even though all of the asphalts tested are supposed to meet the AASHTO M190 specification. Scrape adhesion strength is seen to increase at the low test temperature most likely because the asphalt itself becomes more resistant to flow. The failure mode at 0°C is one of brittle chipping and that at 21°C is one of plastic flow.

Scrape adhesion test data and Elcometer test data follow only a rough correlation with asphalt at 21°C. The correlation coefficient is .82 but the correlation is barely significant at a confidence level of 95 percent, perhaps due to the few data points. The correlation coefficient at 0°C is only .50, and in the comparison with the other primers, the lack of correlation is evident in the data. The reason is that the cohesive strength of the coating is sometimes more dominant than the adhesive strength with the Elcometer method. An adhesive must also be used with the Elcometer test which could affect the coating in some way. The Elcometer test shows reasonable correlation then only when comparing coatings of the same type such as asphalts.

Specification Review

State and American Association of State Highway and Transportation Officials (AASHTO) specifications regarding culvert pipe protection were reviewed. The review was based on the information gathered during the literature search, field survey and asphalt review phases of the study. Each specification was examined for the adequacy of its provisions with regard to type of coating, application methods and installation procedures.

Most state specifications for asphalt and polymer coated culvert pipe refer to AASHTO M190, M243 and M246 and a few supplement the AASHTO specifications with additional requirements. There are several subjects that few State or AASHTO specifications address. These are: transportation and handling of coated pipe, surface preparation prior to coating and backfilling to prevent coating damage. Table XII presents a comparison summary of the various state specification provisions. Appendix E presents a recommended specification for coated culvert pipe which could be used as a guide to revise existing specifications.

AASHTO specification M190-78 provides the basic reference for applying asphalt to galvanized and asbestos bonded steel. This is basically a materials specification which calls out the properties of the asphalt used and the types and thickness of coating. Since the specification is often used unaltered and unsupplemented by the states, it should contain more specific information regarding surface preparation, application and handling of culvert pipe.

AASHTO M190 does not specify the means of application, i.e. spray, dip or brush. Dipping is the method used but the specification does not delineate the procedure that should be used to obtain satisfactory adhesion. We recommend that the practice called out by the Corrugated Steel Pipe Association be included in AASHTO M190 unless a better procedure is found. The NCSPA recommended practice includes minimum immersion times, asphalt temperature range and requires double dipping.

The physical property requirements should be expanded to include penetration at 0°C (32°F) - 25 min. at 200g for 60 sec., penetration at 25°C (77°F) - 25 to 55 at 100g for 5 sec. by ASTM D5 or AASHTO +49, flash point by ASTM D92 or AASHTO T48 - 232°C (450°F) min., specific gravity by ASTM D70 or AASHTO T229 - .98 min. and softening point by ASTM D36 or AASHTO T53 - 93°C (200°F) min./110°C (230°F) max. These suggested values are also referenced from the

NCSPA practice with similar limits recommended by the Canadian Corrugated Steel Pipe Institute (Specification No. 501-78, Revision 11, April, 1978).

Mechanical property requirements in AASHTO M190 are limited to shock testing, flow tests and imperviousness test. These tests should be augmented with four other tests, notably: abrasion resistance by ASTM G6, D658 or a modified procedure, adhesion test similar to that specified in AASHTO M243-75 by ASTM G9 and freeze thaw resistance similar to that specified in AASHTO M246-78. Acceptable values for these tests should be determined through a test program.

Section 5.1 of ASSHTO M190 calls for asphalt samples to be taken from strippings removed from the pipe. We recommend that this be changed to specify that the samples be removed from the asphalt bath at the time of coating. This will eliminate the possibility of contaminating the asphalt with dirt or anti-sticking compounds. Pipe from which samples are taken are unlikely to be installed with the uncoated areas always at the top. These areas could be exposed to the stream flow resulting in earlier coating disbondment and culvert deterioration.

AASHTO specification M243-75 applies to the material and application of field applied asphalt mastic and tar based material. Both materials should be subject to the same performance tests required for asphalt, i.e. shock, flow and imperviousness as well as the additional tests recommended for asphalt (abrasion, adhesion, water penetration and freeze-thaw). Currently, the asphalt mastic is subject to flow, acid and alkali resistance, pliability and adhesion tests. The tar base material is not subject to any performance test.

AASHTO specification M246-78 provides requirements for precoated galvanized steel sheet for culverts and underdrains. We can not recommend any changes to this specification other than to suggest that the average number of permissible holidays (Section 7.4 Holidays) be deleted. Each holiday is a source of blistering and disbondment under exposure conditions. Coatings should be as defect-free as possible.

CONCLUSIONS

1. Durability problems are encountered with all protective coatings now commonly used.

2. Alternate methods are available to protect culverts other than organic coatings and could have been used to advantage at many of the locations inspected in the field study.

3. Organic coatings are, by themselves, not satisfactory under abrasive stream flow conditions.

4. The durability of polymer coatings depends on the amount of salts in the soil or water, the continuity of the coating, the pH and the abrasiveness of the bed-load. Improvements are needed in production techniques to prevent damage which adversely affects performance. Polymer coatings are satisfactory where abrasive flows and high salt conditions are not encountered.

5. Asphalt adhesion to aluminum is poor. This coating would not be satisfactory in abrasive or corrosive environments.

6. Epoxy coatings and vitrified clay liners are effective when used on concrete in acidic streams. They might also be useful on corrugated metal under certain severe conditions.

7. Adhesion between asphalt and galvanized steel can be improved through the use of surface treatments and primers. The benefits of improved adhesion should be evaluated.

8. Asbestos bonded asphalt coating is somewhat more durable than plain asphalt coating but is also subject to deterioration in abrasive or high salt environments.

9. The durability of asphalt coatings is influenced by application procedure, adhesion to the substrate, seasonal temperature changes, water asorption, turbulence in the stream flow and abrasiveness of the bedload. Asphalt is satisfactory where abrasive flows and high salt conditions are not encountered.

10. Asphalt mastic is not a durable coating.

11. Asphalt composition varies widely depending on the source of crude oil. Performance variations of culvert

asphalt are attributable to the water absorption and abrasion properties of asphalt and current methods of application.

12. There are several alternative coatings which should be evaluated for use on culverts. These coatings, while more expensive than current culvert coatings, could be cost effective for selected application such as on inverts.

13. Many state and AASHTO specifications should be made more specific.

RECOMMENDATIONS

1. Evaluate by means of laboratory and field tests, methods of improving the bond between asphalt and galvanized steel and determine which, if any, are cost effective. Appendix F presents a program for this and other recommended evaluations.

2. Evaluate by means of laboratory and field tests, methods of improving the abrasion resistance of asphalt. Appendix F presents a recommended test program.

3. Investigate the variations in asphalt composition and the effects on asphalt erosion resistance and adhesion to galvanized steel. Appendix F presents a recommended test program.

4. Evaluate by means of laboratory and field tests, alternative organic coatings for use on culverts in corrosive environments. Appendix F presents a recommended test program.

5. Utilize organic coatings only for protection in corrosive environments. Use additional invert protection where abrasive bedloads or rapid stream flow are anticipated. Consider using reinforced concrete as invert paving until methods of improving asphalt adhesion and erosion resistance are developed. Consider asphalt paving over polymer coatings.

6. Seal the space at joints between pipe sections to reduce turbulence and lessen the chance of coating and culvert deterioration at these locations. Only the invert area exposed to normal stream flow conditions need be considered for this treatment. A hot poured asphalt would probably be the most effective sealant.

7. Recommend changes in state specifications to improve coating uniformity and to detail application, handling and installation procedures. Appendix E presents a recommended specification.

FIGURE 1 - Removing Core Sample From Culvert to Inspect Exterior Coating

FIGURE 2 - Expandable Rubber Plug Used to Seal Core Hole

FIGURE 3

COATING CONDITION VS. PH, COAL TAR LAMINATE (NEXON)

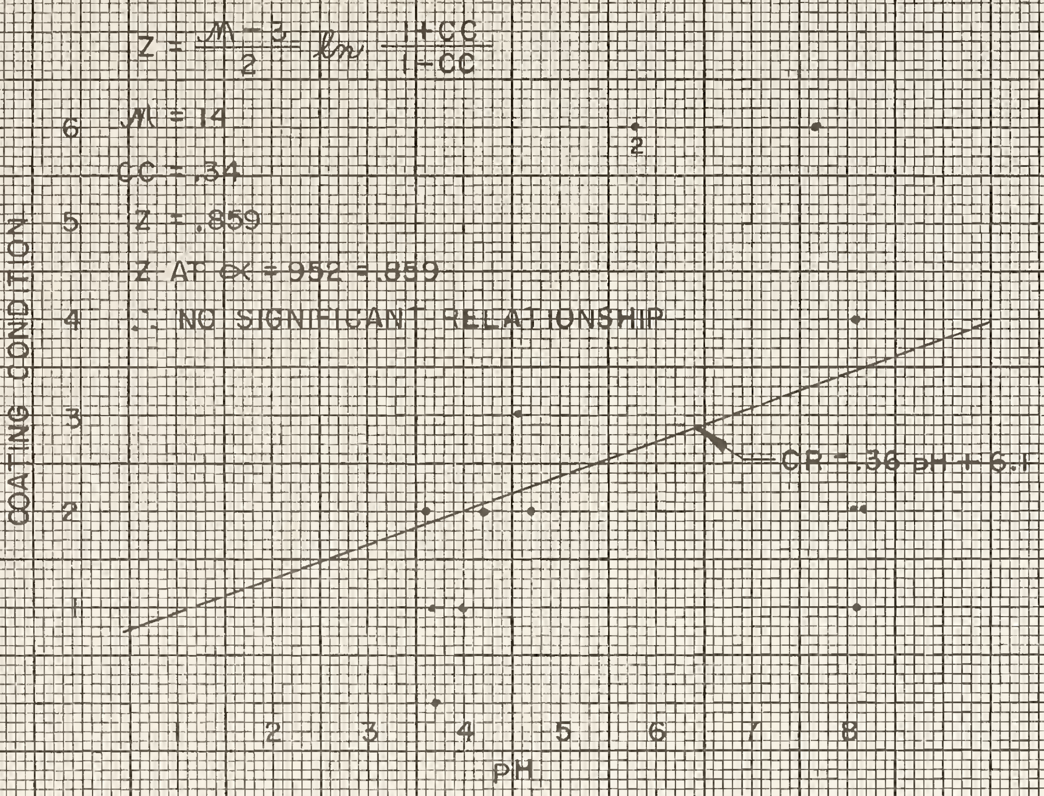

FIGURE 3

FIGURE 4

CORROSION CONDITION VS. RYZNAR INDEX OF STREAM WATER

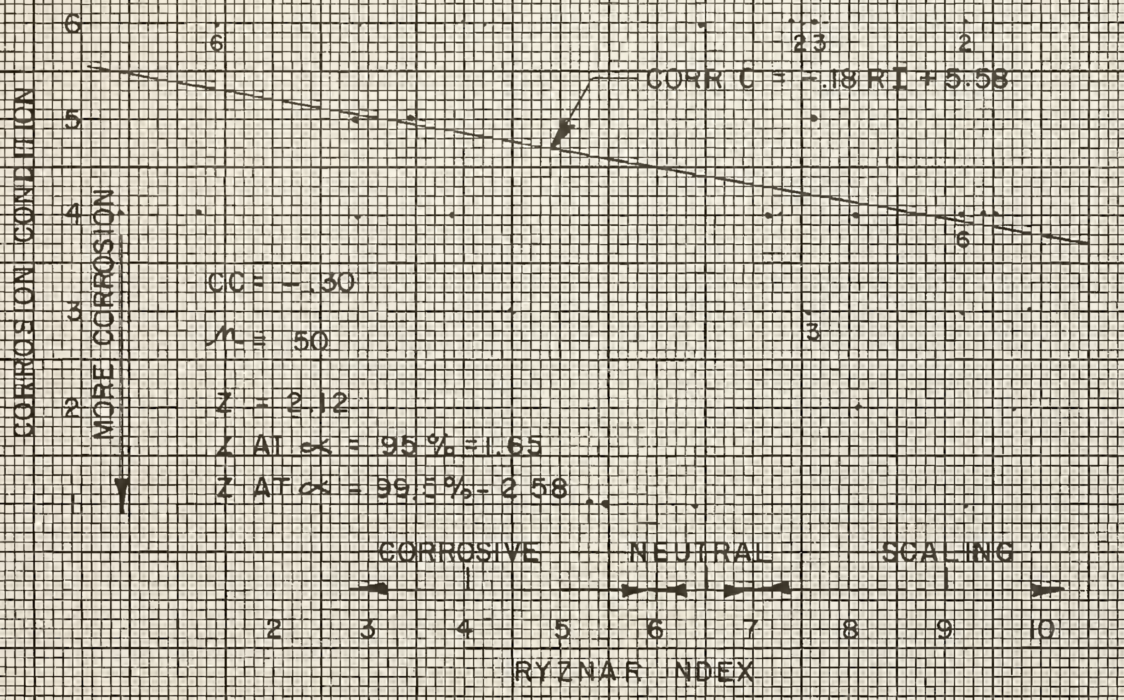

FIGURE 5

FIGURE 5. COATING CONDITION VS.
RYZNAR INDEX OF STREAM WATER

FIGURE 5

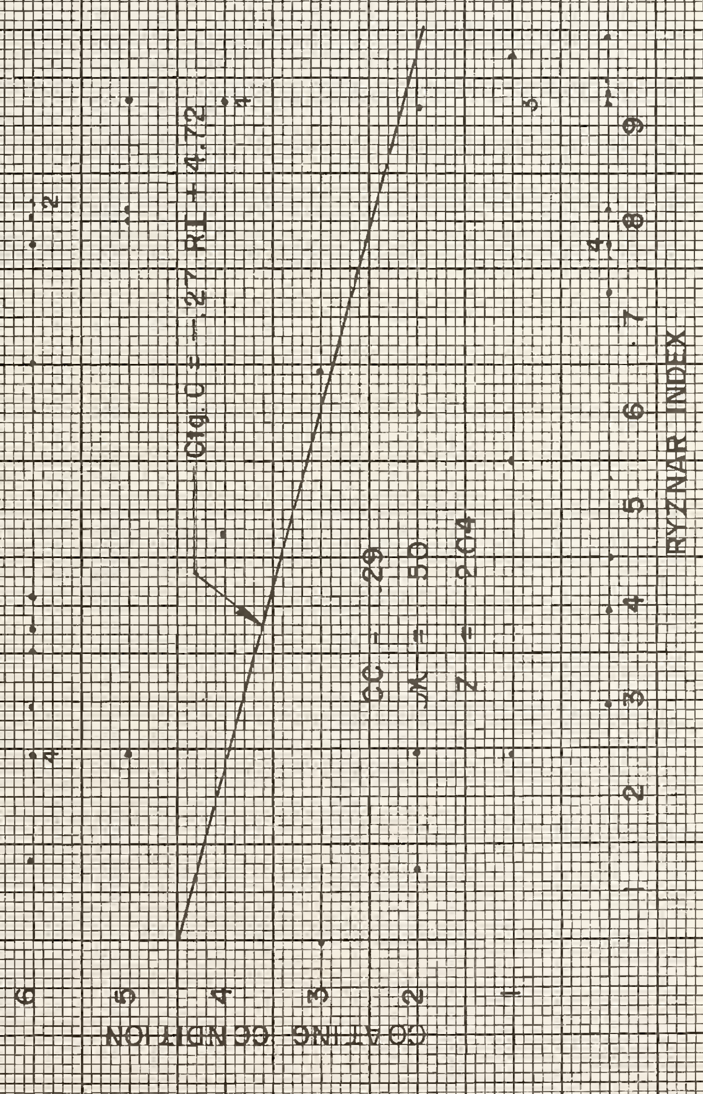

FIGURE 6

CORROSION CONDITION VS. COATING CONDITION

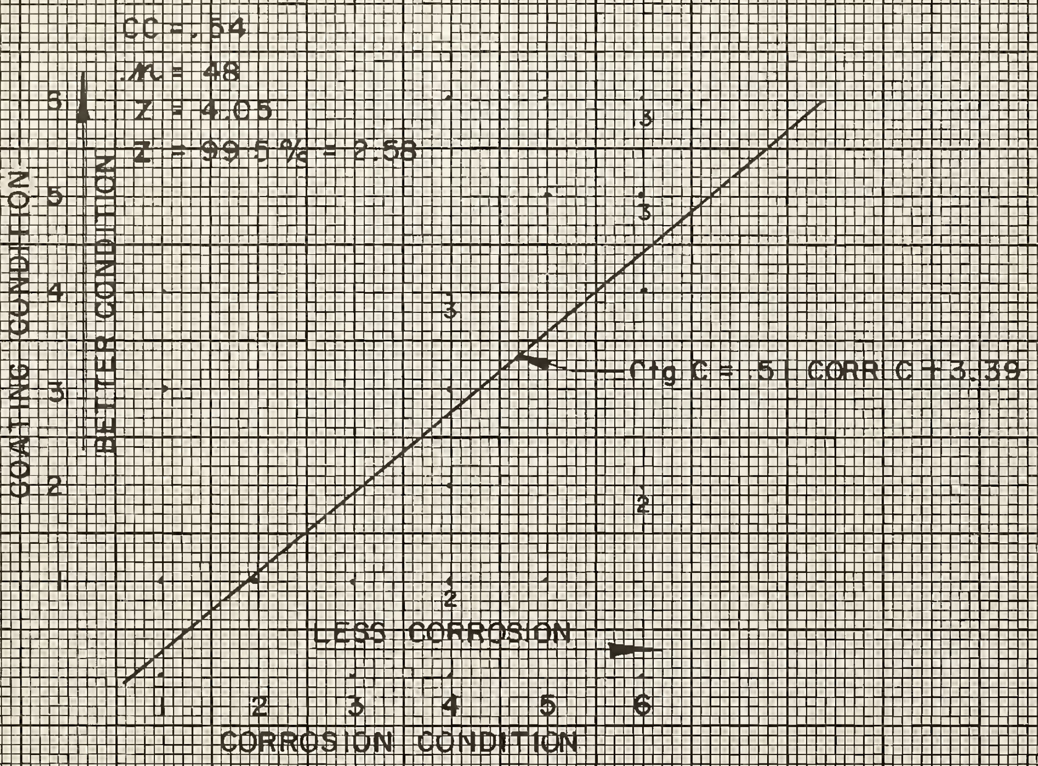

FIGURE 6

FIGURE 7 Field Applied Asphalt Mastic
Site No. 7

FIGURE 8 - Field Applied Asphalt Mastic
Site No. 6

FIGURE 9 - Field Applied Asphalt Mastic
Site No. 29

FIGURE 10 - Asphalt. Site No. 16

FIGURE 11 - Asphalt. Site No. 58

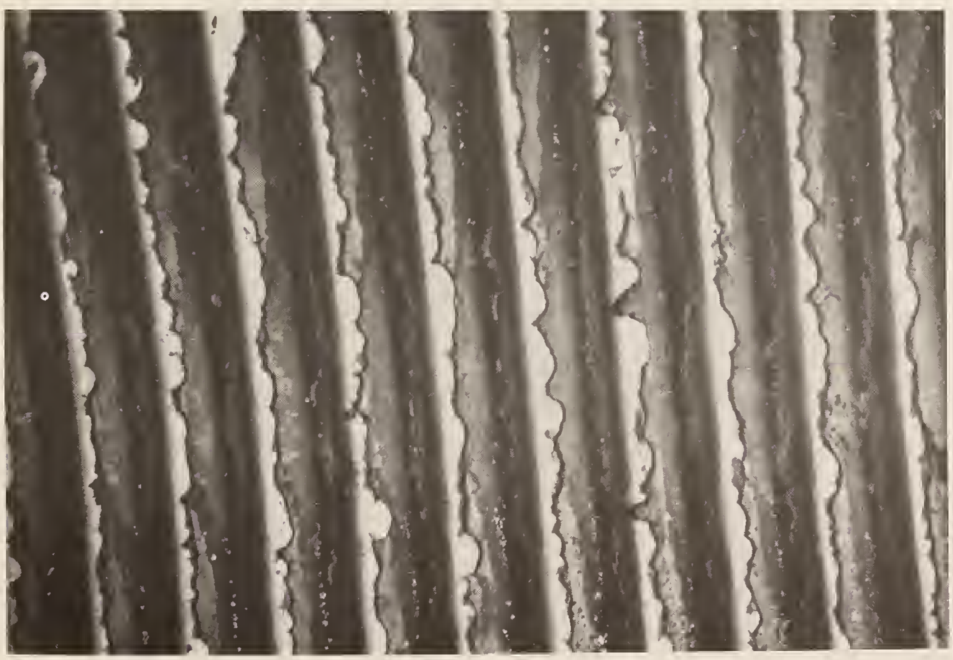

FIGURE 12 - Asphalt. Site No. 62

FIGURE 13 - Crib to Control large debris that might plug culvert. Site No. 63

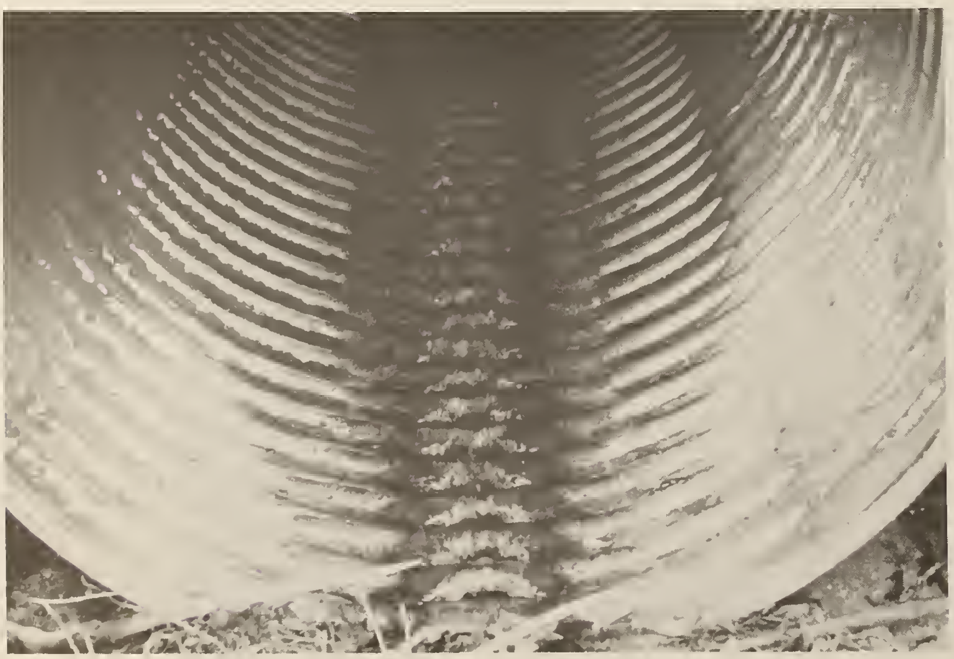

FIGURE 14 - Asphalt Coated Pipe in Figure 13. Site No. 63

FIGURE 15 - Perforation of Field Coated Connecting Band. Site No. 18

FIGURE 16 - Perforations at Section Joints. Site No. 5

FIGURE 17 - Perforation at Section Joint.
Site No. 19

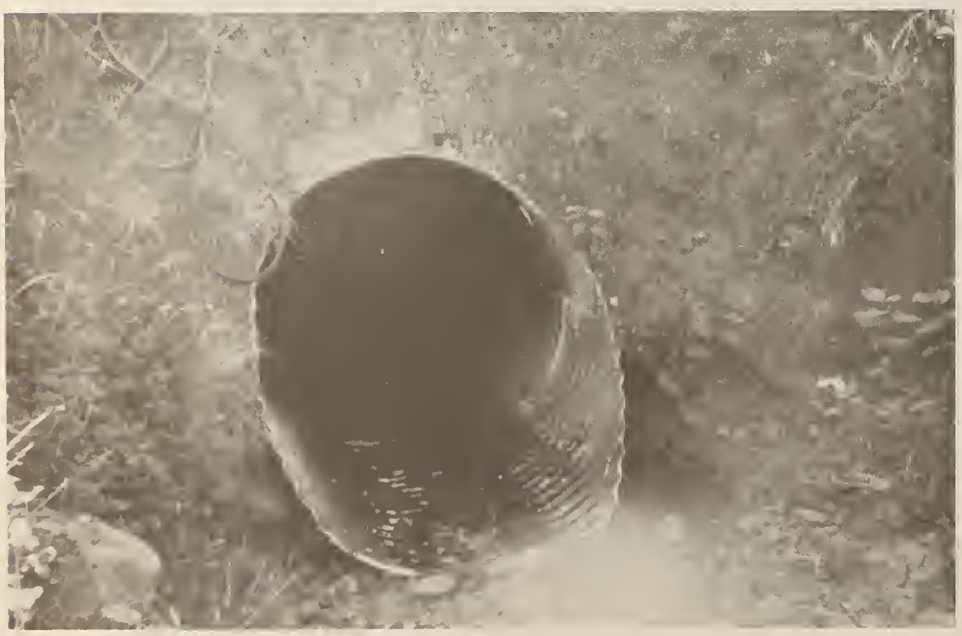

FIGURE 18 - Asphalt Coated Aluminum.
Site No. 25

FIGURE 19 - Asphalt Coated Aluminum.
Site No. 79

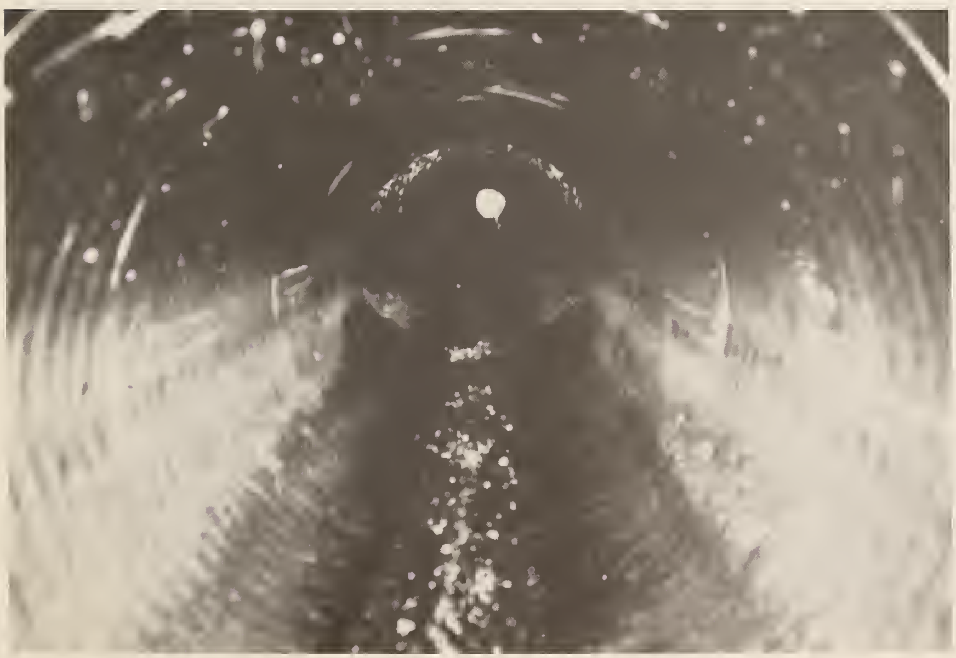

FIGURE 20 - Asbestos Bonded Asphalt.
Site No. 28

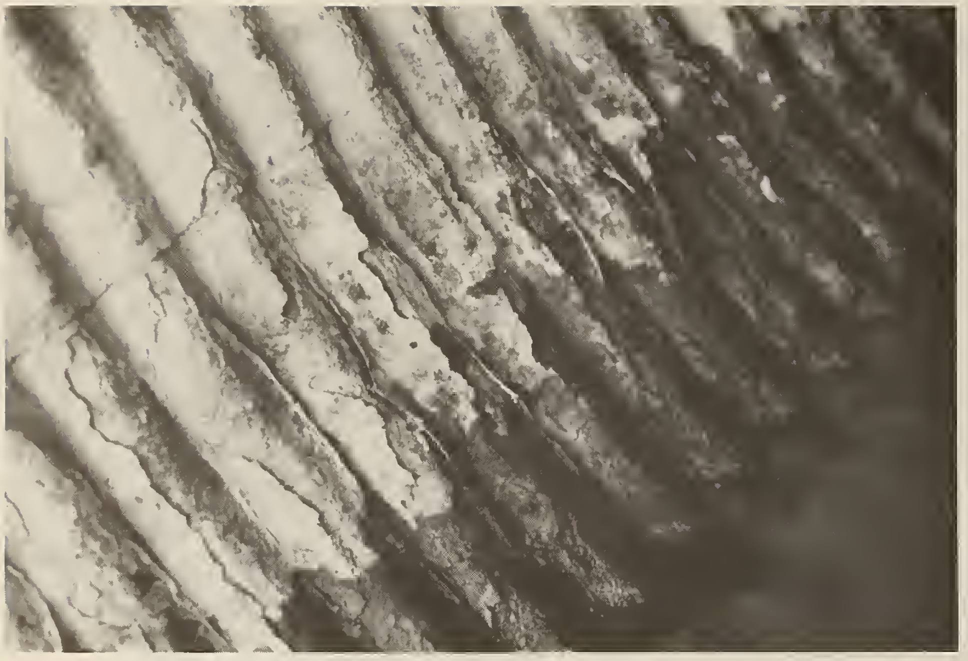

FIGURE 21 - Asbestos Bonded Asphalt.
Site No. 50

FIGURE 22 - Asbestos Bonded Asphalt.
Site No. 65

FIGURE 23 - Asbestos Bonded Asphalt
Site No. 43

FIGURE 24 - Coal Tar Laminate. Site No. 12

FIGURE 25 - Coal Tar Laminate. Site No. 98

FIGURE 26 - Coal Tar Laminate. Site No. 96

FIGURE 27 - Coal Tar Laminate. Site No. 97

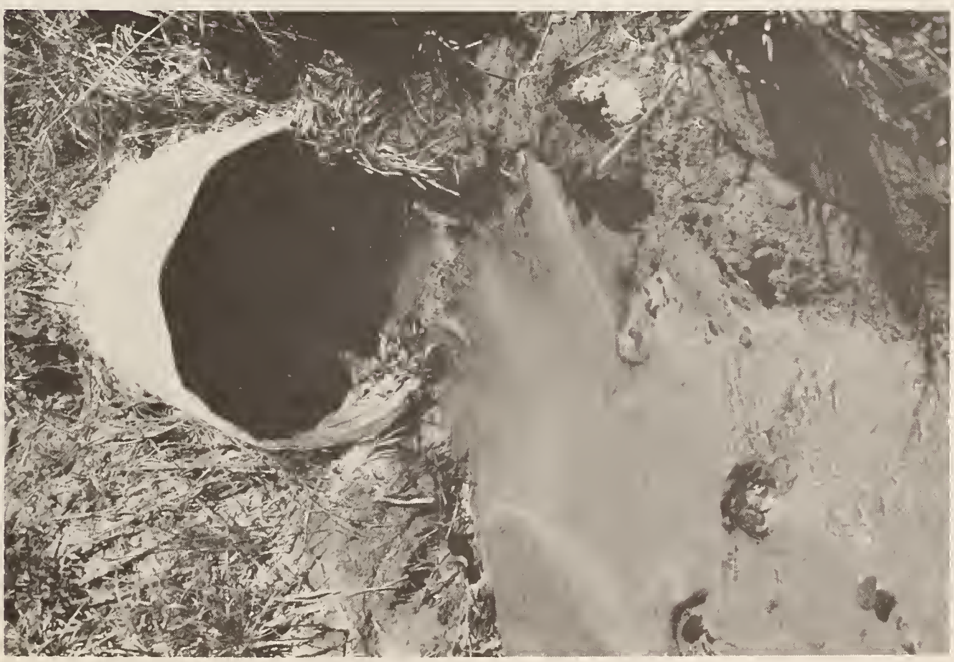

FIGURE 28 - Coal Tar Laminate. Site No. 105

FIGURE 29 - Coal Tar Laminate. Site No. 66

FIGURE 30 - Polyethylene. Site No. 70

FIGURE 31 - PVC. Site No. 71

FIGURE 32 - Coal Tar Epoxy on Concrete.
Site No. 1

FIGURE 33 - Epoxy on Concrete. Site No. 86

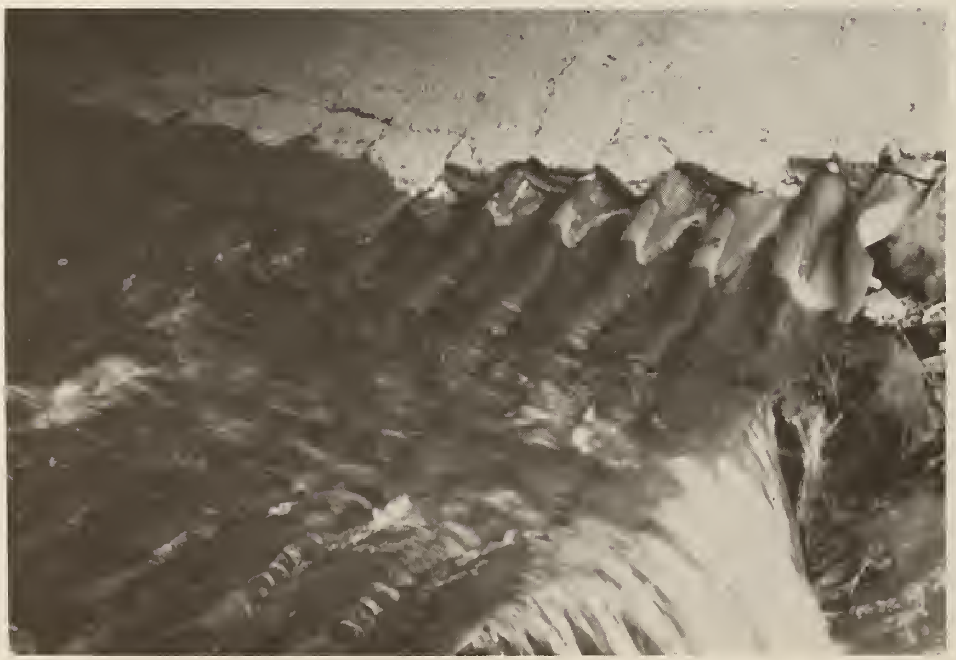

FIGURE 34 - Gunite on Galvanized Steel.
Site No. 92

FIGURE 35 - Concrete on Asbestos Bonded Asphalt. Site No. 27

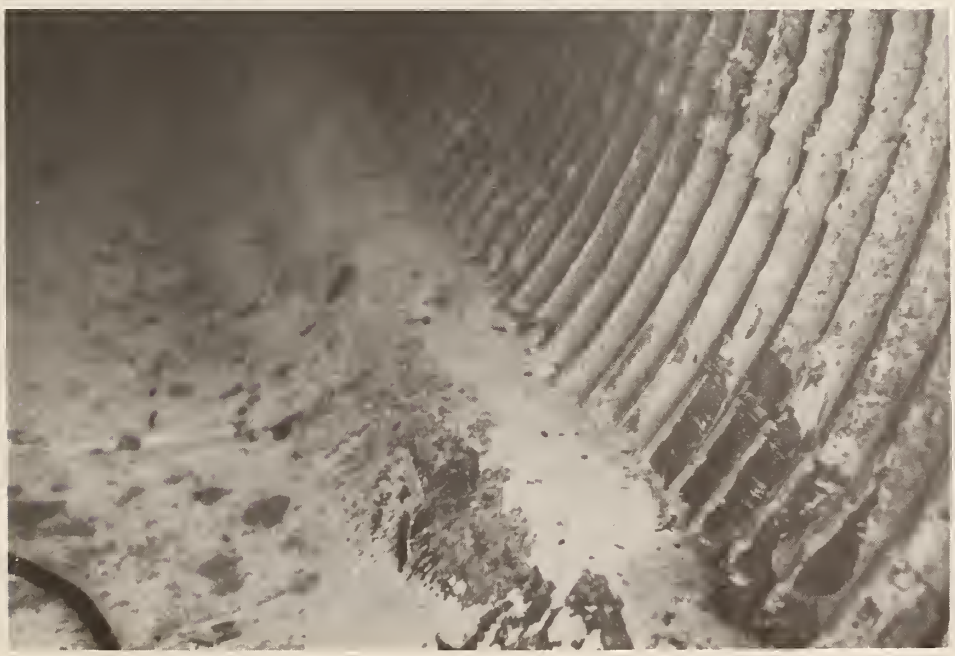

FIGURE 36 - Concrete on Asbestos Bonded Asphalt. Site No. 34

FIGURE 37 - Aluminized Steel. Site No. 44

FIGURE 38 - Galvanized and Aluminum-Zinc.
Site No. 21-22

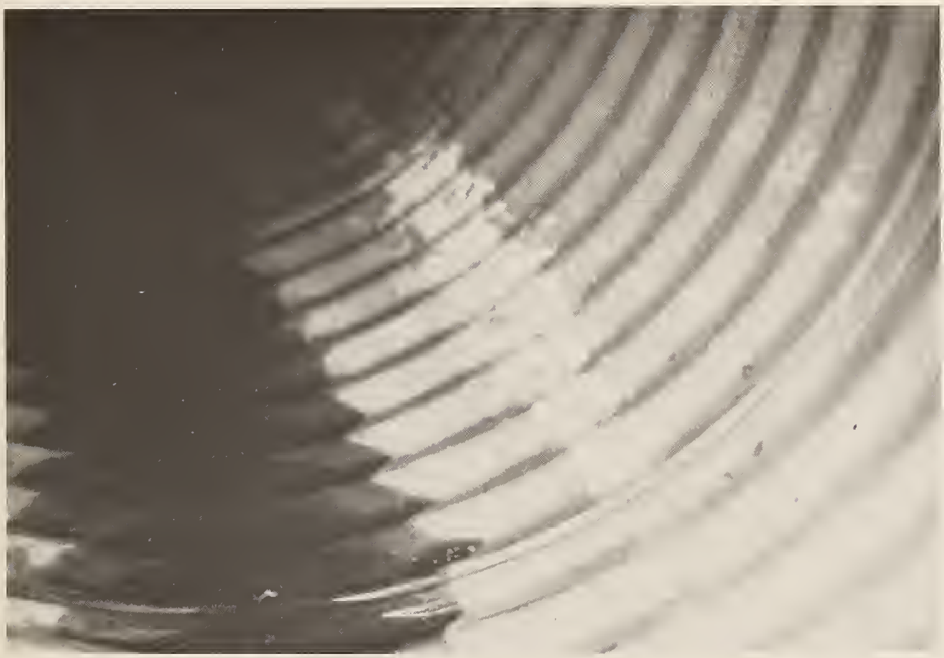

FIGURE 39 - Galvanized. Site No. 22

FIGURE 40 - Aluminum-Zinc (Galvalum)
Site No. 21

FIGURE 41 - Utah Test Site near Henderson

FIGURE 42 - Kentucky Test Site at Morton's Gap

FIGURE 43 - Colorado Test Site, Dillon

FIGURE 44 - Louisiana Test Site near Hackberry

TABLE I

LITERATURE REVIEW RESULTS

(SEE APPENDIX B)

	CULVERT MATERIALS:	GALV. STEEL	ALUMINUM	CONCRETE	OTHER	COATINGS:	ASPHALT	ASBESTOS BONDED	POLYMERS	EPOXY	OTHER	SELECTION CRITERIA:	pH	RESISTIVITY	SULFATES	SOLUBLE SALTS	EXPERIENCE	TYPE ROADWAY	OTHER	NO FORMAL	DURABILITY PROBLEMS:	EROSION	CORROSION	NONE REPORTED	COATING PERFORMANCE:	ADEQUATE	PROBLEMS	DURABILITY STUDIES:	COMPLETE	IN PROGRESS	NONE REPORTED
ALABAMA		x	x	x	x		x		x				x										x						x		
ALASKA		x	x	x	x		x	x					x									x				x					x
ARIZONA		x	x		x		x							x									x						x	x	
ARKANSAS		x	x	x			x													x			x			x					x
CALIFORNIA		x	x	x	x		x	x	x				x	x									x						x	x	
COLORADO		x	x	x			x	x	x				x	x	x				x				x			x			x		
CONNECTICUT		x	x	x	x		x													x		x									x
DELAWARE		x	x	x			x													x						x					x
FLORIDA		x	x	x			x		x				x	x									x				x		x		
GEORGIA		x		x			x		x				x	x									x						x		
HAWAII		x		x	x		x						x	x								x					x				x
IDAHO		x	x	x	x		x	x					x	x								x	x			x			x		
ILLINOIS		x	x	x	x		x	x											x				x				x			x	
INDIANA		x	x	x	x		x	x					x						x	x			x			x					x
IOWA		x		x	x		x												x				x				x		x		
KANSAS		x	x	x			x													x				x			x		x		
KENTUCKY		x	x	x	x		x	x												x			x				x		x	x	
LOUISIANA		x	x	x			x	x					x	x									x				x		x	x	
MAINE		x	x	x			x	x															x				x		x	x	
MARYLAND		x	x	x	x		x															x					x		x		
MASSACHUSETTS		x	x	x	x		x		x		x									x				x		x				x	
MICHIGAN		x	x	x	x		x													x						x			x		
MINNESOTA		x	x	x	x			x	x				x	x									x			x					x
MISSISSIPPI		x	x	x	x		x						x	x									x			x					x
MISSOURI		x	x	x	x		x		x								x						x				x				x
MONTANA		x	x	x			x	x	x				x	x					x				x				x				x
NEBRASKA		x	x	x	x		x													x				x		x					x
NEVADA		x	x	x	x		x	x	x						x								x				x				x
NEW HAMPSHIRE		x	x	x	x		x	x	x		x								x	x		x									x
NEW JERSEY		x	x	x			x						x	x					x				x			x			x		
NEW MEXICO		x	x	x									x	x									x				x				x
NEW YORK		x	x	x			x		x										x				x				x		x	x	
N. CAROLINA		x		x			x												x				x						x		
N. DAKOTA		x	x	x			x													x			x			x					x
OHIO		x	x	x	x		x	x		x	x		x									x	x				x		x	x	
OKLAHOMA		x					x		x										x				x			x			x		
OREGON		x	x	x	x		x	x					x	x									x				x		x		
PENNSYLVANIA		x	x	x	x				x	x			x										x			x			x		
RHODE ISLAND		x	x				x													x				x		x					x
S. CAROLINA		x	x	x	x		x												x			x	x			x					x
S. DAKOTA		x		x			x												x				x								x
TENNESSEE		x	x	x			x						x	x								x						x	x		
TEXAS		x	x	x	x		x	x											x				x			x					x
UTAH		x	x	x	x		x	x	x				x	x	x	x							x						x		
VERMONT		x	x	x	x		x		x											x				x		x					x
VIRGINIA		x	x	x	x		x				x		x									x					x			x	
WASHINGTON		x	x	x	x		x	x	x				x						x			x					x		x		
WEST VIRGINIA		x	x	x	x		x	x		x	x												x				x				x
WISCONSIN		x	x	x									x	x					x				x				x			x	
WYOMING		x	x	x			x	x	x				x		x											x					x

TABLE II

Summary of Culverts Inspected

By State	No. Sites	
California	7	
Colorado	7	(Includes 3 Test Sites)
Kentucky	10	(Includes 1 Test Site)
Louisiana	5	(Includes 3 Test Sites)
New York	11	
Ohio	14	
Oregon	6	
Pennsylvania	12	(Includes 1 Test Site)
Utah	10	(Includes 1 Test Site)

By Coating Type		No. Culverts Inspected
1.	Coal Tar Laminate (U.S. Steel Nexon)	25
2.	Asphalt dipped galvanized	22*
3.	Asbestos bonded asphalt	16*
4.	Epoxy coated concrete	9
5.	Asphalt Mastic	9
6.	Polyethylene (Inland Steel Black Klad)	6
7.	PVC (Wheeling Steel Plasticote)	5
8.	Asphalt dipped aluminum	4
9.	Gunite paved galvanized steel	2
10.	Vinyl Plastisol (Bethlehem Steel Beth Cu Loy PC)	3
11.	Aluminum zinc (Galvalum)	1
12.	Epoxy	1
13.	Aluminized	1
14.	Vitreous clay lined concrete	1
15.	Unbonded polyethylene	1
16.	Inorganic zinc	1
17.	Organic zinc	1

*22 out of the 38 asphalt coated culverts were asphalt paved.

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
1	C	1972	42	E	None	NA		PA, LR 1106, W. Branch Sus-
				I	CTE	-	None	quehanna, Clearfield Cty
2	C	1973	54	E	None			PA, LR 17051, Laurence Twp.,
				I	CTE	-	None	Sta. 78+60, Clearfield Cty, Plate Arch
3	GS	1956	120	E	None			PA, LR 17068, Karthaus Twp.,
				I	AM	.049	A	Sta. 138+02, Clearfield Cty, Plate Arch
4	GS	1956	96	E	None			PA, LR 17068, Karthaus Twp.,
				I	AM	.051	A	Sta. 116+61, Clearfield Cty
5	GS	1958	54	E	A	.100		PA, LR 17052, Goshen Twp.,
				I	A	.107	A	Sta. 508+57, Clearfield Cty
6	GS	1962	96	E	None			PA, LR 17038, Boggs Twp.,
				I	AM	.035	A	Sta. 955+77, Clearfield Cty
7	GS	1964	108	E	None			PA, LR 869, Boggs Twp.,
				I	AM	.055	A	Sta. 492+40, Clearfield Cty, Plate Arch
8	GS	1959	168	E	None			PA, LR 17041, Huston Twp.,
				I	AM	.041	None	Sta. 1025, Clearfield Cty, Plate Arch

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
9	GS	1947	72	E	A	.010		PA, LR 99, Shippen Twp.,
				I	A	.058	A	Sta. 458+64, Cameron Cty
10	GS	1974	72	E	None			PA, LR 103, Coudersport,
				I	AM	.023	C	Sta. 64+72, Potter Cty, Pipe Arch
11	GS	1959	72	E	None			PA, LR 96, Keating Twp.,
				I	AM	.041	A	Sta. 86+41, McKean Cty, Pipe Arch
12	GS	1977	36	E	E	.006		NY, Genessee Expy, Access
				I	CTL	.025	None	Rd. W. of Red School House
13	GS	1977	48	E	None			NY, Genessee Expy., Access
				I	VP	-	None	Rd. W. of Stoner Hill Rd.,
14	GS	1977	36	E	E	-		NY, Genessee Expy, Rock
				I	CTL	-	None	Spring Hill Rd., Structure
15	GS	1977	48	E	E	-		NY, Genessee Expy, E. of Red
				I	CTL	-	None	School House Lane, Access Rd.
16	GS	1958	60	E	A	.100		NY, Ostego Cty, Cty Rd.
				I	A	.060	A	19, S. of Sprout Brook
17	GS	1957	42	E	A	-		NY, NY Rt. 7, W. of Latham
				I	A	-	None	Village Lane
18	GS	1961	60	E	A	.075		NY, Wilkins Ave., Albany
				I	A	.075	A	
19	GS	1959	60	E	A	.100		NY, Rt. 22, 500 ft. S. of
				I	A	.075	A	NY 2 (Peterson)

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
20	GS	1957	84	E I	A A	- .075	A	NY, NY 7 between Latham & Watervliet, Corner of Arcadia
21	S	1973	36	E I	GA GA	.00175 .00175	None	NY, Rt. 32, N. of Smiths Clove Rd. & I87 Underpass
22	GS	1973	36	E I	None None	.003 .003	None	NY, Rt. 32, N. of Smiths Clove Rd. & I87 Underpass
23	GS	1959	36	E I	A A	- .075	None	OR, Rt. 214 at Rt. 22, S. of Overpass, Pipe Arch
24	Al	1967	12	E I	A A	- .125	A	OR, Rt. 22 S. of Lancaster Dr-Four Corners, Under N. Bound exit ramp, Pipe Arch
25	Al	1975	48	E I	A A	.060 .060	None	OR, Rt. 126, 3 mi W. of Mapleton Intersection
26	GS	1971	36	E I	ABA ABA	- .068	None	OR, Rt. 126, 3.5 mi W. of Mapleton, Mile 9.6
27	GS	1953	72	E I	ABA ABA	.06 .125	A+C	OR, U.S. Rt. 101, Mile 310.5, South of Port Orford, Curry Cty
28	GS	1953	42	E I	ABA ABA	- .110	None	OR, US Rt. 101, Mile 309.7, South of Port Orford, Curry Cty
29	GS	1964	72	E I	None AM	.040	None	UT, I80, Black Rock to Saltair opposite Kennecott Smelting plant

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
30	GS	1964	48	E	ABA	.042		UT, I80, 200' W. of Magna
				I	ABA	.042	None	Exit, Pipe Arch
31	C	1975	60	E	None	-		UT, I80, E. of Magna Exit
				I	E	-	None	
32	GS	1959	48	E	ABA	.100		UT, Utah 10, ¼ mi, N. of
				I	ABA	.113	None	Emery Cty line
33	GS	1963	48	E	ABA	.030		UT, Utah 10, 1 mi N. of
				I	ABA	.037	None	Castle Dale, Pipe Arch
34	GS	1963	54	E	ABA	.100		UT, Utah 24, 1.5 mi E.
				I	ABA	-	C	of Sigurd
35	GS	1973	36	E	CTL	.020		UT, I70, 2.2 mi E. of
				I	E	.0055	None	Exit 72, E. of Salina, Pipe Arch
36	GS	1973	60	E	CTL	.020		UT, I70, Frontage Rd.
				I	E	.0055	None	W. side, E. of Exit 72
37	GS	1973	24	E	CTL	.060		UT, I70, E. of Salina
				I	E	.0055	None	Pipe Arch
38	GS	1973	84	E	None			UT, I70, 5 mi. W. of
				I	AM	.014	None	Fremont Jct., Plate Arch
39	GS	1969	24	E	CTL	-		UT, 2 mi. S. of Hunting-
				I	CTL	-	None	don, Utah 10, Test Site
40	GS	1969	24	E	Iz	-		UT, 2 mi. S. of Hunting-
				I	Iz	-	None	don, Utah 10, Test Site, BASF Galvanox

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
41	GS	1969	24	E I	Oz Oz	- -	None	UT, 2 mi. S. of Huntingdon, Utah 10, Test Site, Bennetts 2 Comp. Galv. Paint
42	GS	1969	-	E I	E E	- -	None	UT, 2 mi. S. of Huntingdon, Utah 10, Test Site, Engard 460 & 463
43	GS	1972	24	E I	ABA ABA	- -	None	UT, 2 mi. S. of Huntingdon, Utah 10, Test Site
44	S	-	-	E I	ALM ALM	- -	None	UT, 2 mi. S. of Huntingdon, Utah 10, Test Site
45	GS	1974	-	E I	CTL E	- -	None	CO, U.S. Rt. 6, Fruita, Mesa Cty Test Site
46	GS	1976		E I	PVC PVC	.003 .010	None	CO, U.S. Rt. 6, Fruita, Mesa Cty Test Site
47	GS	1972	-	E I	UPE None	-	None	CO, U.S. Rt. 6, Fruita, Mesa Cty Test Site
48	GS	1974	-	E I	CTL CTL	.020 .020	None	CO, U.S. Rt. 50, 2.8 mi. S. of Olathe, Montrose Cty, Test Site
49	GS	1976	-	E I	PVC PVC	.010 .025	None	CO, U.S. Rt. 50, 2.8 mi. S. of Olathe, Montrose Cty Test Site
50	GS	1948	60	E I	ABA ABA	.05 .053	None	CO, U.S. Rt. 6 at 20 Rd. between Olathe & Grand Junction

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
51	GS	1975	24	E	A	.100		CO, Col. Rt. 139, N. of I70,
				I	A	.100	None	S of US6
52	C	1974	72	E	None			CO, I70, E. of West Rifle
				I	CTE	-	None	Interchange, Box Culvert
53	GS	1972	-	E	E	-		CO, I70, .6 mi. E. of Dillon
				I	CTL	-	None	Interchange Test Site
54	GS	1976	-	E	PVC	-		CO, I70, .6 mi. E. of Dillon
				I	PVC	-	None	Interchange Test Site
55	GS	1973	-	E	PE	-		CO, I70, .6 mi. E. of Dillon
				I	PE	-	None	Interchange Test Site
56	GS	1974	54	E	E	.003		CO, Delaware Ave., S. of
				I	CTL	.020	None	Stanford, City of Englewood
57	GS	1970	48	E	A	-		CA, I15, S. Bound on ramp at
				I	A	.056	None	I80
58	GS	1970	48	E	A	.070		CA, I15, 1 mi. S. of I80
				I	A	.071	None	Interchange
59	GS	1971	42	E	A	-		CA, I8, .5 mi. E. of Willows
				I	A	.100	A	Rd., Alpine exit
60	GS	1957	84	E	A	.050		CA, 98th St. & Harbor
				I	A	.048	A	Blvd., Los Angelos
61	GS	1958	54	E	ABA	.060		CA, Harbor Freeway & 174th
				I	ABA	.060	A	St., Los Angelos, Under NB Ramp

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
62	GS	1976	60	E	A	.050		CA, I15, S. of Calif. 15
				I	A	.056	None	Interchange
63	GS	1968	42	E	A	-		CA, Rt. 138, N. of Cleghorn
				I	A	.040	None	Rd., Milepost 26.08
64	GS	1973	18	E	E	-		LA, Rt. 27, S. of Hackberry,
				I	CTL	.013	None	Test Site
65	GS	1973	18	E	ABA	.064		LA, Rt. 27, S. of Hackberry,
				I	ABA	.064	None	Test Site
66	GS	1973	18	E	CTL	.026		LA, Rt. 27, S. of Hackberry
				I	E	.010	None	Test Site
67	GS	1973	18	E	A	.051		LA, Rt. 27, S. of Hackberry,
				I	A	.051	None	Test Site
68	Al	1973	18	E	A	.019		LA, Rt. 27, S. of Hackberry,
				I	A	.019	None	Test Site
69	GS	1973	18	E	PE	.004		LA, Rt. 27, S. of Hackberry,
				I	PE	.012	None	Test Site
70	GS	1973	18	E	PE	.006		LA, Rt. 27, S. of Hackberry,
				I	PE	.014	None	Test Site
71	GS	1973	18	E	PVC	.007		LA, Rt. 27, S. of Hackberry,
				I	PVC	.015	None	Test Site
72	GS	1973	18	E	E	-		LA, Rt. 27, S. of Hackberry,
				I	CTL	.033	None	Test Site

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
73	GS	1973	18	E I	E CTL	- .015	None	LA, Rt. 27, S. of Hackberry, Test Site
74	GS	1973	18	E I	PVC PVC	.008 .016	None	LA, La Rt. 109, N. of Starks, Test Site
75	GS	1973	18	E I	E CTL	.003 .014	None	LA, La Rt. 109, N. of Starks, Test Site
76	GS	1973	18	E I	ABA ABA	.075 .075	None	LA, La Rt. 109, N. of Starks, Test Site
77	GS	1973	18	E I	E CTL	.003 .026	None	LA, La Rt. 109, N. of Starks, Test Site
78	GS	1973	18	E I	A A	.060 .060	None	LA, La Rt. 109, N. of Starks, Test Site
79	Al	1973	18	E I	A A	.027 .027	None	LA, La Rt. 109, N. of Starks, Test Site
80	GS	1973	18	E I	PE PE	.004 .011	None	LA, La Rt. 109, N. of Starks, Test Site
81	GS	1973	18	E I	PE PE	.006 .013	None	LA, La Rt. 109, N. of Starks, Test Site
82	GS	1973	36	E I	A A	- .017	None	LA, Rt. 63, N. of Livingston, U.S. 190, Pipe Arch
83	GS	1963	44	E I	ABA ABA	.050 .052	None	LA, Rt. 1077, N. of Covington, Pipe Arch

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
84	GS	1957	28	E I	A A	- .088	None	LA, Rt. 1078, N. of Covington
85	C	1961	36	E I	None VC	-	None	KY, U.S. 41 Madisonville Bypass-Sta. 697-95
86	C	1962	60	E I	None None		PAE	KY, Western Ky Parkway, Sta. 4950, Milepost 68
87	C	1962	30	E I	None None		PAE	KY, Western Ky Parkway, Sta. 5129
88	GS	1962	48	E I	ABA ABA	.100 .118	A	KY, Western Ky Parkway, Sta. 3080
89	GS	1949	40	E I	A A	- .095	A	KY, Harlan Cty 568, .85 mi N. of Ky 421, Pipe Arch
90	GS	1949	57	E I	None None		Gunite	KY, Harlan Cty 568, 1.35 mi N. of Ky 421, Pipe Arch
91	GS	1949	57	E I	A A	- -		KY, Harlan Cty 568, 2.05 mi N. of Ky 421, Pipe Arch
92	GS	1949	72	E I	None None		Gunite	KY, Harlan Cty 568, 2.65 mi N. of Ky 421, Pipe Arch
93	GS	1949	38	E I	A A		A	KY, Harlan Cty 568, 3.65 mi N. of Ky 421, Pipe Arch

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Continued

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
94	GS		-	E I	PE PE	- -	None	KY, U.S. 41, Morton's Gap (Madisonville) Test Site
95	-	-	-	-	-	-	-	KY, U.S. 41, Madisonville, Proposed Test Site
96	GS	1969	30	E I	E CTL	- .021	None	OH, Perry Cty 131 at Cty Rd. T227, S. of New Lex-ington
97	GS	1972	36	E I	E CTL	- .019	None	OH, Rt. 328 mi 4.07, S. of Hacking Cty Rd. 330
98	GS	1973	44	E I	E CTL	.008 .021	None	OH, Rt. 328, 5.5 mile-post, N. of Washburn Rd. (T308), Pipe Arch
99	GS	1975	96	E I	ABA ABA	.110 .100	A	OH, Rt. 93, Milepost, 47, Next to house 22497
100	GS	1973	36	E I	E CTL	- .022	None	OH, Rt. 143, Milepost 6.43, Meiss Cty, Next to house 39331
101	C	1973	48	E I	None CTE	.025	None	OH, Rt. 554, Mile 17.18
102	C	1972	60	E I	None CTE	.022	None	OH, Rt. 554, Mile 18.47
103	C	1972	36	E I	None CTE	-	None	OH, Rt. 554, Mile 18.68

Table III - Culvert Test Sites - Description and Location
See Notes at end of Table for Abbreviations, Concluded

No.	Culv. Mat'l	Year Installed	Dia. (in.)	Ext. or Int.	Ctg. Type	Ave. Ctg.* Thick. (in.)	Paving	Location
104	GS	1971	36	E I	E CTL	- .022	None	OH, Rt. 145, .66 mi N. of Lower Salem
105	GS	1972	24	E I	E CTL	- -	None	OH, Rt. 145, Noble Cty, Mile 3.66
106	GS	1975	72	E I	ABA ABA	.100 .100	A	OH, Rt. 564, Noble Cty, Mile 7.23
107	GS	1972	30	E I	E CTL	- .022	None	OH, Rt. 564 and Noble Cty, Rt. 2 N. of Middleburg
108	GS	1971	48	E I	ABA ABA	- -	A	OH, Muskingam Cty Rd 604, ¼ mi S. of US 40, Zanesville
109	GS	1974	36	E I	E CTL	- .021	None	OH, Rt. 669, Mile 4.98, W. of Redfield, E. of Perry Cty Rd. T29

*Includes galvanizing

Table IV - Summary of Field Test Data
See Key at end of Table

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
1	E	7.9	12	ND	NA	NA	29700	34,666							
	I	6.0	19	>200				940	-	-	1.2	3	5	No	Joints Peeling
2	E	7.2	ND	ND	NA	NA	6600	20,500							
	I	2.9	12	>200				1,400	-	-	0.2	2	6	Yes	Rocks and Silt
3	E	7.0	8	ND	-.69	-	7000	22,500							
	I	7.7	ND	ND				31,500	-	-	1.2	1	5	Yes	Min. Ctg. .026"
4	E	6.4	18	ND	-1.20	-	-17900	19,440							Large Rocks
	I	5.2	ND	ND				21,300	-	-	1.2	0	5	Yes	Min. Ctg. .038"
5	E	7.0	ND	ND	-.740	.021	12400	38,250							Joints deteriorated
	I	2.8	25	>200				780	-	-	4	3	1	No	due to Turbulence. Some Corr. of Zn under asph on ext. sample
6	E	4.4	ND	53	-.748	NA	5700	19,000							Min. Ctg. .020"
	I	6.2	16	53				38,500	-	-	0.4	0	1	Yes	
7	E	6.5	ND	ND	-.918	NA	6400	23,000							Min. Ctg. .036"
	I	6.4	16	50				8,400	-	-	Trickle	0	4	Yes	
8	E	5.4	16	ND	-.763	NA	4400	10,904							Min. Ctg. .009"
	I	6.5	38	ND				7,800	-	-	1	0	3	Yes	Pits to .010"
9	E	5.9	ND	ND	-.700	.023	6400	13,885							Some Corr. of Zn
	I	6.6	8	ND				14,400	-	-	2	0	4	Yes	under asphalt on ext. sample

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
10	E	7.7	4	ND	-.993	NA	9900	31,333							Min. Ctg. .003"
	I	7.2	ND	ND				17,500	-	-	2	4	4	Yes	Erosion, Holidays
11	E	7.3	8	ND	-.715	NA	2580	14,482							Min. Ctg. .028"
	I	7.1	ND	ND				14,000	-	-	0.5	0	3	Yes	Pits to .075"
12	E	7.1	12	200	-.995	.110	5554	2,912							Metal exposed at corr.
	I	-	-	-				1,020	-	-	Dry	4	6	Yes	crests & lock seams
13	E	6.2	12	115	-1.01	NA	3830	2,000							Some thickness loss
	I	7.1	-	-				-	-	-	Dry	6	6	No	at corr. crests on int.
14	E	-	-	-	-	-	-	-							Blistering, Disbondment
	I	-	-	-				-	-	-	Trickle	0	6	No	in flow channel
15	E	-	-	-	-	-	-	-							
	I	-	-	-				-	-	-	None	3	6	Yes	
16	E	7.3	8	80	-.940	.0027	5170	10,840							Min. Ctg. .045"
	I	7.5	14	61				2,000	-	-	1.5	1	4	Yes	Checking on ext. of sample
17	E	7.0	8	95	-.670	.0425	7947	11,800							Half full water &
	I	6.9	44	ND				3,850	-	-	0.5	0	4	No	sediment. No ctg. left on lower half
18	E	7.0	8	85	-.448	.137	12448	16,000							Turbulence at joints
	I	7.2	16	90				1,800	-	-	10.7	3	4	No	Connecting band perforation Gas bubbles & Corr. of Zn under ctg. on ext.
19	E	7.4	12	ND	-.775	.055	11490	19,000							Turbulence & Ctg.
	I	7.1	78	ND				2,900	-	-	<1	3	1	No	deterioration at joints

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_C Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
20	E	5.3	ND	ND	-	-	3447	11,750							
	I	6.9	16	ND				5,100	-	-	5	3	4	No	
21	E	8.3	25	80	-.560	-	29682	17,618							Ctg. deteriorated on
	I	7.9	49	ND				3,350	-	-	None	0	4	No	exterior
22	E	8.3	25	80	-.950	-	29682	17,618							Ext. Ctg. in good
	I	7.9	49	ND				3,350	-	-	Trickle	0	4	No	condition (etched)
23	E	6.0	<10	63	-.625	.0064	21100	17,555							Min. Ctg. .064"
	I	6.3	<10	<50				24,500	34	68	None	6	6	No	Bottom silted
24	E	5.3	ND	ND	-.185	.015	4860	6,400							Poor Ctg. bond to alum.
	I	-	-	-				-	-	-	Dry	5	6	No	
25	E	7.7	<10	ND	-.724	.0034	9430	39,250							Min. Ctg. .020"
	I	6.7	<10	<50				15,500	34	51	4	4	6	No	Poor bond
26	E	-	-	-	-.595	.0015	9480	-							6" silt and gravel
	I	7.0	<10	<50				30,000	0	68	Trickle	6	6	No	
27	E	7.2	10	73	-.600	.075	21070	5,600							Concrete erosion
	I	7.4	22	57				2,600	240	240	Trickle	5	6	No	by water flow
28	E	-	-	-	-.600	.015	19150	-							Ctg. intact at outlet
	I	7.4	22	<50				8,500	51	68	4.5	2	1	No	where stream slows down
29	E	7.2	198	480	-1.00	-	-	1,242							
	I	7.5	960	1250				275	668	171	None	0	2	No	Min. Ctg. .020"
30	E	7.0	78	ND	-.530	.041		12,143							Min. Ctg. .020"
	I	-	-	-				-	-	-	Dry	4	-	Yes	Ctg. det. below water

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
31	E	NA	NA	NA	NA	NA	NA	NA							Previous G S culvert
	I	7.6	720	1200				380	1044	273	8	-	-	Yes	failed in 6 years
32	E	8.0	26	2100	-.585	.00145	1915	2800							Min. Ctg. .100". Asph.
	I	-	-	-				-	-	-	Dry	6	6	No	delaminates from asbestos on ext. sample
33	E	7.5	18	300	-.690	.101	958	5500							Min. Ctg. .020", Ctg. good
	I	8.0	26	3000				370	1711	256	3	0	4	No	cond. where water flow slow
34	E	6.9	210	3150	-.703	.040	3543	1000							Asph. disbonds from
	I	-	-	-				-	-	-	Dry	6	6	No	asbestos on ext. sample
35	E	7.0	20	ND	-.892	.0072	2394	3880							
	I	-	-	-				-	-	-	Dry	6	6	No	
36	E	7.2	144	ND	-.700	.00022	1245	1300							
	I	-	-	-				-	-	-	Dry	6	6	No	
37	E	-	-	-	-.640	.00055	1532	-							Epoxy det. only at
	I	8.0	114	580				920	650	359	1	0	4	No	water line
38	E	-	-	-	-1.02	-	2202	-							Min. Ctg. .0035"
	I	-	-	-				-	-	-	Ice	3	4	No	
39	E	7.6	42	2870	-	-	-	353							
	I	7.7	42	1500				450	154	102	None	6	6	No	
40	E	7.6	42	2870	-	-	-	353							Complete deterioration
	I	7.7	42	1500				450	154	102	None	0	3	No	where buried
41	E	7.6	42	2870	-	-	-	353							Complete deterioration
	I	7.7	42	1500				450	154	102	None	0	3	No	where buried

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
42	E	7.6	42	2870	-	-	-	353							Complete deterioration
	I	7.7	42	1500				450	154	102	None	0	3	No	where buried
43	E	7.6	42	2870	-	-	-	353							Asphalt disbonded
	I	7.7	42	1500				450	154	102	None	0	6	No	from asbestos
44	E	7.6	42	2870	-	-	-	353							Corrosion at mudline
	I	7.7	42	1500				450	154	102	None	5	5	No	& weld
45	E	7.2	1080	5125			306	141							CTL disbonding at
	I	-	-	-				.	-	-	Dry	2	4	No	lock seams
46	E	7.2	1080	5125			306	141							Corrosion at exterior
	I	-	-	-					-	-	Dry	4	4	No	lock seam
47	E	7.2	1080	5125			306	141							Unbonded polyethylene
	I	-	-	-					-	-	Dry	0	1	No	offers no protection
48	E	6.8	1740	7175			268	73							Deterioration at
	I	-	-	-				-	-	-	Trickle	4	4	No	lock seams
49	E	6.8	1740	7175			268	73							Blistering at lock
	I	-	-	-				-	-	-	Trickle	4	6	No	seams
50	E	7.9	10	ND	-.638	.039	3447	3609							Min. Ctg. .030",
	I	8.1	264	1800				400	1386	308	1	1	2	No	Asph. delam. from asbestos
51	E	-	-	-	-.978	.0082	-	-							10 ft. exposed to air
	I	-	-	-				-	-	-	Dry	6	6	No	Int. Coating disbonded
52	E	-	-	-	-	-	-	-							
	I	7.1	66	1000				660	718	239	1	6	6	No	

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
53	E	-	78	550	-	-	68940	-							
	I	-	-	-				-			Dry	6	6	No	
54	E	-	78	550			68940	-							
	I	-	-	-	-	-		-	-	-	Dry	6	6	No	
55	E	-	78	550	-	-	68940	-							
	I	-	-	-				-	-	-	Dry	6	6	No	
56	E	-	-	-	-.672	.043	2489	-							One area of abrasion
	I	-	-	-				-	-	-	Ice	5	6	No	at corr. crest
57	E	-	-	-	-	-	2777	-							Min. Ctg. .037"
	I	8.5	144	125				1950	291	325	Trickle	0	3	No	
58	E	7.2	528	300	-.930	.0195	4500	1117							Min. Ctg. .067"
	I	7.6	26	63				4900	103	86	2.5	0	4	No	Undercutting of Ctg., Ext. adhesion poor, corr. of Zn under ext. ctg.
59	E	-	-	-	-	-	22981	-							No Ctg. left on
	I	7.6	18	ND				7800	103	103	1	6	4	No	connecting bands, one area of paving gone
60	E	8.1	8.0	ND	-.625	.007	3159	1523							Min. Ctg. .020",
	I	7.5	14	ND				4900	154	170	None	6	6	No	Corr. of Zn under ctg. Holidays at Rivets
61	E	7.3	ND	ND	-.560	.0061	5362	-							Min. Ctg. .035"
	I	7.6	20	ND				4900	86	137	Trickle	6	6	No	

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
62	E	8.2	ND	ND	-.700	.0037	25854	75000							Min. Ctg. .035",
	I	-	-	-				-	-	-	Dry	2	4	Yes	Erosion of Zn Erosion Profile of ctg.
63	E	-	-	-	-.600	.0078	30641	-							Min. Ctg. .020"
	I	7.6	14	ND				3400	ND	240	1.5	0	4	Yes	
64	E	7.3	228	+	-	-	1244	3800							Blisters water filled
	I	8.1	1920	175				310	719	120	None	2	6	No	Epoxy gone
65	E	7.3	228	+	-	-	1244	3800							Some checking;
	I	8.1	1920	175				310	719	120	None	5	6	No	Disbonded at impact areas
66	E	7.3	228	+	-	-	1244	3800							CTL Cond. 4
	I	8.1	1920	175				310	719	120	None	0	4	No	
67	E	7.3	228	+	-	-	1244	3800							Ext. Ctg. cond. 1
	I	8.1	1920	175				310	719	120	None	4	3	No	
68	E	7.3	228	+	-	-	1244	3800							Ext. Ctg. cond. 1
	I	8.1	1920	175				310	719	120	None	4	4	No	
69	E	7.3	228	+	-	-	1244	3800							
	I	8.1	1920	175				310	719	120	None	4	4	No	Ext. Ctg. cond. 2
70	E	7.3	228	+	-	-	1244	3800							
	I	8.1	1920	175				310	719	120	None	4	4	No	Ext. Ctg. cond. 2
71	E	7.3	228	+	-	-	1244	3800							
	I	8.1	1920	175				310	719	120	None	4	4	No	Ext. Ctg. cond. 2
72	E	7.3	228	+	-	-	1244	3800							Ext. Ctg. cond. 0
	I	8.1	1920	175				310	719	120	None	1	4	No	Int. Ctg. disbonding

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
73	E	7.3	228	+	-	-	1244	3800							Ext. Ctg. cond. 0
	I	8.1	1920	175				310	719	120	None	4	1	No	
74	E	5.2	8	ND	-	-	4960	1857							One small area of
	I	5.8	<8	ND				25000	34	51	None	6	7	No	blisters at lock seam
75	E	5.2	8	ND	-	-	4960	1857							Minor blister at cut
	I	5.8	<8	ND				25000	34	51	None	6	7	No	edges on interior
76	E	5.2	8	ND	-	-	4960	1857							Asph. disbonding from
	I	5.8	<8	ND				25000	34	51	None	1	7	No	asbestos layer
77	E	5.2	8	ND	-	-	4960	1857							Ext. Ctg. cond. 5
	I	5.8	<8	ND				25000	34	51	None	6	7	No	
78	E	5.2	8	ND	-	-	4960	1857							Ext. Ctg. cond. 1
	I	5.8	<8	ND				25000	34	51	None	1	5	No	Disbondment
79	E	5.2	8	ND			4960	1857							Min. Ctg. .009"
	I	5.8	<8	ND				25000	34	51	None	0	4	No	
80	E	5.2	8	ND			4960	1857							Ext. Ctg. cond. 5
	I	5.8	<8	ND	-	-		25000	34	51	None	6	6	No	
81	E	5.2	8	ND	-	-	4960	1857							Ext. Ctg. cond. 5
	I	5.8	<8	ND	-	-		25000	34	51	None	5	6	No	
82	E	7.2	8	ND	-.750	.0044	3640	2160							Min. Ctg. .008"
	I	5.3	15	ND				22000	17	34	None	6	6	No	Holidays at seams, rivets
83	E	7.0	8	ND	-.600	.0023	12447	2166							Min. Ctg. .029"
	I	6.7	10	ND				21500	34	51	None	6	6	No	Asbestos appeared moist under asph.

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CprC	Abr	Comments
84	E	4.8	<8	ND	-.600	.0029	28725	2200							Channel eroded in
	I	6.4	18	ND				13800	51	86	1	0	3	No	concrete
85	E	-	-	-	-	-	-	-							Erosion of mortar
	I	2.2	324	60				200	-	ND	1	6	5	No	at joints to ¼"
86	E	-	-	-	NA	NA	-								Sand filler in epoxy
	I	6.0	8	300				8200	68	34	2	6	5	No	
87	E		-	-											Water eroding concrete
	I	3.1	26	400				800	975	ND	2	6	4	No	under coating
88	E	6.4	42	86	-.668	.0051	5075	2500							Paving checked
	I	3.4	26	400				1300	410	ND	2	2	1	No	Throughout length
89	E	6.2	ND	ND	-.642	.024	3150	5500							Paving appears eroded
	I	6.7	<8	130				3900	154	34	1	1	1	Yes	KDOT pH 3.5
90	E	-	-	-	-	-	-	-							Gunite completely
	I	6.6	8	160				2600	205	51	2	0	1	Yes	eroded, KDOT pH 3.5
91	E	-	-	-	-	-	-	-							Paving checked
	I	5.0	-	-				-	-	-	-	1	4	Yes	throughout length
92	E	-	-	-	-	-	-	-							Gunite completely
	I	6.0	<8	65				5200	119	68	3	0	4	Yes	eroded, KDOT pH 5.5
93	E	-	-	-	-	-	-	-							Rock & silt in invert
	I	-	-	-				-	-	-	1	2	4	Yes	
94	E	-	-	-	-	-	-	-							Disbondment at edges
	I	3.05	22	180				698	1352	0	.5	4	4	No.	only deterioration

Table IV - Summary of Field Test Data
See Key at end of Table, Continued

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
95	E	4.05	<8	125	-	-	-	4000	-						Proposed test site
	I	2.95	48	175				415	-	0	.5	-	-	No	
96	E	6.0	10	192	-.888	.023	5000	21700							Disbondment at lock
	I	4.0	360	200				798	565	ND	1.5	1	1	Yes	seams
97	E	6.3	10	140	-.975	.028	4980	7000							Most disbondment
	I	3.7	20	200				901	685	ND	0.6	1	4	No	1-2" at lock seams
98	E	6.8	10	50	-.931	.058	4780	20500							CTL eroded to .011"
	I	4.5	26	125				3020	137	7	1	3	4	Yes	thick at crests
99	E	7.6	10	300	-.818	.056	10500	25000							Silt and rock on
	I	3.8	18	200				2450	154	ND	1	6	6	No	invert, asph. delam. from asbestos
100	E	5.1	10	350	-.930	.108	2860	2985							Silted to 6" deep
	I	3.6	309	-				216	-	ND	0.5	2	6	No	
101	E	-	-	-	NA	NA	NA	NA							½ full sediment
	I	6.2	-	-				-	-	-	None	6	6	No	and water
102	E	-	-	-	NA	NA	NA	NA							Silt in invert most
	I	7.5	-	-				-	-	-	None	6	6	No	Ctg. .0015"
103	E	-	-	-	NA	NA	NA	NA							
	I	7.3	-	-				5100	-	-	1	6	6	No	
104	E	7.15	10	190	-.962	.042	3440	11333							Abrasion at crests
	I	4.72	16	880				976	736	7	1	2	4	Yes	
105	E	-	-	-	-	-	-	-							Invert reported
	I	3.7	-	-				-	-	-	1.5	0	0	No	Perforated in 1 yr.

Table IV - Summary of Field Test Data
See Key at end of Table, Concluded

No.	Ext. or Int.	pH	Cl mg/l	Sulf mg/l	E Volts	I_c Amps	ρ Ω-cm	ρmin Ω-cm	H mg/l	mALK mg/l	WFR ft/s	CtgC	CorC	Abr	Comments
106	E	7.1	29	350	-.862	.006	5750	2414							Asph. eroded on
	I	7.1	10	520				1250	582	34	2.2	6	6	Yes	rotated inlet section
107	E	6.1	-	-	-.985	.034	2680	3939							Abrasion & Tearing
	I	8.1	<10	200				1470	445	137	1	2	4	Yes	at crests
108	E	-	-	-	-.694	-	7920	-							
	I	7.2	-	-				1250	-	-	1.5	6	6	No	
109	E	7.1	20	360	-1.016	.136	2960	4380							No abrasion
	I	4.2	78	560				1180	560	410	1.3	2	5	No	

Abbreviations

Al	-	aluminum
A	-	asphalt dipped
AM	-	asphalt mastic
ABA	-	asbestos bonded, asphalt dipped
C	-	concrete
CTL	-	coal tar laminate - U.S. Steel Nexon
CTE	-	coal tar epoxy
E	-	epoxy
GS	-	galvanized steel
PE	-	polyethylene - Inland Steel Black Klad
PVC	-	polyvinyl chloride - Wheeling steel plasticote
PAE	-	polyamide epoxy
VP	-	vinyl plastisol - Bethlehem Steel
VC	-	vitrified clay
GA	-	galvalume - Bethlehem Steel
IZ	-	inorganic zinc
OZ	-	organic zinc
S	-	steel
ALM	-	aluminized

Key to Terms used in Table IV

1. Ext. or Int. - External (soil side) and Internal (water side)

2. pH - pH of soil or water if present. Soil side data not taken if no external coating present or representative sample unobtainable.

3. Cl - Chloride content in mg/l

4. Sulf - Sulfate content in mg/l

5. E - Potential of pipe exterior with respect to a saturated copper sulfate reference electrode in volts.

6. I_c - Corrosion current on exterior pipe surface measured by polarization curve. Tafel slope extrapolation or polarization resistance, amps

7. ρ - average soil resistivity taken by 4 pin Wenner method, reported at 5 ft. depth in ohm-cm.

8. ρ min. - minimum resistivity of saturated soil or resistivity of water, ohm-cm.

9. H - Hardness of water measured in mg/l $CaCO_3$

10. mALK - methyl orange alkalinity expressed in mg/l $CaCO_3$

11. WFR - Water flow rate at time of inspection, essentially stagnant water indicated by "None"

12. CtgC - Coating condition

No.	Asphalt	Polymer	Epoxy
6	No Deterioration	No Deterioration	No Deterioration
5	Checking, Erosion of Invert	Roughening of Ctg. at Corr. Crests, Blisters at edges <1/4"	Checking, some deterioration at ends
4	Chipping at Crests, incomplete ctg.	Disbondment at edges/seams to 1/4" Blisters to 1/2" dia.	Disbondment at joints to 1"
3	Disbondment at joints	Tearing of coating at Corr. Crests	Disbondment >1" less than 6"
2	Ctg. removed from one side of Corrugations	Disbondment at edges/seams to 1", Blisters to 1" dia.	Disbondment >6", <2'
1	50-90% removal from invert	Disbondment sufficient to collect debris - create blockage	Disbondment >2', <3'
0	Complete removal from invert	Complete disbondment/delamination or removal	Complete removal

13. CorrC - Corrosion Condition

No.	
6	No Corrosion
5	Zinc Corroding, Concrete eroding on invert or where exposed
4	Mild General Corrosion of Steel, Concrete erosion undermining ctg.
3	Steel pitting
2	Layer type corrosion of steel
1	Steel perforated at waterline or joints
0	Invert missing

14. Abr - Abrasion a factor

15. Min. Ctg. - minimum coating thickness measured

16. Metric Equivalents:

2.54 cm = 1 inch
30.48 cm = 1 foot

TABLE V

Typical Specification Limits
Of Culvert Asphalts As Reported By The Refiners

Property	Spec.	Windsor PC-1	Husky (1) S-209	Pioneer (2) Mastic	Koppers (2) Bitumastic 50
Penetration at 77°F	AASHTO 243	30-50	34	5-25	5-25
Penetration at 32°F	ASTM D5	25+	17	-	-
Penetration After LOH	AASHTO M190	85% min.	85% min.	-	-
Flash Point, °F	ASTM D92	450°+	485°	80°	-
Loss on Heating	AASHTO M190	1% max.	.05	1% max.	-
Solubility, C. Tet.	ASTM D2042	99% min.	99.9	99% min.	-
Ash Content	ASTM D271	-	-	.2% max.	15-25%
Bitument Content	ASTM D2172	-	-	30%	-
Softening Point, °F	AASHTO 243	200-220	217	205-240	205-240
Shock Test	AASHTO M190	Pass	Pass	Pass	-
Flow Test	AASHTO M190	Pass	Pass	Pass	-
Density, lb./gal.	AASHTO M243	N/A	8.54	8-9.5	8.2-8.9
Specific Gravity		1.00-1.04	1.021	-	1.2-1.4
Imperviousness Test	AASHTO M190	Pass	Pass	Pass	Pass
Percent Solids	AASHTO M243	N/A	N/A	60-68	60-68

(1)Typical
(2)Field applied mastics, AASHTO 243 applies but not M190

TABLE VI

Variation In Asphalt Composition Within AASHTO Specification Limits

Test	Spec. Limits	Composition, Percent			
		Parafins (1)	Carbenes (1)	Asphaltenes (2)	Saturated Hydrocarbons (2)
Penetration at 77°F	30-50	0-7.3	0-.5	17-18	19-30
Penetration of Residue	85% min.	-	-	20.2-23.1	5.4-29.6
Solubility in C. Tet.	99% min.	-	-	6.5-42.8	2.6-30.3

(1)Reference 64, 8 different origins (26 types)
(2)Reference 67, 2 different origins (7 types)

TABLE VII - Criteria for Using Metallic Coated Pipe Without a Supplemental Organic Coating

State	Criteria
Alabama	GS, AL: pH > 8.5 but not >> 8.5
Arizona	GS, AL: pH 6-9, SR > 2000
Arkansas	SER: pH 4.5-7.5
California	SER: pH 4-9, SR 100-100,000 Use graphical relationship between pH, SR and service life
Florida	SER: pH 5.2-8.4, SR 107-83,000 GS, AL: pH > 5.9, SR > 4500; use CA method where above criteria not met
Hawaii	SER: pH 4-9; use CA method and 40 yr design life
Idaho	AL: pH 5-9; SR > 1000; use CA method and 40 yr design life
Indiana	AL: pH 4-8, material depends on road type
Kansas	SER: pH 5.7-8.5, SR 700-2300
Louisiana	SER: pH 4-9, SR 200-30,000 AL: pH 5-9, SR > 1500, no iron ore present
Mississippi	GS: use CA method and 40 year design life
Montana	SER: pH 2.5-9; GS: pH 6-9, SR > 1000; AL: pH 5-8.5, SR > 800 and flow < 2.1 m/s
Nebraska	SER: pH 6.5-7.5, SR > 1000
Nevada	GS: sulfates > 1500 mg/l
New Jersey	AL: pH 4.5-8.5, flow < 2.4 m/s
New Mexico	SER: pH 5.9-11.4, SR 100-55,000; use CA method and 50 year design life
Oregon	SER: pH 4-10, SR 250 and greater; GS, AL: pH 4.5-10, SR > 1500

Pennsylvania	SER: pH 3-9; GS, AL: pH 5-8
Texas	SER: pH 4-10, SR 150-4000; AL: pH 5-9, SR > 1000
Utah	Use chart relating pH, SR, soluble salts with desired service life
Washington	SER: pH 4.4-8.9, SR 200-30,000, AL: pH 5.8-.5, geographic criteria
Wisconsin	AL: pH 5-9, SR > 1000
Wyoming	GS: sodium sulfate < .2%; AL: pH 5-8, alkali < .1%, sulfate in water < 150 mg/l

Notes:

1. SER = Service Exposure Range in state
   SR = Soil Resistivity in ohm-cm
   GS = Galvanized Steel
   AL = Aluminum
2. States not listed either do not allow uncoated pipe or have no formal criteria

TABLE VIII - Typical Material Costs for Flame Spray Coatings for Abrasion Resistance

Material	$Cost/Ft.^{2}$*
Type 316 Stainless Steel	$ 1.91
Aluminum Bronze	2.66
Molybdenium	13.81
60 Nickel - 16 Chromium	3.27
Monel	3.75
Chrome Oxide	14.51
Aluminum Titania	6.03
Aluminum Oxide	6.22
Phenolic Sealer for coatings	.049

*Based on coverage rate of 1/2 pound for .010 inch

Metric Conversion:

1 pound = 454 g
1 foot = .305 meter

TABLE IX - Alternative Coating Costs Compared to Existing Coating Systems

Existing Coatings:	Cost/lin. ft.[1]	Cost/sq. ft.
1. Asphalt at .050"	$ 3.20-4.57	$ .168
2. Asbestos Bonded Asphalt Dipped	4.67	.172
3. Polymer Precoat at .010" nom.	5.34-7.42	.235
4. Asphalt Mastic at .050"	8.04	.296
5. Asphalt Dip + Invert Paving	8.07-9.57	.353
6. Asbestos Bonded Asphalt Dipped + Paving	9.89	.364
Alternative Coatings:		
1. Coal Tar Enamel at .050"	5.27	.194
2. Polyamine Epoxy at .005"	9.90	.365
3. Fusion Bonded Epoxy at .008"	11.20	.415
4. Asphalt Epoxy at .014"	11.48	.423
5. Synthetic Primer + Asphalt Dip at .050"	11.91	.438
6. Synthetic Primer + Coal Tar at .050"	12.29	.452
7. Chlorinated Rubber at .004"	12.47	.451
8. Asphalt Mastic + Primer at .050"	12.67	.466
9. Coal Tar Epoxy at .016"	12.91	.476
10. Polyamide Epoxy at .012"	13.09	.482
11. Coal Tar Spray Applied at .050"	14.61	.538
12. Flake Glass Polyester	18.48	.681
13. High Build Tar Epoxy at .030"	20.43	.753
14. Polyurethane Elastomer at .040"	20.54	.757
15. Neoprene Paint at .015"	33.19	1.22
16. Neoprene Sheet at .125"	75.00	2.76
17. Butyl Rubber	75.00	2.76
18. Natural Rubber	69.00	2.54

(1) See page 98 for footnotes.

Notes

(1) Based on coating a 48-inch galvanized steel culvert pipe, 16 gauge, 2-2/3 x 1/2 inch corrugations, both sides. Costs are averages or ranges obtained from at least two suppliers, F.O.B. mill. Application costs of $6.73 per lin. ft. (.248/sq. ft.) for alternate system Nos. 2-15 includes $4.00 cleaning and degreasing and $2.73 for application (27.14 sq. ft.) except fusion bonded epoxy for which preparation is grit blasting. Cost of primers included.

(2) 1 sq. ft. = .0929 sq. m
1 in. = 2.54 cm

TABLE X - PRIMER ADHESION TO GALVANIZED CULVERT SHEET

Coating Type	Supplier	Coating Thickness Mils	Scrape Adhesion grams, 21°C	Elcometer Adhesion psi, 21°C
Zinc Chromate, vinyl butyral acid wash primer	Engard 135	1.00	750	200
Chlorinated Rubber primer	Engard 172	1.80	675	180
Wash Primer	Royston 701	1.05	700	200
Synthetic Resin*	Royston 716	1.20	400	180
Synthetic Rubber & Resin*	Royston A36	1.70	400	180
Synthetic Rubber & Resin*	Royston 713	5.80	3550	180
Vinyl Wash primer	Endcor 400	1.45	850	180
Polyamide Epoxy	Endcor 750	2.50	1700	250
Vinyl Butyral/ Phosphoric Acid Wash primer	Porter 1799 VC-17	1.20	450	225
Synthetic Resin*	Koppers Jet-Set	1.15	475	185
Zinc Dust Alkyd Resin	Mobil 13-F-22	4.30	2200	210
Polyamine Epoxy	Mobil 78-J-5	6.30	4050	190

Coating Type	Supplier	Coating Thickness Mils	Scrape Adhesion grams, 21°C	Elcometer Adhesion psi, 21°C
Epoxy	Mobil 13-R-159	4.4	3900	250
Coal Tar Epoxy	Mobil 578J1	8.15	1400	200
Vinyl Wash primer	Utility Prod. Petrol Proof	2.0	3900	210
Coal Tar primer*	Reilly Universal Black Magic	1.3	950	180
Synthetic Resin*	Reilly #122 Black Magic	1.2	125	180
Synthetic Resin*	Industrial Petr. Prod. PA-980	1.5	3500	170

Notes:
1. Data are average of 2 readings per condition
2. * indicates compatibility with hot asphalt
3. PSI x 6.895 = KPa
   1 mil = .001 inch = .00254 cm

TABLE XI - ASPHALT ADHESION TO GALVANIZED CULVERT SHEET

Supplier	Coating Thickness mils	Scrape Adhesion grams		Elcometer Adhesion psi	
		21°C	0°C	21°C	0°C
Empire Steel Co. (Husky Oil)	20.7	1050	2300	190	200
Husky Oil	39.2	1300	2700	290	340
Lane Metal Products (Windsor Service, Inc.)	1.5	450	1300	180	190
Syracuse Tank (Windsor Service, Inc.)	18.7	600	1300	180	190
Trumble Asphalt	14.0	650	1100	190	275
Primer/Asphalt Combinations					
Royston 713 + Husky Oil Asph.	26.5	1650	3700	275	225
Koppers Jet Set + Husky Oil Asph.	37.0	1900	3500	200	200
PA-980 + Husky Oil Asph.	29.0	775	1200	200	325

Notes:
1. Data are average of 2 readings per condition
2. PSI x 6.895 = KPa
   1 mil = .001 inch = .00254 cm
3. Precision
   Elcometer Adhesion: ±25 psi

TABLE XIII - SUMMARY OF STATE SPECIFICATIONS

	COATINGS INCLUDED:				SPECIFICATIONS:				PROCEDURES FOR:					
	Asphalt Mastic	Asphalt	Asb. Bonded Asphalt	Polymeric	AASHTO M190	AASHTO M243	AASHTO M246	State Spec.	Surf. Prep.	Double Dip	Galv. Repair	Coating Repair	Handling	COMMENTS
ALABAMA	X	X			X	X					X			
ALASKA		X	X		X						X			
ARIZONA		X			X									Specify Min. Asphalt Application Temp. of 199°(390°F).
ARKANSAS		X		X			X	X						
CALIFORNIA	X	X		X	X	X	X		X		X	X	X	
COLORADO		X	X	X	X		X'			X	X			
CONNECTICUT		X		X	X		X							Specifies tar based pitch for structural plate.
DELAWARE		X			X									
FLORIDA		X	X		X									
GEORGIA		X		X	X		X				X	X		Asbestos Bonded smooth lined spec.
HAWAII	X	X	X		X									No. Spec. on asphalt mastic.
IDAHO		X	X	X	X		X				X			
ILLINOIS		X		X	X		X							
INDIANA		X			X			X	X	X				Asphalt application spec.
IOWA		X		X	X		X					X		
KANSAS		X			X						X			
KENTUCKY	X	X	X	X	X		X							
LOUISIANA		X	X		X									
MAINE		X			X									
MARYLAND		X	X		X									
MASSACHUSETTS		X			X									
MICHIGAN		X			X									
MINNESOTA		X	X	X			X				X	X	X	Require 1.5 oz./sq. ft. zinc on asb. bonded.
MISSISSIPPI		X	X		X			X						
MISSOURI		X			X						X	X		M190 only used on aluminum.
MONTANA	X	X			X		X							Require 1.5 oz./sq. ft. zinc on asb. bonded. Water vapor permeability test on asphalt mastic.
NEBRASKA		X			X									Coated pipe no longer used.
NEVADA		X	X		X									
NEW HAMPSHIRE	X	X	X	X	X		X				X			FSS TT-C-494 used on structural plate.
NEW JERSEY		X						X						Detailed asphalt physical property tests.
NEW MEXICO		X	X		X						X			
NEW YORK		X			X						X	X		
N. CAROLINA		X	X	X	X		X							Aluminized pipe permitted.
N. DAKOTA		X			X									
OHIO		X	X		X									
OKLAHOMA		X			X									
OREGON		X	X		X			X	X		X	X		Asphalt application spec.
PENNSYLVANIA				X			X							Previously used M190.
RHODE ISLAND		X	X		X									
S. CAROLINA		X			X									
S. DAKOTA		X	X		X									
TENNESSEE														No specifications received.
TEXAS		X	X					X			X			
UTAH	X		X		X						X		X	
VERMONT	X	X			X		X				X		X	
VIRGINIA	X	X			X	X			X	X				Application Spec.
WASHINGTON		X	X		X									Application Spec., Require 1.35 oz. per sq. ft. zinc on asb. bonded.
WEST VIRGINIA		X	X	X	X		X							
WISCONSIN		X												
WYOMING		X	X	X	X		X				X	X		

APPENDIX A

CORROSION AND EROSION EFFECTS ON CULVERTS

Corrosion is defined as the deterioration of a material by chemical interaction with the environment in which it is exposed. While this definition allows any material, metal or nonmetal to corrode, corrosion is generally thought of as occurring to metals. The corrosion of metal under drainage pipe exposure conditions is caused by electrochemical reactions. That is, both electrical and chemical phenomena occur on the metal surface.

The classical corrosion cell has four characteristics, all of which must be present for corrosion to occur. First, there must be an anode where oxidation or the loss of electrons takes place. Secondly, a cathode must be present. The reaction at the cathode involves the gain of electrons and is called reduction. The anode corrodes, the cathode does not. Differences in metal composition, structure or differences in the environment surrounding the metal can give rise to anodic and cathodic areas on the same piece of metal. A single piece of steel may rust because of microscopic anodes and cathodes on its surface created by compositional differences.

The third item required in the classical corrosion cell is an electrolyte. An electrolyte is defined as any chemical substance or mixture containing electrically charged atoms or groups of atoms which can move in an electrical field. Natural water and soil containing soluble salts are electrolytes.

Finally, in the classical corrosion cell, there must be an electrical connection between the anode and cathode. If a copper bar (cathode) and an iron bar (anode) are suspended in water, without a metallic path between them, no corrosion current can flow between the two metals. But, if they touch or are otherwise joined through a metallic path, current will flow causing corrosion of the iron. Note that the iron and copper will both corrode individually even if not connected due to microscopic anodic and cathodic areas on their surfaces.

Chemical reactions occur simultaneously at the anode and cathode. For the reactions to proceed, the gain in electrons at the cathode must equal the loss in electrons at the anode. Examples of reactions at the anode are:

		E_o, volts
Fe	$Fe^{+2} + 2e^-$	+.440
Al	$Al^{+3} + 3e^-$	+1.662
Zn	$Zn^{+2} + 2e^-$	+.763

Where E_o = standard oxidation potential at 25°C using a hydrogen electrode

The metal is transformed into an ion or charged atom and electrons. The metal ion passes into the electrolyte. The electrons move via the metallic path to the cathode. Possible reactions at the cathode are:

$$M^+ + e \rightarrow M$$

$$M^+ + e \rightarrow M^{+2}$$

$$2H^+ + 2e^- \rightarrow H_2$$

$$O_2 + 4H + 4e \rightarrow 2H_2O$$

$$O_2 + 2H_2O + 4e \rightarrow 4OH^-$$

where M is the metal corroded such as iron, aluminum or zinc. The chemical reactions proceed because the anode and cathode are electrically different. If one could separate the anode and cathode and place a voltage measuring device between them, a voltage would be observed. Voltage is a measure of the driving force of the reaction.

All corrosion affecting drainage pipe is caused by voltage differences from one surface to another. Corrosion occurs from several causes, such as: local composition differences on the metal surface, bimetallic couples, oxygen differential cells, pH differential cells and interference from nearby cathodic protection systems. Anaerobic sulfate reducing bacteria (sporovibrio desulfuricans) usually found in wet clay soils of neutral pH, cause corrosion attack by acting as depolarizing agents. Aerobic sulfur-oxidizing bacteria, such as thiobaccillus thiooxidans cause corrosion in low pH environments by the production of sulfuric acid. Bacteria have been reported as causing corrosion of steel culverts and are known to attack aluminum but corrosion of aluminum culverts by this mechanism has not been reported.

Corrosion can occur in a uniform manner over a large surface area or in localized areas. There are different forms of localized corrosion that can affect drainage pipe. Pitting corrosion causes the formation of cavities extending into the thickness of the metal. Other forms of localized corrosion in addition to pitting are known to affect aluminum alloys under certain circumstances. Exfoliation is the preferential corrosion of aluminum grain boundaries which causes a scaling off of the surface in flakes or layers. Intergranular corrosion of aluminum is preferential grain boundary corrosion extending into the metal thickness.

Erosion can accelerate the effects of corrosion. Aluminum and iron (under certain conditions) form protective oxide films which can inhibit further corrosion. Stones and other debris can abrade this film allowing further corrosion to occur. This results in a more rapid deterioration than would normally occur with corrosion or abrasion alone.

APPENDIX B

LITERATURE REVIEW SUMMARY

The results of interviews and summaries of technical reports are included in this Appendix. Appendix C presents the published references. Other sources of information are listed after each state's summary.

Alabama

Alabama has acid soil areas, coastal areas and swampy areas. Galvanized steel, uncoated concrete and clay pipe are used for culvert pipe. Aluminum pipe is used but not extensively. Galvanized steel is always installed with an asphalt coating and paving applied according to AASHTO Specifications. Some polymeric coatings have also been used but in-service performance is not known. Metal pipe can be used with a soil pH of 4.5 or greater. Concrete or clay pipe is used in acid areas, coastal and swampy areas.

A study conducted in 1969[23] concluded that asphalt paving deteriorated in areas of high erosion and extreme acidity or alkalinity and that water eventually penetrates asphalt.

Service life prediction charts using pH, soil resistivity and dissolved oxygen content are presented. Criteria for materials used are presented as follows:

$pH < 4.5$ - use concrete or vitrified clay. In areas of extreme acidity, use coating on concrete.

$4.5 < pH < 8.5$ - use concrete, bituminous coated galvanized steel or bituminous coated aluminum

$pH > 8.5$ - use concrete galvanized steel or aluminum

$pH >> 8.5$ - use concrete, coated galvanized steel or coated aluminum

Additional References:

Highway Specification Section 530
Special provision 1147, 6-1-77

Technical Memorandum No. 3-70(2), 6-1-70 rev. 3-23-76, "Criteria"
Mr. Edward Eiland, Engineering Dept., Highway Dept., Montgomery, AL

Alaska

Both galvanized steel and aluminum culvert pipe are used at the contractor's option. Concrete, clay, asbestos cement and bituminous fiber pipe are also used for drainage pipe. Asphalt coating and asbestos bonded asphalt coated galvanized steel are used in areas of high acidity or alkalinity. Most culverts are installed uncoated. Coatings are reported to be performing satisfactorily. Abrasion on the invert is reported to be the worst problem.

Additional References:

Highway Sepcifications, Section 602, 603, 706, 707
Mr. Ray Shumway, Highway Dept. Juneau, Alaska

Arizona

Galvanized steel, aluminum, aluminized steel (no installations yet), bituminous fiber, asbestos cement and cast iron are permitted under state specifications. Galvanized steel and aluminum are normally used uncoated. Galvanized steel is coated when the soil resistivity is below 2,000 ohm-centimeters. Asphalt coating and paving are used on galvanized steel and applied according to ASSHTO Specifications. Culvert durability problems are caused mostly by external corrosion.

A study completed in 1973[10] reports good correlation between electrochemical measurements and soil corrosion. Cathodic protection studies using sacrifical anodes on galvanized steel culvert pipe yielded unsatisfactory results. Cathodic protection tests used magnesium anodes to protect uncoated galvanized culvert. The cost of providing protection in this manner was judged unreasonable. Bituminous coatings reportedly increase service life by at least fifteen years.

Developments since the 1973 report indicate that aluminum culvert pipes are giving satisfactory service in soil with resistivities greater than 500 ohm-centimeters. Field coatings on galvanized steel are not as durable as factory-applied asphalt. Aluminized steel pipe is being evaluated in the laboratory and in field tests.

Additional References:

Highway Specifications, Section 707
Mr. Steve Dana, Research Engineer, Phoenix, AZ

Arkansas

Concrete, galvanized steel and aluminum are allowed as contractor's options. Asphalt coating of galvanized steel was used in the past but state experience indicates that the coatings are not needed. No durability problems for culvert coatings were reported.

Additional References:

Highway Sepcifications, Section 606
Mr. A. E. Johnson, Asst. Chief Engineer, Little Rock, AR.

California (Selected for Field Study)

Galvanized steel, aluminum, asbestos cement and concrete are permitted for use as culvert pipe. Coatings used include asphalt and polymeric coatings applied to AASHTO Specifications. Polymeric coatings are currently limited to areas where interior abrasion is not severe. A procedure was developed in California[3,37] for estimating service life utilizing resistivity and pH. Fifty years is used as the basic design life criteria. A reported 8 to 20 additional years service life are obtained for asbestos bonded bituminous coated and paved invert, 5 to 15 years for bituminous coated and paved and zero to 8 years for bituminous coating (Highway Design Manual, Table 7-851.3A). The lower life expectancy is for abrasive bed loads at flow velocities greater than 7 feet per second (.213 meters per second). California has new criteria for using aluminum using a 50 year design life. Aluminum is permitted where the pH is greater than 5.5 and less than 8.5 and the resistivity is greater than 1500 ohm-cm. Aluminum culverts are not permitted where experience shows that deterioration can take place. Additional provisions are made for backfill and marginal pH and resistivity situations.

A study completed in 1973[18] evaluated 4 coatings, including asphalt, United States Steel "Nexon", Daubert Chemical Co. "Pioneer Culvert Mastic No. 1008" and Pacific Corrugated Culvert Co. "Copoly X Terrashield" and "Raceway". Laboratory abrasion tests indicate that the "Nexon" coating has a better abrasion resistance than asphalt or Pioneer mastic but would wear through faster than the asphalt due to the thinner film. Salt spray tests revealed a loss of bond between the asphalt and test plate with the others retaining their bond.

A study completed in 1964[2] recommends using coated aluminum where the pH is less than 5 and the pH is greater than 8. The researchers found no relationship between resistivity and corrosion and also that cathodic protection can control corrosion when soil resistivity is below 1,500 ohm-centimeters. Other findings were that aluminum should not be used under abrasive conditions or when the resistivity is below 2,000 ohm-centimeters.

In a 1977 study on abrasion[77], hot dipped asphalt, coal tar laminate (Nexon) and PVC (Plasticote) were compared using a rotating drum abrasion test. Test results indicated that the two polymeric coatings have abrasion resistance equal or better than asphalt but do not have equal resistance to abrasive flow. Polymeric coatings are approved for use on the soil side of culverts and on the interior where abrasive flow is not expected.

Additional References:

Highway Specifications, Jan. 1979 Ed, Section 66
California Test Method 643, 1978
Standard Special Provision 66.01, 1-3-78
Highway Design Manual, 5-1-72, Sections
7-841, 7-851
Mr. J. Robert Stoker, Cal Trans, Sacramento, CA
Mr. Roy Chalmers, Cal Trans, Sacramento, CA

Colorado (Selected for Field Study)

Galvanized steel, aluminum and concrete are used for culvert pipe. Specific restrictions are based on a criteria utilizing pH, chloride, sulfate and resistivity information. Coatings used include asphalt, asbestos bonded asphalt and polymeric coatings.

A culvert performance study completed in 1968 found that asbestos bonded asphalt coated galvanized steel and reinforced concrete were useful in acidic or alkaline waters. Uncoated galvanized steel and aluminum were usable in all but highly alkaline environments. Stainless steel culverts exhibited corrosion in alkaline environments.

Another study published in 1977[39] states that clad aluminum performs better than galvanized steel and that galvanized steel corrodes in high alkali, acid or salt environments. Stainless steel culverts were found to corrode rapidly in high salt and alkaline soil. Asbestos bonded asphalt coated pipe was found to offer only temporary protection due to abrasion and thermal cracking. An unbonded plastic wrap over an epoxy coating was tried but found to lead to worse deterioration than if the plastic wrap was not used. Several polymeric coatings, including U.S. Steel Corporation "Nexon", Wheeling Corrugating Company "Plasticote" and Inland Steel Company "Blacklad" are in test at various test sites throughout the state. Some loss in bond was noted at the seams of the Nexon coated sample but no other deterioration was reported.

Additional References:

Highway Specs., 1976 Ed and 8-1-76 Supplement - Section 624
Mr. Herb Swanson, Research Engineer, Denver, CO

Connecticut

Galvanized steel, aluminum, concrete, asbestos cement and bituminized fiber pipe are used in Connecticut. Galvanized steel is always installed with asphalt coating and paving. There are no formal material selection criteria. Abrasion at the invert is the worst problem. Field applied tar based pitch is used on structural plate culverts.

Additional References:

Highway Specs. & 11-77 Supplement, Section M.08
Mr. George Upton, Highway Engineer, Hartford, CT

Delaware

Galvanized steel and aluminum are used in Delaware. Concrete is no longer used. Galvanized steel is installed with asphalt coating and paving. There are no formal material selection criteria. A granular backfill is used around culverts under major highways.

Additional References:

Highway Specs., Sections 617 & 618
Mr. Watson Baker, Jr.-Chief, Materials & Research, Dover DE

Florida

Galvanized steel and concrete are used as alternate materials. Aluminum is used but only at selected installations. Bare galvanized steel is used where the pH is greater than 5.9 and resistivity is greater than 4,500 ohm-centimeters. Where the pH is less than 5.9 and resistivity is less than 4,500 ohm-centimeters, the California test method is used. Specifications are currently being written for aluminum. Galvanized steel is asphalt coated and paved. A polymeric coated culvert was installed four years ago. The basic durability problem with asphalt is a coating breakdown caused by exposure to water and light.

A 1975 study[5] found that bituminous coatings extend culvert life ten years and paving adds another thirty years to culvert life. Principle metal loss in Florida is due to interior corrosion.

Additional References:

Highway Specs., 1977 Ed., Section 943-6
Mr. R. P. Brown, State Materials Engineer, Tallahassee, FL

Georgia

Georgia utilizes galvanized steel and concrete for culverts. Asphalt and polymeric coatings are used where pH and resistivity criteria show it to be needed. Paving is used where an abrasive load is expected. Only limited service history is available for polymeric coatings. Aluminum pipe is not used. An uncoated galvanized steel culvert failed in a stream with a pH of 2.8 in less than six months. Failures originate on interior surfaces.

Additional References:

Highway Specs., Section 844
Mr. Hugh Tyner, Chief, Research & Development Bureau, Forest Park, GA

Hawaii

Concrete, galvanized steel and asbestos cement pipe are used. Concrete is used in the more corrosive environments. Asphalt coating was used but has been discontinued because of rapid failure due to erosion by silt and sand. Hawaii uses California Method 643 to determine culvert life and a 40 year design life criteria. Pipe thickness is increased in acidic soils to give the required design life.

Additional References:

Highway Specs., Sections 603.03, 707.03
Mr. Walter Kuroiwa, Materials Testing & Research Branch, Honolulu, Hawaii

Idaho

Galvanized steel, aluminum, concrete, asbestos cement and acrylonitrile-butadiene-styrene (ABS) are used for drainage pipe. Coatings are applied to both steel and aluminum and include asphalt and asbestos bonded asphalt dipped. Paved inverts are used. California Method 643 is used to estimate culvert life. Deterioration of both interior and exterior surfaces occur with coatings judged to be successful.

Several studies were performed in Idaho on culvert durability[7,15,35,36]. Uncoated galvanized pipe is recommended unless the California test method indicates a life of less than 40 years. Uncoated aluminum pipe is acceptable if the resistivity is greater than 1,000 ohm-centimeters and the pH is between 5 and 9.

Additional References:

Highway Specs., Sections 601, 706
Mr. J. W. Hill, Research Supervisor, Boise, ID

Illinois

Drainage pipe materials include galvanized steel, aluminum, concrete, asbestor cement and clay. Concrete is used on major projects. Asphalt and polymeric coatings applied to AASHTO Specifications can be used. Paved inverts are sometimes used. Deterioration of the asphalt and paving at the water line was reported. In general, asphalt coatings have not performed well. Asphalt deterioration at the water line, and resulting corrosion, are considered major factors. Corrosion mainly occurs on the inside surface. An aluminum culvert installed 10 years ago in a pH 4 environment is reported to be performing well where both a steel and concrete culvert previously failed. Fertilizer and mine runoff are major problems in Illinois.

Additional References:

Highway Specs., 7-1-76 Ed, Sec. 602, 710
Supplemental Spec. for Sec. 603, 7-1-77
Supplemental Spec. for Sec. 602, 2-1-77
Culvert Design Manual (6-200), 12-75
Subsurface Drainage (6-400), 3-78
Mr. Don Fowler, Design Engineer, Springfield, IL

Indiana

Indiana utilizes galvanized steel, aluminum, concrete, vitrified clay, asbestos cement, ABS and cast iron. Asphalt coating and paving are used as well as asbestos bonded asphalt coated pipe. Both asphalt paving and concrete paving are used. Highway specifications require concrete paving to be 2-inches (5 cm) thick over corrugation crests and also that wire fabric, welded to the invert, be used as reinforcing. Aluminum is used where the pH is between 4 and 8 and traffic flow is not greater than 200 vehicles per hour. Asbestos bonded asphalt coated pipe is used if the pH is less than 4. The type of roadway to be constructed generally determines the culvert material used. No known coating problems were reported. Internal deterioration is considered to be the worst. A 2 year study has started to evaluate culvert coatings. The study includes laboratory evaluations of coatings in a low pH environment.

Additional References:

Highway Specs., Sections 715, 907
Drainage Design Manual, Section 7-400, 2-77
Mr. S. R. Yoder, Chief, Div. of Design, Indianapolis, IN

Iowa

Galvanized steel, concrete and clay are used for culvert pipe and aluminum pipe is under study. Bituminous coating without paving is used. The designer chooses the material to be used. Corrosion from both acid and alkaline waters is reported to cause corrosion on the pipe bottom from the soil side. Cathodic protection was considered at one time but never used because of cost considerations.

A 1970 study of 52 culverts which were 2-6 years old indicated that the asphalt coating on all of the culverts had deteriorated. Temperature fluctuations are thought to be the cause. The worst deterioration was at the culvert ends and at the silt line.

Additional References:

Highway Specs., 1977 Ed, Sec. 4141
Mr. R. H. Given, Chief Engineer, Ames, IA

Kansas

Concrete, galvanized steel and aluminum are used as culvert materials in Kansas. Bituminous coatings are used but do not perform well. Studies indicate that bituminous coatings crack and disbond after about three years[43,44]. Most corrosion occurs on the interior of the invert. A 1968 laboratory study[44] indicates that etching the zinc coating improves adhesion of asphalt by 21 percent. The study reports that alternate wetting and drying loosens the bond of asphalt to zinc. Both studies recommend that the use of coatings in Kansas be discontinued.

Additional References:

Highway Specs., 1973 Ed, Section 1009
Mr. Carl Crumpton, Assistant Engineer, Planning and Development, Research Section, Topeka, KS

Kentucky (Selected for Field Study)

Coated galvanized steel, coated aluminum, asbestos cement, bituminized fiber and concrete are used in Kentucky. Coatings include asphalt, asbestos bonded asphalt and paving. A study is now in progress to develop useful material selection criteria. The most severe problem in the state is acid mine runoff. A study at the acid runoff test site at Morton's Gap, near Madisonville, indicates deterioration of asphalt coated pipe[22]. Studies are in progress in the acid stream, pH between 2-2.5, to evaluate aluminum and stainless steel.

Concrete pipe is sometimes paved with vitrified clay or epoxy. The epoxy paving consists of a primer and epoxy mortar top layer. The primer consists of an epoxy resin with polysulfide polymer and amine catalyst. The mortar is made with the same epoxy resin as the primer plus silica mortar sand and mineral fiber as fillers.

Additional References:

Highway Specs., 1976 Ed, Sections 809.01, 810
Special Provisions Nos. 7(76) & 14(76)
Special Specifications for Protective Coating of

Reinforced Concrete Culvert Pipe, Ohio County, WK5-2
Mr. W. B. Drake, Assistant State Highway Engineer, Research, Frankfort, KY

<u>Louisiana</u> (Selected for Field Study)

Uncoated aluminum, asphalt coated steel and concrete pipe are used in Louisiana. Asbestos bonded asphalt is also used where the pH is less than 5 and the resistivity less than 1,500 ohm-centimeters. Adhesion problems with asphalt coatings are being experienced. There is no serious abrasion problem but there is a sulfide problem.

A study in 1971[1] indicated that the California test method was applicable to Louisiana and that asphalt coatings added 8 years to culvert life. Asbestos bonded asphalt was considered superior to asphalt.

Studies are ongoing in the state to evaluate various coatings, including asphalt, asbestos bonded asphalt, polymeric coatings (coal-tar laminate and polyethylene) and uncoated steel and aluminum[28,29]. Results reported to date indicate that asbestos bonded asphalt is out-performing other coatings. Coating disbondment is occurring on asphalt coated aluminum, asphalt coated steel, polyethylene and coal tar laminate in some environments. Complete pipe perforation occurred on the galvanized steel, aluminum plate arch, asphalt coated steel, coal tar laminate coated steel, and polyethylene coated steel at the most severe test locations. The test samples were installed in 1973.

Additional References:

Highway Specs., 1977 Ed, Section 1007
Engineering Directives & Standards Manual, No. II, 2.1.6, 2-24-77 and 2.1.1, 1-3-77
Mr. E. J. Breckwoldt, Research Div., Baton Rouge, LA

<u>Maine</u>

Galvanized steel, aluminum and concrete are used for culverts in Maine. Bituminous coated and paved galvanized steel culverts with granular backfill are used. Asbestos bonded asphalt coating is used in coastal areas. Corrosion problems are limited to the pipe interior. One smooth bore culvert was installed with U.S. Steel Nexon coating in 1972 in Palermo, Maine. The environment is non-abrasive and the culvert is reported to be performed well. A five year old aluminum zinc coated test culvert is out-performing a galvanized test culvert. Personnel report problems occurring in the last two years with disbonding of bitumenous coatings. Studies are currently being conducted on aluminum pipe, asbestos bonded pipe, aluminum coated steel, polymeric coatings (some freeze thaw separation is occurring), epoxy coatings (bubbles and disbonds at pH 4) and aluminum zinc coated steel.

Studies in 1974[25] and 1976[24] indicate that ten extra years of life can be obtained with bituminous coatings, six if there is high stream flow. Aluminum culverts perform better than galvanized steel if the pH is between 5.8-7.9 and resistivity is greater than 8,250 ohm-centimeters. A study in 1975 determined the average metal loss probability of galvanized steel culverts.

Additional References:

Highway Specs., Section 707
Mr. K. M. Jacobs, Materials and Research Div., Bangor, ME

Maryland

Galvanized steel, clay, concrete, asbestos cement, bituminized fiber and aluminum pipe are used. Aluminum is being used at test locations only. Bituminous coated galvanized steel was used in areas of high sulfate mine waters. Aluminum coated steel is being considered.

A study completed in 1971[27] concluded that bituminous coatings add four years life and paving adds eight years life to culverts and was, therefore, not warranted. Bituminous coatings are no longer used.

Additional References:

Highway Specs., 1968 Ed., 1975 Revision and Draft for 1979 Ed.
Mr. Nathan L. Smith, Jr., Assistant Chief Engineer,
Materials and Research, Brooklandville, MD

Massachusetts

Concrete, coated galvanized steel and coated aluminum are optional culvert materials. Asbestos cement, clay and cast iron are also used for drainage pipe. Both galvanized steel and aluminum are coated with asphalt and paved according to AASHTO-M190. Polymeric coatings are also approved for use. An aluminum-zinc coated steel culvert was installed at one location but no performance data is available. There are no formal material selection criteria.

Additional References:

Highway Specs., Sections 230, M5.03
Mr. Gene Bastansa, Research & Materials Engineer, Wellesley Hills, MA

Michigan

Concrete, galvanized steel and aluminum, clay, bituminized fiber, cast iron polyvinylchloride (PVC), polyethylene (PE) and ABS pipe are used for culverts and other drainage pipe. Bituminous coatings are used for some pipes. There is no written selection criteria. There is a section along Interstate Highway 75 where deteriorated galvanized steel culverts are being lined with polyethylene.

A study completed in 1975[33] used polarization curves and potential measurements to evaluate culvert corrosion. A good correlation was found between the corrosion current determined by polarization and the visual performance rating. Resistivity, chloride, sulfates and pH were found to be good indicators of corrosion but no relationship was reported. Bacterial corrosion is considered an important factor.

Another report presented results of laboratory tests on three polymeric coatings[17]. Results of immersion tests in several chemicals indicate disbondment of coating due to dissolution of steel or zinc.

The most recent study, completed in 1979, included only two coated culverts, a nine year old asphalt coated culvert and a nine year old asbestos bonded asphalt coated culvert[49]. Both coatings had deteriorated in the invert portions and the metal corroding. It was felt that the coatings did not provide a significant increase in life expectancy. Service conditions for these two culverts are not provided in the referenced report.

Additional References:

Highway Specs., 1976 Ed., Section 8.08
Mr. Glen Caldren, Design Engineer, Lansing, MI

Mississippi

Concrete, PVC, aluminum and galvanized steel are used for culverts and other drainage pipe. Bituminous coatings are used on both aluminum and steel. Invert paving is sometimes used. Mississippi uses the California Test Method 643 method to determine whether or not to use metal and if coating is needed. Corrosion on interior and exterior surfaces is a major problem with culvert durability.

A 1964 study indicated that bituminous coatings added 2-7 years to the life of galvanized culverts[48].

Additional References:

Highway Specs., Section 709
Mr. Buford Stroud, Design Engineer, Jackson, MS

Missouri

Clay, concrete, galvanized steel and aluminum are the culvert and drainage materials used. A bituminous coating for galvanized steel was used but was dropped from the specifications because of adhesion problems. The cause is thought to be water absorption and freezing. Polymeric coatings are used but no experience data is available yet. Material selection is based on an evaluation of existing installations. Corrugated metal pipe is not used under major highways.

Additional References:

Highway Specs., 1977 Ed., Sections 725, 1020, 1021, 1024
Mr. Gerald Manchester, Design Engineer, Jefferson City, MO.

Montana

Galvanized steel, concrete and aluminum pipe are used in Montana. Asphalt, asbestos bonded asphalt and polymeric coatings are used. Material selection criteria is based on a test of soil conditions. Non-metallic or bituminous coated aluminum pipe are used if the soil resistivity is less than 1,000 ohm-centimeters and the pH is greater than 5. Bituminous coated galvanized steel is used if the soil pH is less than 6 or greater than 9. Charts are given for corrosivity of steel versus alkalinity and pH. Uncoated galvanized steel is considered usable in the pH range 6-9 and uncoated aluminum is approved if the pH range is 5-8.5

and resistivity is greater than 800 ohm-centimeters and non-abrasive flow velocity is less than 7 fps (2.13 m/s). Concrete is approved if the pH is greater than 6 and the soluable sulfate content is less than .25 percent. Bituminized coatings and vitreous clay are used in other areas. Concrete paving is used on large culverts under abrasive flow conditions.

Additional References:

Highway Specs., Section M-170
Special Provisions I90-1(77)22, Unit 7
Montana Dept. of Highways Criteria
Survey & Plans Manual, Part 15, Section 15-333
Mr. Carl Peil, Design Engineer, Helena, MT

Minnesota

Aluminum, vitrified clay, asbestos cement, galvanized steel and concrete are used for culverts and other drainage pipe. Asbestos bonded asphalt and polymeric coatings are used. Asphalt coatings tend to check and oxidize. Asbestos bonded asphalt is performing well. Paving is specified for both bituminous coated and polymeric coated culverts in abrasive conditions. Corrosion deterioration on both interior and exterior surfaces occur. The state is divided into four zones which are used as criteria for the use of metal culvert pipe. The four zones are based on the results of a study published in 1969 (Investigation No. 116, "Serviceability of Corrugated Metal Culverts") which related the life expectancy of metal pipes to soil acidity and wetness. Increased metal thickness and coatings are used where flow velocities are expected to exceed 5 feet per second (1.52 m/s).

Additional References:

Highway Specs., Sections 2501, 2502, 2503, 3226
Drainage Design Manual 5-294.300, 12-12-77; 5-294.343, 4-23-74
Mr. F. W. Thorstenson, Director, Materials, Research & Standards, St. Paul, MN

Nebraska

Concrete, galvanized steel, aluminum, clay and cast iron are used for culverts and other drainage pipe. Bituminous coating and paving were used in some areas depending on local conditions but coatings are no longer considered needed and are no longer covered in the specifications.

Additional References:

Highway Specs., 1965 Ed. and 2-19-70 Supplemental Specs., Section 99
Mr. Donald Swing, Materials & Tests Engineer, Lincoln, NB

Nevada

Aluminum, asbestos cement, bituminized fiber, clay, concrete and galvanized steel are used for culverts. Bituminous and coal tar laminate coatings are approved for use. Material selection is based on a chemical analysis for sulfate salts. A coating is used if the sulfate content exceeds 1,500 ppm. Asphalt performance is not considered satisfactory since salts are trapped under the coating and accelerate corrosion. Most corrosion occurs on the bottom exterior culvert surface.

Additional References:

Highway Specs., 1976 Ed., Sections 601, 709
Mr. J. M. Desmond, Asst. Chief Materials Engr., Carson City, NV

New Hampshire

Concrete, galvanized steel, aluminum, asbestos cement and plastic pipe are used for culverts and other drainage pipe. Coatings include bituminous, asbestos bonded asphalt, polymerics and aluminum coated steel. Polymeric coatings are limited to non-abrasive conditions. An aluminum coated steel culvert is currently being tested. There are no written materials selection criteria. The design engineer evaluates the bed load, slope and type of runoff to determine the type of pipe and coating. Interior abrasion is the worst problem although future problems from road salts are anticipated. Differences in asphalt performance with manufacturer are reported. Problems are reported in maintaining the structural integrity of aluminum during construction.

Additional References:

Highway Specs., 1974 Ed., with 11-77 Addendum #3, Section 591, 603
Mr. Joseph Grady, Design Engr., Concord, NH

New Jersey

Galvanized steel, concrete and aluminum are used for culverts in New Jersey. All metallic pipe is coated with asphalt and sometimes paved. Material and coating criteria are based on a statistical method developed by New York. The New York method uses probability curves for corrosion rates to determine service life. New Jersey's largest durability problem is on the inside of the pipe.

A 1974 study[34] presents criteria for using aluminum pipe, steel and concrete. Concrete is used where the pH is less than 4.5 and aluminum can be used if the pH is between 4.5 and 8.5 and the flow velocity is less than 2.4 meters per second (8 feet per second).

Additional References:

Highway Specs., Section 8.1.3
Mr. Kenneth Afferton, Design Engr., Trenton, NJ

New Mexico

New Mexico generally utilizes uncoated galvanized steel, aluminum and concrete. Only one coated installation was reported. This involved a galvanized steel culvert in a highly alkaline area (pH 12) of northwestern New Mexico where the zinc deteriorated. In this case, an asphalt mastic coating (Fed. Spec. WW-P-405B, Coating F) was used. Erosion of this coating has been observed after 1 year. California Method 643 is used as well as test coupons buried at the construction sites for larger culvert structures. Mechanical problems during construction of aluminum culverts are reported.

Additional References:

Highway Specs., Section 501
Mr. R. S. Busch, Bridge Construction Engineer, Santa Fe, NM

New York (Selected for Field Study)

Bituminous coated and paved galvanized steel and uncoated aluminum pipe are used. New York experiences durability problems with plain asphalt coated pipe. The state is divided into corrosion rate zones according to a new study which is not yet published. One zone corrodes steel at the rate of .00508 cm per year (.002 inch per year) and the other at .01016 cm per year (.004 inch per year).

Corrosion occurs primarily on the inside surface. Polymeric coatings are used in three installations. One installation on the Genessee Expressway is experiencing abrasion and disbondment problems after one year. Concrete pipe is used exclusively on Long Island. Coated and paved pipe is thought to extend culvert life by twenty-five years, but this is to be verified by a test program. Reinforced concrete paving (Class D Portland Cement Concrete) can be used on uncoated steel or aluminum. Highway specifications allow the use of smooth lined steel or aluminum pipe (corrugated outer surface and smooth interlocking interior).

The study on uncoated steel and aluminum is to be published in 1978 or 1979. A previous study had established a procedure using corrosion rate probability curves and a corrosion rate zone map for estimating service life. The present study indicates that this method might not be realistic because of the test methods and conditions at the time[13] of the original study.

Additional References:

Highway Specs., 1978 Ed. and Addendum No. 1, 1-2-79,
Sections 600, 501, 707
Mr. Pete Bellair, Senior Civil Engineer, Albany, NY

North Carolina

Coated galvanized steel and concrete pipe are used for culverts. Asphalt coating, sometimes with paving, is used in the central and western portions of the state while concrete is used on the eastern coastal plain. Interior corrosion is a major problem and paving is sometimes lost during periods of high runoff. Specifications allow the use of aluminized pipe in place of galvanized steel and the use of polymeric coatings in place of asphalt.

An early study in 1944[32] recommends that asphalt coatings be used in areas of continuous flow and persistent organic water. Asphalt coated and paved galvanized steel performed well in this investigation.

Additional References:

Highway Specs., Section 824, 932, 1978 Ed.
Project Special Provisions, Corrugated Steel Culvert Pipe, Section 932, 8-3-79
Mr. M. P. Strong, Research Engineer, Raleigh, NC

North Dakota

Galvanized steel, aluminum, cast iron and concrete pipe are acceptable for drainage pipe in North Dakota. Asphalt coating was used at one time but is now considered unnecessary. There is no criteria for material selection. Severe corrosion on a structural plate pipe is now being investigated to determine the cause.

Additional References:

Highway Specs., Section 830
Mr. Robert T. Peterson, Research Engineer, Bismark, ND

Ohio (Selected for Field Study)

Concrete, vitrified clay, coated galvanized steel and aluminum are used for culverts and underdrains. Asphalt lined and paved pipe and asbestos bonded asphalt pipe are used to coat galvanized steel. A vitrified clay lining is sometimes used. New design criteria call for asphalt coated and paved steel pipe and field paving of structural plate structures where the pH is between 4.0 and 5.5. Vitrified clay or lined reinforced concrete are to be used where the pH is below 4.0 or above 9.5. Concrete pipe is sometimes lined with a polyamide cured coal tar epoxy (MIL-P-23236) at a dry film thickness of .0762 cm (.030 inch). Asbestos bonded asphalt with paving, structural plate steel pipe with stainless steel bottom plates and structural plate steel with concrete paved bottom and vitrified clay invert are also to be used where industrial wastes are expected. Lined concrete, asbestos bonded asphalt or vitrified clay are to be used in highly acid or alkaline soils. Coal tar laminate (Nexon) coated culverts have been used in acid mine water areas.

An as yet unpublished study on culvert durability6 indicates that adherence problems of asphalt coatings are largely due to improperly cleaned pipe and improper pipe temperature during coating application in addition to low resistance to thermal cycling. Bituminous coatings alone are thought to be of little value. Field applied concrete paving erodes rapidly under acidic conditions. Vitrified clay lines and asbestos bonded asphalt are reported resistant to acidic conditions. The coal tar laminate tested had poor resistance to abrasive flow and bed loads over 2.54 cm (1 inch) and also exhibited delamination at lock seams. Corrosion of rivets on laminate coatings in acid waters is reported. Recommendations for applying asphalt include an acid wash of the zinc, and asphalt bath temperature of 204°C ± 15° (400°F ± 5°) where the pipe is not preheated and 193.3°C ± 15° (380°F ± 5°) where the pipe is preheated to 149°C (300°F).

Another unpublished study of culverts in Ohio by the University of Akron indicates that, of the culverts examined in the previous study[6], the average service life of bituminous coatings was 3.16 years and bituminous coating with paving was 18.71 years.

Additional References:

Highway Specs., 1977 Ed, Section 1104.25, 1104.26, 707
Draft of ODOT Location & Design Manual, 2-78
Mr. John Herl, Hydraulic Engr., Columbus, OH

<u>Oklahoma</u>

Galvanized steel is the culvert material used in Oklahoma. Bituminous or coal tar laminate coating is used in the eastern third of the state and paving is used where the velocity is expected to exceed 2.44 m/s (8 fps). The eastern part of the state has low pH and high resistivity soil. Coal tar laminate coatings are used in western Oklahoma where salt areas exist. Coal tar laminate is thought to have 2-4 times more abrasion resistance than bituminous coated pipes but paving is considered necessary in areas of high flow velocities and abrasive loads. Aluminum is not used for culverts because of problems. Differences in asphalt performance and lack of durability of unpaved pipe are reported. A test installation yielded three months life with an asphalt coating and six years life with a coal tar laminate.

A study published in 1971[21] evaluated culvert performance and California Method 643 with respect to its applicability in Oklahoma. The accuracy of the California method was found to vary with location. The same study recommended that pavement cover at least 25 percent of the periphery and be at least .318 cm (.125 inch) thick above the top corrugation.

Additional References:

Highway Specs., Section 726
Mr. Curtis J. Hayes, Project Engr., Oklahoma City, OK

Oregon (Selected for Field Study)

Aluminum, galvanized steel, concrete, asbestos cement and bituminized fiber pipe are used for drainage in Oregon. Steel and aluminum are coated with asphalt west of the Cascades. Concrete or asbestos bonded asphalt culverts are used in coastal areas and aluminum seems to perform well in swampy areas. Uncoated steel and aluminum are generally used east of the Cascades.

Studies on culvert durability[11,41] recommend that uncoated galvanized steel be used where the pH range is 4.5-10 and the resistivity is greater than 1,500 ohm-centimeters and east of the Cascades. Asbestos bonded or bituminous coated and paved pipe are recommended in western Oregon. Uncoated aluminum can be used where the pH is between 4.5 and 10 and the resistivity is greater than 1,500 ohm-centimeters.

Additional References:

Highway Specs., Sections 603, 707
Mr. Stephen Macnab, Hydrologic Engineer, Salem, OR

Pennsylvania (Selected for Field Study)

Galvanized steel, aluminum, stainless steel, concrete, vitrified clay and PVC pipe can be used for drainage. Design criteria are:

a. pH 3.5 or less, use stainless steel, vitrified clay, clay lined concrete, coal tar epoxy lined concrete, coated galvanized steel or aluminum

b. pH 3.5-5.0, use coated galvanized steel or coated aluminum, concrete

c. pH 5.0-8, use galvanized steel, aluminum or concrete

d. pH 8 and above, use coated galvanized steel, coated aluminum, concrete

e. High sulfur content - same as pH 3.5 or less

f. Highly abrasive conditions, use a .0254 cm (.010 inch) polymeric coating on the outside surface

g. Water pH less than 5 or greater than 8 and soil pH 5-8 and soil resistivity 6,000 ohm-centimeters or greater, use a .0254 cm (.010 inch) interior polymeric coating

h. Water and soil pH as in (g) but soil resistivity 2,000-6,000 ohm-centimeters, use .0254 cm interior and .00762 cm (.003 inch) exterior coating

i. Water pH less than 5 or greater than 8 and soil pH less than 3.5 or greater than 8 and soil resistivity less than 2,000 ohm-centimeters, use .0254 cm (.010 inch) interior and exterior coating.

Pennsylvania used asphalt coatings with paving but only found a three to five year coating life. Polymeric coatings are now used exclusively.

Laboratory studies in 1972 indicated that polymeric coatings are superior to asphalt coatings (plain or asbestos bonded) in abrasion resistance, chemical resistance and weathering. A study in 1976[16] reports that bituminous coatings are lost in the majority of culverts within three years.

Additional References:

Highway Specs., Supplement Section 707, 1-17-78
Design Manual, Change 24 to Publ. 13, Sections 2.12.15.02-2.12.15.05, Part 2, 4-12-77
Mr. Eugene Eckert, Engineering Coordinator, Harrisburg, PA

Rhode Island

Galvanized steel, aluminum and cast iron are used for drainage. All galvanized steel is asphalt coated and some is paved. There are no formal material selection criteria.

Additional References:

Highway Specs., Section M.04.02
Mr. Nicholas A. Giardino, Assistant Materials Engineer, Providence, RI

South Carolina

Concrete, galvanized steel, aluminum, vitrified clay and cast iron are used for drainage. Asphalt coating is used in some cases and paving is used depending on stream flow conditions. Concrete is generally used because the other materials are more costly. Coated pipe is used where erosion is expected.

Additional References:

Highway Specs., Sections 714, 715, 716
Mr. Richard Stewart, Research & Materials Engineer, Columbia, SC

South Dakota

Concrete and galvanized steel are used for culverts. Coatings are not used. Soil maps, showing areas corrosive to steel and concrete, are used for design. Deterioration is basically corrosion from the outside of the pipe. Severe corrosion is reported in shale soils.

Additional References:

Highway Specs., 1977 Ed., Section 1000
Mr. Merle Buhler, Design Engineer, Pierre, SD

Tennessee

Concrete, galvanized steel and aluminum are used for culverts. Bituminous coating of the invert was used until six years ago. Coatings are no longer used since the coating tended to crack and erode. Resistivity and pH are used as material selection criteria.

Additional References:

Mr. J. B. Wilee, Materials & Test Engr., Nashville, TN

Texas

Galvanized steel, aluminum, concrete, clay, asbestos cement, bituminized fiber, ABS and PVC are used for drainage. There is no aluminum pipe in service yet. Asphalt coated pipe is occasionally used and asphalt bonded asphalt coated pipe is permitted but has not been used. Interest in polymeric coatings was expressed. Internal and external corrosion problems exist. There are no formal material selection criteria.

Additional References:

Highway Specs., 1972 Ed., Items 460, 464

Special Provision to Item 460, 8-78
Special Provision to Item 464
Special Specification, Item 4233, 8-78
Mr. Gilbert Barr, Supervising Field Engr., Austin, TX

Utah (Selected for Field Study)

Galvanized steel, aluminum, concrete and clay pipe are used for drainage. Asbestos bonded asphalt, coal tar laminate and asphalt coatings are used. Design criteria are detailed in a 1974 study[42]. Reinforced Portland cement paving is specified in some installations.

The 1974 study reports that the total soluble salt content is the most important factor in pipe corrosion. The effects of pH and resistivity are greatest at soluble salt contents of less than 1.5 percent and both lose dominance at higher salt concentrations. The corrosive effects of salts peak at 5 percent. Additional service life is reported to be 26 years for asbestos bonded asphalt coated steel and 16 years for asphalt coated steel. Sulfate contents exceeding .5 percent might be the principle deteriorating agent for concrete according to the study. An expression was derived relating the pipe condition to the soluble salt content, pH, soil resistivity and age.

Additional References:

Highway Specs., 1970 Ed., Section 715, 514
Mr. Dale Peterson, Research & Development Engineer, Salt Lake City, UT

Vermont

Galvanized steel, aluminum, concrete and asbestos cement are used. Asphalt coating is used on major highway construction and polymeric coatings are approved but have not been used. There are no material selection criteria for durability. No problems are reported with coating durability.

Additional References:

Highway Specs., Section 601, 711
Mr. Robert F. Shattuck, Hydraulics Engineer, Montpelier, VT

Virginia

Galvanized steel, aluminum, concrete, vitreous clay, PVC and bituminized fiber pipe are used for drainage. Aluminum pipe is used uncoated. Bituminous coating, paving and increasing metal thickness are used to prolong pipe life. Concrete pipe is used where the pH is less than 4 or greater than 9 or abrasive conditions are present. Bituminous fiber pipe can also be used in acidic areas. Fiberglass pipe was installed in an area of acid runoff on Interstate 95 near Quantico. Criteria were developed for pipe selection based on road classification and project location. A study is in progress to evaluate coating performance.

Additional References:

Highway Specs., Section 240
Instructional & Information Memorandum
LD-76(R)11.7
Mr. R. V. Fielding, State Materials Engineer and
Mr. C. F. Boles, III, Design Engineer, Richmond, VA

Washington

Galvanized steel, aluminum, concrete, asbestos cement, bituminized fiber and vitrified clay are used for drainage. Bituminous coating and paving is used west of the Cascade Mountains, asbestos bonded asphalt coatings are used in areas of salt water exposure and concrete or coated steel are used in alkaline conditions. Uncoated galvanized steel can be used east of the Cascades. Coal tar laminate has been used in several locations for about ten years but its performance has been inadequate in abrasive situations. Interior pipe surfaces offer the worst durability problem. Aluminum is used in a pH range of 5-8.5 but not if tidal action or a heavy bed load are present.

A 1965 study[4] found no correlation between service life, pH and resistivity. Cathodic protection is not considered practical as interior deterioration is the primary problem in Washington. Comparison of results with the California method indicate that the California method gives conservative information as to service life. Bituminous coating on aluminum was found to be poor and unpaved bituminous coatings were found to be ineffective against erosion.

Additional References:

Highway Specs., 1977 Ed., Section 9.05

Mr. Roger LeClerc, Materials Engineer, Olympia, WA

West Virginia

Galvanized steel, aluminum, stainless steel, concrete, clay, asbestos cement, bituminized fiber and plastic are used for drainage. Asphalt coated, asbestos bonded asphalt and sometimes paving are used for steel. Coal tar epoxy coating or a clay plate liner are used on concrete in high sulfate environments. Some adhesion problems are encountered with asphalt coatings if they are stored above ground for an extended period. Specification has a provision for asphalt sealed hot applied asphalt-sand mix reinforced with wire mesh and applied to primed galvanized steel. Alternate provisions for Portland cement or Shotcrete are provided.

Additional References:

Highway Specs., 1978 Ed., Section 604, 713
Mr. John Judy, Director, Materials Control, Soil & Testing Division, Charleston, WV

Wisconsin

Galvanized steel, aluminum and concrete are used for culvert pipe. Coatings are generally not used because deterioration from ice occurs. Bituminous coatings do not adhere to pipe. The California method is used to determine service life. Sulfides are measured to detect anaerobic bacteria. Aluminum is used where the pH is between 5 and 9 and resistivity is more than 1,000 ohm-centimeters. Aluminum is installed uncoated. Aluminum is successfully used in acidic (pH5) and agricultural runoff areas.

Materials currently in test are aluminum clad steel, stainless steel and a polymeric (polyethylene) coating. Bacterial corrosion, boggy acidic soils and agricultural runoff are major problems. An evaluation in 1972 reports that aluminum and stainless steel are outperforming uncoated and asphalt coated galvanized steel. Test conditions are generally acidic (pH 4.7-7) with relatively high resistivity soil (15K to 30K ohm-centimeters). A later report[12] indicates that both aluminum and stainless steel are performing better than galvanized steel after 9 years exposure. The bituminous coatings on both aluminum and galvanized steel were removed from the metal surfaces in immersion areas.

Additional References:

Highway Specs., Section 520, 521, 523
Mr. George Zuehlke, Wisconsin DOT, Madison, WI

Wyoming

Concrete, galvanized steel and aluminum are used for culvert pipe. Present selection criteria call for using concrete pipe or coated metal pipe when the percent of sodium sulfate in the soil is greater than .2 percent. Aluminum pipe is installed uncoated. Coatings include asphalt, asbestos bonded asphalt and precoated polymerics all applied according to AASHTA Specifications. They report that asphalt coatings and aluminum are performing well.

New material selection criteria are proposed utilizing analysis of soil and water pH and sulfate content. Under the new criteria, guidelines for using uncoated steel, coated steel, aluminum, the types of coating and Types II or V cement are given in a table.

Additional References:

Highway Specs., 1974 Ed.
Special Provision for Corrosion Resistant Pipe to Sections 603, 607
Pipe Selection Chart Design Criteria - Proposed
Mr. Robert G. Warburton, State Materials Engineer, Cheyenne, WY

Other Studies

1. In a project for U.S. Steel Corporation, the Southwest Research Institute evaluated U.S. Steel's "Nexon" coal tar laminate in comparison with asphalt coated and asbestos bonded asphalt coated galvanized steel[9]. Among the findings of these laboratory tests are: both Nexon and bituminous coatings disbonded from substrate, corrosion deterioration did not occur on any of the coated samples, coating disbondment did not occur during freeze-thaw cycling and lock seam joints are superior to riveted joints. Asphalt spalling was observed during the freeze-thaw cycle. Abrasion tests indicated higher wear rates for asbestos bonded asphalt and roughly similar wear rates for asphalt and Nexon. However, depending on the bed load, the thinner Nexon coating abraded away at about the same time as bituminous coatings. Extensive delamination of all coatings occurred during chemical exposure tests in calcium

chloride, sodium chloride, sulfuric acid, sodium sulfate, ammonium carbonate, fertilizer, seawater and deionized water.

The bond between Nexon and asphalt paving was noted as poor. Chemical attack on asbestos fibers in sodium chloride, sulfuric acid and sodium sulfate caused delamination in some cases. Chemical attack on zinc also occurred leading to delamination.

The investigators noted differences between manufacturers regarding bituminous coating adhesion to the metal on the as-received samples.

2. A study by U.S. Steel Corporation[38] compared the performance of pot galvanized steel with continuous galvanized strip. Zinc coating by the pot dip process was heavier than by the continuous process, .079 g/sq. cm. (2.59 oz/sq. ft.) versus .065 g/sq. cm. (2.12 oz/sq. ft.). Although pot dipped galvanized steel showed an advantage at one test site in Washington, no significant differences in overall performance were reported. The study also indicated that there is no advantage to galvannealed steel over galvanized steel in either corrosion or erosion performance.

Tests utilizing 66°C (150°F) 2.5 percent sodium hydroxide wash on zinc coated steel indicated an improvement in asphalt adhesion where abrasion is severe.

Type 409 stainless steel performed well in the U.S. Steel exposure tests when exposed to aggressive conditions, including acid coal mine drainage and abrasion.

3. Bethlehem Steel Corporation is testing Galvalume (aluminum-zinc) coated steel culverts at 16 locations along the east coast. Test sites range in resistivity (soil & water) between 315-168,000 ohm-cm and pH between 5.1-8.5. Galvalume is performing slightly better than galvanized steel on the average[45]. This investigator inspected the test site in New York as described in the Field Survey section.

4. Armco Steel Company has conducted exposure tests of aluminized and zinc coated steel at various test sites throughout the country[46]. The results of these tests seem to indicate that aluminized type 2 steel is superior to zinc coated steel from both a

corrosion and abrasion standpoint. The test sites included fresh water marsh, alkali soils and "normal" soil. Range of pH was relatively narrow, pH 6.3-8.1 with one value to pH 9.5, so that information on acidic and extreme alkaline conditions is not known.

5. A study by the U.S. Department of Commerce in 1964 involved an inspection of culverts along the Blue Ridge Parkway in North Carolina[47]. Their findings indicate a reduction of 3-11 points in asphalt penetration and an increase in the softening point up to 10.8°F after 19 years. Most changes occurred on the sidewalls.

6. A study of the Soil Conservation Service[50] indicates that:

a. Corrosivity is not closely related to soil resistivity

b. Asbestos bonded pipes perform better than other pipes and that the asphalt is retained better when asbestos bonding is used.

c. Asphalt coatings do not stay on the invert of pipes subject to wet conditions.

d. Paving is of little use in pipes subject to high velocity flows. Turbulence at pipe joints is instrumental in removing paving from the pipes.

e. Use of non-corrosive backfill is desirable.

The study encompassed 72 corrugated steel pipes in Iowa, Kansas, Missouri and Nebraska. It is Soil Conservation Service practice to apply cathodic protection to pipes where the soil resistivity is less than 4,000 ohm-cm or the pH is less than 5. Details of the method of cathodic protection is not given in this report, however, another Soil Conservation Service report provides a method[51] using sacrificial magnesium or zinc anodes. This report recommends cathodic protection for asbestos bonded asphalt coated pipe and presumably all coated pipe.

7. A study at California State Polytechnic University[52] attempted to develop a method of evaluating coated and uncoated culvert pipe performance using polarization methods. Corrosion rates were

calculated for uncoated galvanized and asphalt dipped galvanized steel culverts, using the E-log I polarization method. No attempt was made to compensate for the effect of coating defects when calculating corrosion current densities.

8. Asphalt properties were recently investigated by the Asphalt Institute[53]. The study indicated that although asphalt properties have not changed over the years (adhesion to metals was not tested), asphalt properties do vary substantially depending on grade, method of manufacture and source. No single factor could be isolated to explain this. The properties of asphalt are reportedly changed on heating.

9. In a study conducted for Armco Steel Corporation, Battelle Columbus Laboratories[55] inspected asbestos bonded asphalt coated corrugated sewer pipe over 20 years old. The investigators found that asbestos bonded pipe was generally satisfactory except in areas of: salt water tidal action, low resistivity soil with decaying vegetation, acidic waters, highly abrasive environments and organic solvent containing environments.

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APPENDIX D

Corrugated Steel Pipe Fabricators Interviewed and Visited

Asphalt Refiners Interviewed

1.	American United Products Co., Natchez, MS, Bob Swanzy, Plant Manager	601-442-5405
2.	Armco Steel Co., Middletown, OH Gil Morris, Senior Sales Engr.	(Visited) 513-425-2083
3.	Bancroft & Martin, Portland ME Henry Darvey	207-799-8571
4.	Brown Pipe Co., Montgomery, Al R. C. Brown	205-262-6444
5.	Caldwell Culvert Co., Greenville, MS W. Loveless	601-332-2625
6.	Clinton Culvert Co., Clinton, IA Jeanette Refbord, President	319-242-6864
7.	Culverts & Industrial Supply Co., Inc., Casper, WY, George M. Royer, Vice President	307-234-7121
8.	Empire Steel Manuf. Co., Billings, MT Thomas Brien, President	(Visited) 406-252-0101
9.	Florida Steel Co., Tampa, FL Jim Goddard	813-621-3511
10.	Lane Metal Products, King of Prussia, PA, M. Cathers	(Visited) 215-272-4531
11.	Lane Metal Products, Bedford, PA R. T. Way, Plant Manager	(Visited) 814-623-1191
12.	Lane Metals, Pulaski, PA L. Lanthiter	412-652-7747
13.	The Levine Co., Inc. Des Moines, IA H. R. Craig, Jr., Vice President	515-262-5613
14.	Midwest Culvert Co., Sioux City, IA J. Troel	712-255-3503

15.	Northeastern Culvert Corp., Westminster, VT, A. Rogers	802-722-3359
16.	Penn Culvert Co., Billerica, MA	617-667-3837
17.	Ramco Steel, Inc., Houston, TX J. Morrison	713-443-3400
18.	Republic Steel Co, Canton, OH B. J. Andrews, General Manager	(Visited) 216-493-2680
19.	Smith Culvert Co., Enid, OK R. Vise	405-233-5555
20.	Southern Tank & Culvert Co., Cowpens, SC, D. R. McCaa	803-463-4311
21.	Southwest Manuf. Co., Oklahoma City, OK, L. Hall	405-236-3056
22.	Syracuse Tank & Culvert Co., Syracuse, NY, S. Steel, Plant Manager	(Visited) 315-476-3181
23.	Texas Steel Culvert Co., Arlington, TX G. Wetzel	817-265-2255
24.	Tri State Culvert Co., Laurenceville, GA, D. Johnson	404-963-9256

Asphalt Refiners Contacted

1. Husky Oil Company, Cody, WY
2. Windsor Chemical Co., Reading PA
3. Trumble Asphalt Co., Summit, IL
4. Vulcan Refining Co., Cordova, AL (no longer in culvert asphalt business)
5. Warrior Asphalt Co., Tuscaloosa, AL
6. Standard Oil Co., Cleveland, OH (no longer in culvert asphalt business)
7. Lion Oil Co., El Dorado, AR

APPENDIX E

Suggested Culvert Coating Specification

1. Application

1.1 This specification applies to coatings defined in 1.2 applied to corrugated galvanized steel (AASHTO M36), corrugated aluminum (AASHTO M196 & M219) or any other metallic coated corrugated drainage pipe.

1.2 Coatings included in this specification included asphalt applied by immersion, cold applied asphalt mastic or coal tar, asbestos bonded asphalt, precoated polymer types and pavings.

2. Coatings

2.1 Asphalt

2.1.1 Asphalt used to coat corrugated drainage pipe must meet the requirements of AASHTO M190 and, in addition, the following physical properties:

1. Penetration at 0°C (32°F), ASTM D5 or AASHTO T49 - 25 minimum at 200g for 60 seconds

2. Penetration at 25°C (77°F) - 35 to 55 at 100g for 5 seconds

3. Flash point, ASTM D92 or AASHTO T48 - 232°C (450°F) minimum

4. Specific Gravity, ASTM D70 or AASHTO T229 - .98 minimum

5. Softening Point, ASTM D36 or AASHTO T53 - 93°C (200°F) minimum/110°C (230°F) maximum

2.1.2 Tests shall be conducted with each day's coating run to include:

1. Softening Point

2. Penetration at 25°C (77°F)

The test results shall not vary outside the limits given in 2.1.1. Samples shall be removed directly from the vat.

2.2 Asphalt mastic and coal tar

2.2.1 These coatings shall meet the requirements of AASHTO M243 and:

1. Penetration at 25°C (77°F), ASTM D5 or AASHTO T49 - 5-25 at 100g for 5 seconds

2. Softening Point, ASTM D36 or AASHTO T53, 30-34°C (205-240°F)

3. Percent Solids, AASHTO M243 - 60 to 68

Asphalt mastic shall meet the additional requirements from Fed. Spec. WW-P-405B as follows:

	Min.	Max.
Filler		
Percent by weight	20.	40.0
Inorganic filler containing long fiber asbestos and fine inert minerals, percent	100	-
Vehicles, percent	60	-
Asphalts, percent	45	65
Petroleum, percent	35	55
Non-volatile bitumens, calculated by difference, percent	30.0	-
Pigment, percent by volume of non-volatile	25.0	-
Flash point of solvents, °F.	80.0	-

Coal tar shall meet the requirements of Fed. Std. FSS TT-C-494.

2.3 Asbestos bonded asphalt

Steel sheets for culverts shall be coated with a layer of asbestos fibers, applied in sheet form by pressing them into a molten zinc bonding medium. The galvanizing or spelter coating shall meet the requirements of the provisions of AASHTO M36. It shall be applied at such a rate per square foot, that, when sampled in accordance with specified methods, the recoverable amount of spelter, after the asbestos-bond has been removed, shall be not less than 1.5 ounce per square foot of double exposed surface. Asbestos-bonded metal pipe culverts shall be fabricated from asbestos-bonded sheets, the base metal of which shall meet the requirements of AASHTO M218. Both sides of the metal sheets shall be coated with a layer of asbestos fibers. Immediately after the metallic bond has solidified, the asbestos fibers shall be thoroughly impregnated with a bituminous saturant. The finished sheets shall be of first-class commercial quality, free from blisters and uncoated spots. After the asbestos-bonded sheets have been fabricated into culvert sections, an asphalt coating meeting the requirements of section 2.1 shall be applied according to section 3.

2.4 Polymeric Coatings

Polymeric precoated sheet shall meet the requirements of AASHTO M246. Coatings shall be completely free of defects such as pinholes, blisters or cracks.

2.5 Pavings

Asphalt paving material shall meet the requirements of section 2.1.

3. Application

3.1 Asphalt Dip (Plan galvanized and asbestos bonded)

3.1.1 Pipe must be clean of all dirt, grease and water prior to coating. Minimum pipe temperature prior to application shall be 5°C (41°F). Aluminum pipe should be lightly sandblasted or chemically etched prior to coating to provide a good surface profile.

3.1.2 Pipe shall be immersed in asphalt at 204°C ± 3° (400° ± 5°F) according to the following schedule:

Thickness	Minimum Immersion Time
.132 cm (.052 in.)	2.0 minutes
.163 (.064)	2.5
.201 (.079)	3.0
.277 (.109)	5.0
.351 (.138)	6.5
.427 (.168)	8.0

The pipe shall then be dipped a second time for a sufficient time to obtain a minimum asphalt thickness of .127 cm (.050 in.).

3.2 Paving

3.2.1 Asphalt shall be poured into the pipe invert with dams constructed at the ends in order to cover all corrugations and provide a smooth invert. Asphalt depth above the crests of the corrugations shall be .318 cm (.125 in.). Minimum asphalt temperature during the casting operation shall be 93°C (200°F). The extent of paving shall be in accordance with AASHTO M190 unless otherwise specified.

3.2.2 Paving applied to polymer coatings shall demonstrate satisfactory adhesion. Asphalt shall not peel or disbond from the polymer when a putty knife is forced between the asphalt and polymer.

3.3 Asphalt Mastic

3.3.1 Pipe must be clean of all dirt, grease and water prior to coating. Pipe temperature must be above 4.4°C (40°F).

3.3.2 Apply the mastic by either troweling, brushing or spraying to a thickness such that the final dry film thickness will be no less than .127 cm (.050 in.). The coated pipe shall be free of missed spots, pinholes, blisters and other defects.

3.3.3 The coating shall be allowed to fully cure prior to allowing water flow through the pipe.

4. Transportation and Handling

4.1 Coated pipe shall be handled at all times with equipment such as wide canvas slings and wide padded skids designed to prevent damage to the pipe coating. Bare cables, chains, bars or narrow skids shall not be permitted to come into contact with the coating. All handling and hauling equipment shall be approved by the inspector before use.

4.2 In truck shipments, the pipe should be supported on wide cradles of suitably padded timbers. All chains, cables or other equipment used for fastening the load must be padded.

4.3 Pipe shall be stored along the trench side supported on wooden timbers placed under the uncoated ends of the pipe to hold the pipe off the ground.

4.4 Pipe shall be hoisted from the trench side to the trench by means of a wide canvas or leather sling. Chains, cables, tongs or other equipment, likely to cause damage to the coating, or dragging or skidding the pipe, will not be permitted.

4.5 Any damage shall be repaired before lowering the pipe into the trench. Repairs should be made using asphalt mastic or coating approved by the manufacturer.

4.6 At all times during construction of the culvert, the contractor should use every precaution to prevent damage to protective coating of the pipe. No metal tools or heavy objects shall be unnecessarily permitted to come in contact with the finished coating.

4.7 Any damage to the protective coating from any cause during the installation of the culvert and before final acceptance of the purchase shall be repaired as directed by the inspector by and at the expense of the contractor.

5. Preparation of Ditch and Backfill

5.1 Bottom of ditch shall be free of rocks or other debris which would tend to damage the coating during or after lowering in.

5.2 Ditch shall conform to the pipe so that no forcing of the pipe is required when lowering in.

5.3 In extremely rocky areas, ditch shall be padded with sand or soft fill to prevent excessive damage to the protective coating. Measures required to be at discretion of the inspector.

5.4 Backfilling shall at all times be conducted in a manner to prevent damage and abrasion to pipe coating.

5.5 Placing of backfill about pipe shall only be done in the presence of the inspector after his final inspection and acceptance of the pipe coating.

5.6 After placing and aligning pipe in the trench, loose backfill shall be placed about the pipe to a depth of one foot above the pipe. This backfill shall consist of fine soil or sand.

5.7 Settlement of backfill in the trench shall be as directed elsewhere in the construction specifications.

APPENDIX F

Recommended Test Program

We recommend a test program to evaluate alternative coatings, surface preparations and asphalt modifications. The test program should be divided into two phases, that is, laboratory tests to screen a large number of alternatives and then field tests to evaluate the best methods determined in the laboratory.

Laboratory Program

The test program should include:

1. Evaluation of methods to improve the bond between asphalt and galvanized steel and aluminum. Methods include surface treatments and primers.

2. Evaluation of methods to improve the abrasion resistance of asphalt. The program should include the use of fillers and blends of asphalt.

3. Evaluate alternative organic coatings. The evaluation should include those coatings listed in Table VIII of this report and Zincrometal.

4. Evaluate the effects of asphalt composition on its erosion resistance and adhesion to galvanized steel.

5. Evaluate alternative means of protecting culverts other than organic coatings such as flame sprayed coatings and fiberglass. Reinforced Portland cement, concrete sealants and polymer-concrete mixtures might best be evaluated in field tests.

Laboratory tests should be used to screen the various coatings and methods. Tests should address the various physical and mechanical properties of the coating system under test, and should include:

1. Abrasion Resistance - see Discussion

2. Water Penetration - ASTM G9

3. Outdoor Weathering - ASTM G11 or G23

4. Impact Resistance - ASTM D2794 or G14

5. Ductility - 180° bend test

6. Freeze Thaw Resistance - AASHTO M246

7. Chemical Resistance - ASTM G20

8. Adhesion - ASTM D2197

There are several methods for evaluating abrasion, that is: air blast (ASTM D658), falling sand method (ASTM D968), pipeline coatings - rotating drum (ASTM G6) and Taber abrasion test. Non-standard tests, such as the rotating drum tests used by Johns and Crozier and a rocker arm test used by Dr. Emery at McMaster University, have been applied to culverts and drainage pipe. The rotating drum test used by Crozier accommodates the most samples in the least space and would probably be the most practical.

Field Tests

Laboratory tests are not suitable to accurately predict field performance, but should, instead, be used to select coatings for field evaluation. Several sites throughout the country should be selected to represent various exposure conditions. Exposure conditions should include: abrasive stream flows (both mild and severe), salt water, brackish water, alkaline, acidic, freeze-thaw, ice, decaying vegetation, swamp and neutral non abrasive exposure. State DOT research personnel should be consulted to determine exact locations. Sites should be selected so that all test culverts are exposed to the same stream flow conditions. Culverts should be installed and be large enough (at least 36 inch diameter) that the interiors can be inspected without excavation. Exterior coating performance can be evaluated from coupons on smaller pipe sections buried nearby.

Detailed information should be obtained to characterize the soil and water at each test site both initially and at each inspection. Information documented should include: pH, resistivity, chloride, sulfate, nitrate, phosphate, hardness, alkalinity, stream level, stream flow velocity and bedload type and size. Optimum data would also include maximum stream flow depths and velocity and the exposure time of those flows.

Inspections should be made initially, after six months, then yearly until the rate and mode of deterioration can be established. Measurements to be obtained include:

film thickness (including abrasive loss), blistering, cracking, disbondment, film continuity and evidence of metal substrate corrosion. Detailed photographs are needed at each inspection and a uniform rating system should be established and used at each test site.

American Society for Testing and Materials (ASTM) Subcommittee A05-17 is currently developing a field test program. ASTM is located at 1916 Race Street, Philadelphia, PA.

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FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.