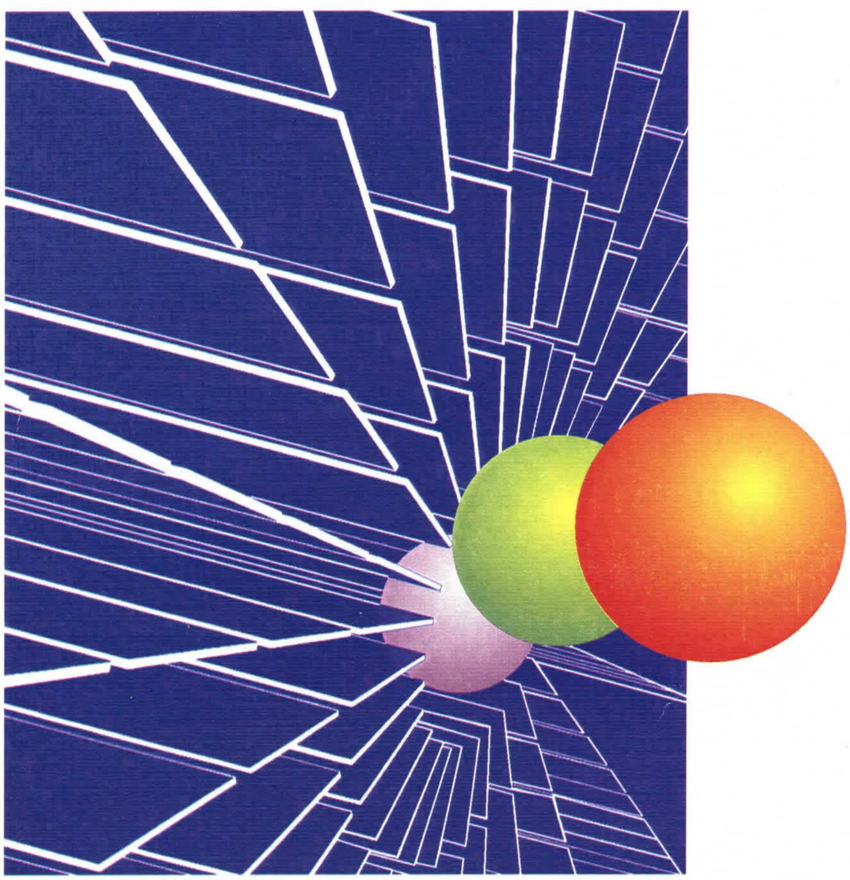
MoDOT

Research, Development and Technology

RDT 00-004

Culvert Study Report

RI 91-011



August, 2000

RDT 00-004

RESEARCH INVESTIGATION 91-11

CULVERT STUDY REPORT

PREPARED BY

MISSOURI DEPARTMENT OF TRANSPORTATION

RESEARCH, DEVELOPMENT AND TECHNOLOGY

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JEFFERSON CITY, MISSOURI

AUGUST, 2000

EXECUTIVE SUMMARY

The purpose of this report is to assess the results to date of the Missouri Department of Transportation's (MoDOT) culvert study. This report will provide some insight as to what has been accomplished in the past, what is being done now, and recommendations for the future. Topics discussed in this report are testing methods, quality of different pipe materials, visual inspections, and life span of pipes with respect to environmental conditions.

The diagnostic plot analysis in Appendix C indicates that pipe installed from the time period of 1900 to 1939 metal pipe lasted approximately 60 years. However, metal pipe installed after 1940 has only lasted an average of about 40 years. Corrugated galvanized steel pipe (GSP) was originally expected to last at least 50 years. Due to an insufficient number of failed reinforced concrete pipe (RCP), it was not possible to determine service life at this time. RCP has demonstrated a service life of at least 75 years to date in Missouri, but may last well beyond. Polyethylene pipe has only been evaluated for 15 to 20 years, since its initial installation in Missouri, so a service life based on statistical analysis cannot be determined at this time.

Steel, reinforced concrete and polyethylene pipes are all susceptible to some sort of environmental condition. Steel and concrete pipes are subject to corrosion by pH levels and soil resistivity. Concrete pipe is also affected by sulfate levels. Ultra-violet degradation is a concern with polyethylene pipe. However, some manufacturers provide UV protection in the pipe. Carbon black is mixed with the polyethylene resin to inhibit degradation.

The best practice for choosing the appropriate type of pipe is knowing about the environmental conditions and the properties of the different pipe materials. Familiarity with the pH level, soil resistivity, sulfate level, and other general information about the potential or

existing site should help indicate what type of pipe is suitable.

This study, like other studies prior, found that attempting to correlate culvert field performance and service life to field testing techniques, including pH and soil resistivity, proved inconclusive. Other field testing conducted in this study identified little or no correlation to field performance.

Tracking and monitoring the performance of the different pipe materials used throughout Missouri is felt to be a worthwhile effort. It is recommended that the culvert study continue on an ongoing basis. However, it should be re-designed to provide a study which is more efficient and provides effective results.

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INTRODUCTION

The Materials & Research Division started a formal investigation and inspection of a select number of experimental pipes in 1991 known as RI 91-11, The Culvert Study. During the summer and fall of 1994, research personnel visited maintenance buildings throughout the state trying to locate different pipe materials including polyethylene, aluminized, aluminum, polymer coated, poly-vinyl chloride (PVC) and polyethylene liners, and concrete. Upon locating each site, these pipes were tested and the log mile of the site reaffirmed. A list containing 141 culvert pipes in fifty-three counties throughout the ten districts was created to sample the performance of various types of pipes. This study was an annual investigation until 1997. It was decided that the culvert inspections should be performed on a bi-annual basis, so the 1998 season was the fourth year for the inspection of these pipes. The number of culverts inspected has increased since 1994. The list now contains 230 culvert pipes in seventy-one counties throughout the ten districts. The types of pipe inspected include double wall polyethylene (DWP), single walled polyethylene (CPE), poly-liner, aluminized, aluminum, polymer coated, concrete box, poly-vinyl chloride (PVC), PVC liner, insituform, fiberglass, slotted drain, galvanized, and reinforced concrete. A full list of the 230 pipes can be found in Table 2 in Appendix A.

The testing and inspecting aspect of the survey consists of several components. Testing procedures will be discussed in detail later in the report. All pipes are visually inspected to determine if any damage, erosion, or abrasion has occurred since it was last inspected. A picture is taken of the inlet and outlet of each pipe. Beginning in 1995, a video was taken of the inside of the pipe to determine the condition of the joints, view any possible deflections along the length of the pipe, and discover any deterioration of the pipe itself. All videos and pictures are kept on file.

HISTORY

In 1931-32, a total of 1349 culverts were inspected by the Materials and Research Division. All possible original locations were resurveyed in 1946-47. In 1964, a comprehensive culvert pipe survey was completed which included 2,149 corrugated metal culvert pipes and 880 reinforced concrete culvert pipes. Many of the culverts in the previous surveys were not resurveyed in 1964 due to route relocation (i.e. the county road system changed). All culverts in the 1964 survey were rated on structural and material durability. The rating of these culverts was based on methods used by the states of Georgia and Tennessee with slight modifications based on experience gained from the department's previous culvert pipe surveys of 1931-32 and 1946-47. The purpose of the survey was to determine service life of the culverts. All of the surveys mentioned above concluded that CSP had a predicted life of less than 50 years and that RCP would approach 100 years.

In 1987 a departmental report was written, MR87-1, Study of Use, Durability and Cost of Corrugated Steel Pipe on the Missouri Highway and Transportation Department's Highway System. One aspect of this report was the installations of several types of coating for corrugated steel pipe. The types of coatings used were epoxy, bituminous, bituminous and paved, polymer, and aluminum (known as aluminized pipe). Aluminized pipe was found to be the only coating accepted as equal to the galvanized (or zinc) coated pipe. Also in 1987, a database was created to track the life of culverts. When a pipe was installed, maintenance personnel filled out a form called a Culvert Rehabilitation, Replacement, or Construction Report. The form is now sent to Research, Development and Technology (RDT) where the data from the form is entered into the original database. This database is referred to as the culvert inventory.

Another comprehensive culvert report was written in 1991, MR91-1, Life Expectancy Determination of Zinc-Coated Corrugated Steel and Reinforced Concrete Pipe Used in Missouri. This report strictly compared metal and concrete culvert pipe. It found that CSP has a service life of approximately 44 years. A service life for RCP was not predicted due to an insufficient number of RCP having deteriorated. MR91-1 summarized all of the previous culvert surveys. The report also indicated that others have tried to relate service life of pipe culverts to measurable parameters such as pH, abrasion, soil resistivity, chemical characteristics of the effluent, and watershed characteristics. According to the report, these efforts were also attempted in this study. However, the results showed that neither a single or combination of measurable parameters were found to exist, which would predict the service life of pipe placed anywhere in the state. Although two isolated incidences were identified which did relate early deterioration to certain conditions, when incorporating these influences into the total survey data, they were subsequently "wiped out." Lastly, report MR91-1 recommended the investigation of plastic or fiberglass pipe liners and also the investigation of pipe materials other than those considered in the study (zinc-coated or galvanized corrugated steel and reinforced concrete).

A more recent report written in 1995, RI91-11B, Performance Evaluation of Aluminized and Galvanized Steel Culverts, provided conclusions to an on-going study which had been initiated in 1980. This study involved a direct comparison of the performance of aluminized culvert sections to galvanized culvert sections, which were installed at specific locations in 1952. The 1995 report conclusions indicated that aluminized culverts have a longer life expectancy than galvanized culverts in similar environments.

OBJECTIVE

This report has three primary objectives. The first objective is to review current field and laboratory testing procedures. The second objective is to review current data and build on findings from past surveys. The third objective is to address the quality and durability of different pipe materials.

DISCUSSION OF PRESENT CONDITIONS

The culvert study consists of a biannual investigation of 230 culverts located in seventy-one counties. The large number of culverts and variation in location provides adequate representation of various pipe materials proposed for specific environmental conditions.

Seven tests are conducted by the culvert crew during the biannual culvert inspection. These tests are the soil pH, water pH, 4-pin resistance, soil box resistance, soil to pipe resistance, water hardness and pipe thickness. All seven tests are not appropriate for every type of pipe. The technical report section explains when and how these tests are performed. All the tests are conducted at the inlet end of the pipe, unless the inlet is not accessible, then the outlet end is tested. It is then noted on the culvert inspection sheet if the outlet end is tested. Some of these tests provide significant data and some do not. The soil to pipe resistance and the water hardness data does not show any consistency or trends. The hardness of the water does not affect a pipe unless it stays in the pipe for an extremely long time. Since most pipes are installed with a slope, water does not remain in the pipe for very long. On the other hand, tests such as soil and water pH should potentially furnish valuable information.

Besides performing tests on the culverts, problems are also detected by means of a visual inspection. One of the most common problems is mower damage. Fifty percent of the single wall polyethylene culverts, eighteen percent of the double wall polyethylene culverts, eighty percent of the aluminum culverts, twelve percent of the aluminized culverts, and ten percent of the polyethylene liners experienced mower damage. Another problem is deformation or indentation of the pipe. The single wall polyethylene and aluminized culverts were affected the most by this problem. Other problems exist but they are minimal. Overall, the condition of the culverts has been favorable**.**

Another aspect of culvert monitoring or tracking is the useful life of culverts. When a culvert is replaced or new construction occurs, district personnel send a report to RDT (see Figure 1, Appendix A). The report contains information about the old and new pipe. Information from this report is then entered into RDT's culvert replacement database, which is used to help determine useful life of culverts. The new type of pipe material for replacement or new construction is decided by the districts. In most districts, this decision is the responsibility of either the maintenance superintendent or area engineer.

CURRENT CULVERT STUDY TEST METHODS AND RESULTS

The following is an explanation of how and when the seven culvert tests are performed. This section will also explain a pending NCHRP project that concerns testing methods for soil resistivity and pH measurements.

Soil and Water pH

PH is a measure of the relative acidity or alkalinity of water. It is defined as the negative log (base 10) of the hydrogen ion concentration. Soil and water with a pH of 7 is neutral; lower pH levels indicate increasing acidity, while pH levels above 7 indicate increasingly basic solutions.

A soil and water sample is collected in the field and submitted to the chemical laboratory for the determination of pH. Obviously, if there is not any water in the inlet, then a sample is not collected. When inspecting a slotted drain, a soil sample is not required because there is not any soil present.

Although soil and water pH is an important aspect of the culvert study, several studies have found little relationship between pH alone and rates of corrosion of aluminum or steel. Therefore, one should not rely solely on pH as indicating absence or presence of corrosive soil or water.

4 Pin Resistance Test

The purpose of the 4-pin resistance test is to determine if the soil around the pipe is corrosive. This test is performed on every culvert except slotted drains.

The procedure is as follows. The first pin is inserted in the ground 4' from the inlet of the pipe. The next pin is placed two feet from the first. The third is placed two feet from the second, and so forth. The four pins should follow the flow line of the water entering the culvert (i.e., the ditch line). After the pins are placed, an electric pulse is sent to the ground via the electrodes (pins) and the resistance is measured by a Nilsson 400 soil resistance meter. All numbers are reported in ohms. Afterwards the value obtained from the meter is multiplied by a formula (reading* distance in feet*191.51=soil resistivity) (1) to determine resistivity in ohms-cm. Below is a table showing the level of soil corrosiveness for specific resistivity ranges (2).

Table 1 - Soil Corrosiveness and Resistivity

Soil Corrosiveness	Resistivity (ohm-cm)
Very low	10,000>R>6,000
Low	6,000>R>4,500
Moderate	4,500>R>2,000
Severe	2,000>R

There has been some inconsistency in the resistivity readings in the past. This is attributed to several factors. The most common error is misinterpreting the resistance meter. In the first couple of years of the study, some operators read the multiplier dial on the resistance meter differently than others. During the 1998 inspections, all culvert crew members were shown the proper way to read the meter. Another problem is the location of the pins. A record was not kept of where the pins were placed in previous inspections, so in 1998 a drawing of the pin's location was attached to the back of the inspection sheet. This schematic shows the distance and direction of the pins from the inlet. Some difference in resistance readings could also be caused by nature such as non-homogeneous fill materials around the pipe, acidity from rain water, and saturation of the soil. The soil resistance readings, combined with pH measurements, are useful indicators of corrosive environments.

If field testing of culverts is continued, it is recommended that the 4-pin resistance test be eliminated from procedures. As previously discussed, the test has produced results with significant variability which have been misleading. In addition to improper interpretation of the meter, misplacement of the pins with regards to the previous location of testing poses a problem. Regardless of providing a diagram for placement of the pins, it is difficult to place the pins in the exact location, as well as, repeating the test under the same environmental conditions. The procedures of setting the pins at 2 feet intervals also dictates that the resistance level recorded is actually two feet deep, which may have no bearing on the pipe itself.

Soil Box Resistance

The purpose of the soil box test is to consider the worst case scenario for the type of soil around a pipe. The worst case occurs when the soil is saturated. Saturated soil gives a low resistance reading, and a low resistance reading indicates high corrosion. Table 1 shows this correlation.

Minimum resistance is determined by adding distilled or de-ionized water to 400 grams of prepared soil such to obtain the minimum resistance reading from the soil box. It was determined that an amount of water that creates a pudding like consistency will give the minimum resistance. Several water contents may be used to check the validity of this procedure. The dimensions of the box have been chosen so that the measured resistivity can be expressed in ohm-centimeter. Therefore, all values are recorded in ohms-cm.

The soil box test uses the same Nilsson 400 soil resistance meter as the 4 pin resistance test. Therefore, the problems experienced with operating the meter will be similar. To allow for a more controlled test, the soil box test should be performed in the lab after the moisture content has been determined. This test is performed on the all culverts except for slotted drains.

Soil to Pipe Resistance

The soil to pipe resistance test is performed only on metal culverts, and is the measure of resistance between the pipe and a pin placed in the soil 4' from the inlet. The first pin used in the 4-pin resistance test setup can also be used for this test. One red and one black wire are connected to the culvert, and the other red and black wires are attached to the pin. The two wires from the culvert are plugged into one side of the resistance meter. The two wires from the pin are plugged into the other side of the meter. Then a resistance reading is recorded. All numbers are reported in ohms-cm. Again, low resistivity readings indicate a more corrosive soil condition.

The soil to pipe resistance test also uses the same resistance meter as the 4-pin resistance and soil box resistance tests. Therefore, the problems experienced with the meter will be similar. There is not a correlation in the soil to pipe resistance readings from year to year. Therefore, it is recommended not to perform this test in future culvert investigations.

Water Hardness

The water hardness test is performed by titrating a buffer solution into a water sample and adding a hardness pill. The step by step procedure is located in the RDT Culvert Manual. This test is performed when there is an ample amount of water in the inlet to be tested. The purpose of the water hardness test is to test the hardness of the water. Soft water has a more adverse affect on metal than hard water. Hard or soft water must remain in contact with a pipe for an extremely long time in order to affect the pipe. Most of the pipes that are tested are sloped, so this condition does not apply to any pipes in the culvert survey. Therefore, it is recommended that this test not be performed in future culvert investigations. The results from the hardness test are displayed in Tables 3, 4, and 5, Appendix A.

Pipe Thickness

The purpose of the pipe thickness test is to determine if the pipe material is thinning in certain areas (e.g., where the water runs through the pipe). Pipe thickness is measured using the Krautkramer Branson DME. This instrument measures the thickness of culvert pipes by means of an ultrasonic sound wave passing through the material and measuring the known velocity of the sound waves. The sound waves reflect from the first interior surface encountered. This meter is used on steel, aluminum, single and double wall polyethylene, and some polyethylene liners. However, most liners cannot be tested because they exceed the maximum measurable thickness of 1/2". Special care must be taken when measuring double wall polyethylene pipe. A reading should be taken at a point where the interior and exterior walls are the farthest apart. If a measurement is taken where the two walls meet, the reading will be incorrect. Since the meter measures the thickness according to the known velocity of the material, the meter must be calibrated for the specific material that is being tested. Also, the operator must make sure the units of the recorded readings are in inches.

Test Results

Table 3, 4, and 5 shows the test results from the bi-annual culvert investigation. It is obvious from this data that the test results are often unpredictable. Many of the readings are drastically different from year to year. What is not so apparent from these results is the correlation between the readings and the deterioration of the pipes themselves. For example, only 4 out of the 19 soil pH readings in district 7 were below 5.5. This would indicate that, for the most part, the soil in district 7 is not acidic. However, past field performance indicates that the soil is too corrosive for metal pipe; therefore, district 7 only installs concrete and plastic pipe. Soil resistivity readings from the 4-pin resistance test also indicate some inconsistencies. Perhaps future testing should consider testing for the presence of other substances such as sulfate, fertilizers, and other chemicals that might influence these readings. The pipe condition does not always coincide with what is expected from the soil maps. Therefore, RDT could try to relate the soil pH from the field samples to the soil maps. The readings vary so much from year to year that it is difficult to make a correlation between the readings and the condition of the pipe. NCHRP has initiated a project that would help address this issue. The project is described in the next section.

NCHRP Project

According to NCHRP Project 21-06 (3),"Corrosion in the Soil Environment: Soil Resistivity and pH Measurements," there is a major dispute concerning the proper laboratory and field test procedures to use for soil resistivity and pH measurements to determine soil corrosivity. The two methods of measuring soil resistivity are AASHTO T 288, *Determining Minimum Laboratory Soil Resistivity* and ASTM G57, *Standard Test Method for Field Measurement of Soil Resistivity Using the Wenner Four-Electrode Method*. ASTM G57 is the method utilized by RDT, and is currently being revised by the NCHRP Project 21-06. The method will be replaced by a two-part standard. The first part will deal with measurements taken in the field with the four-pin method. The second part deals with soil box tests taken in the field and the laboratory.

The type of testing instrument is not specified for testing soil resistivity. Because different testing instruments use different frequencies, numbers of pins and pin material, this could cause different resistivity readings from the same soil. There is nothing that says one method is better than another. However, one method needs to be chosen and set as the standard. Besides testing instruments, soil compaction can also affect resistivity readings. The appropriate level of compaction needed in a soil box to represent actual field conditions is not known.

There are also two methods for testing soil pH measurements AASHTO Method T289, *Determining pH of Soil for Use in Corrosion Testing*, and ASTM G51, *Standard Test Method for Measuring pH of Soil for Use in Corrosion Testing.* Just as the soil resistivity methods differed, so do these methods. Again, there is no basis on which to select one method over the other.

This NCHRP study will provide (3):

> 1) practical test methods for laboratory and field measurements of soil resistivity and pH that yield more precise, accurate values than existing methods and 2) correlation factors between results obtained with the new methods and those from existing methods and equipment...... This information will help engineers effectively manage investment in the construction and rehabilitation of metal-containing structures and facilities that are fully or partially buried in soil.

The study will associate soil resistivity and pH with actual corrosion. Correlating corrosion to soil resistivity and pH measurements will assist in deterring the corrosion of buried metal structures. As of this date, there is a contract pending to carry out this 4-year study.

PIPE MATERIALS AND PERFORMANCE

Performance Factors

What is Corrosion?

According to NCHRP Synthesis 254 (2), "corrosion is a cause of deterioration, dissolution or destructive attack on material properties by chemical or electrochemical reaction with the environment." When a metal corrodes, it releases energy. The energy is released in the form of electrical energy. The four basic components of a corrosion cell are as follows:

Electrolyte	-	soil moisture around buried pipes, or fluid in the pipe, transferring an ionic current between the anode and the cathode.
Anode	-	an area on a metal surface (possibly the pipe itself) on which oxidation occurs, forming an insoluble compound on the metal. This component gives up electrons and thus corrodes.
Cathode	-	an area on a metal surface (possibly the pipe itself) that receives electrons and does not corrode.
Conductor	-	a metal connection (possibly the pipe itself) that allows electrical current flow and completes the circuit.

A voltage difference between the anode and the cathode causes a current to flow through an electrolyte. In culverts, the potential difference is often associated with two locations on the pipe embedded in soil with each location having different electrical properties (an anode and a cathode).

Because of uncontrollable factors affecting corrosion, a metal's potential difference cannot always be easily estimated. Some of these factors include the environment that the metal is located in, such as, temperature, the chemistry of the soil or backfill material, fertilizers, soluble salts and concentrations of oxygen.

Cinders, specifically coal cinders, will almost certainly carry acid or acid-forming compounds. Coal cinders are highly corrosive to those pipe materials vulnerable to acid attack (particularly metal pipe). Coal cinders also contain unburned carbon. Unburned carbon serves as a cathode, and may cause accelerated corrosion in metal pipes.

Corrosion is also accelerated when dissimilar metals are adjoining. The rate of this corrosion depends on the electrical resistance between the metals, the potential difference, the conductivity of the soil, the ratio of cathode to anode area and the polarization characteristics of the metals.

In much the same way that dissimilar metals can cause corrosion cells, a pipe passing through dissimilar or non-homogeneous soils can also establish corrosion cells. The half-cell potential of a metal with respect to its environment can vary with differences in the soil composition.

Corrosion Indicators

Generally, the most frequently considered indicators of corrosion susceptibility are pH, resistivity, conductivity, oxidation-reduction potential, soil characteristics, precipitation and flow velocity.

As mentioned before, a pH value of 7.0 is neutral, values of less than 7.0 are acidic and values of more than 7.0 are alkaline. Soils or waters having a pH = 5.5 or less are considered significantly acidic; those of pH = 8.5 or more are considered significantly alkaline. Both high and low pH values effect corrosion. Low pH affects metal pipe and high pH affects concrete. A change of one unit of pH represents an order of magnitude difference (a factor of 10) in relative acidity or alkalinity. For example, a solution with pH = 4 is 10 times more acid than one with pH = 5, or 100 times more acid than one with pH = 6. However, several studies have found little relationship between pH alone and rates of corrosion of aluminum or steel. One should not rely solely on pH as indicating absence or presence of corrosive soil or water.

Corrosion

Culverts can be made from many different types of pipe material. Three popular types of pipe material used in Missouri are polyethylene, corrugated steel (galvanized or aluminized), and reinforced concrete.

Polyethylene pipes are highly resistant to pH and to chemically and electrochemically induced corrosion. Unlike metals, plastics are nonconductors; and therefore, not subject to galvanic corrosion. The problem with steel pipe is that it is susceptive to corrosion and abrasion. The reasons for replacing a steel pipe are categorized as rusted, crushed, or undermined. The pipe could be replaced for a combination of these reasons. According to Missouri data, seventy-six percent of the pipes were replaced due to rusting alone. Therefore, the culvert data indicates that most of the metal pipes are replaced because of corrosion. There are many factors that affect the corrosion of steel, for instance: soil pH, water pH, soil resistivity, coal mining areas, deicing road salts, non-homogeneous backfill material, ground water, and surface water. RCP is prone to many of the same corrosion factors as steel pipe. The potential for chemical attack of concrete includes sensitivities to low pH and soluble salts in both soil and drainage water. Again, similar to steel pipe, mining areas have a substantial affect on RCP. While Missouri has reported no problems with RCP due to low pH or the presences of sulfates, there have been some RCP's replaced in locations of mining operations. Cyclic freezing and thawing also has a negative influence on RCP. The cyclic freezing and thawing of moisture that remains in, or has been absorbed by, exposed concrete may cause spalling of the surface leaving it open to further acid and/or sulfate attack.

Abrasion

Generally, polyethylene pipe is resistant to abrasion by relatively small aggregates and fine sands that are transported by water flowing at normal flow rates. The effects of continuous abrasion by larger debris, such as stones and cobbles, along with high velocity are not as clearly defined. Coupled with the potential for corrosion, the nature of the abrasive aggregate bed load determines durability and useful life of steel pipe. The bed load refers to aggregate or rock debris carried by the water flowing through the pipe. Aggregates contained in the bed load generally are much harder than the steel and typically harder than the protective coatings of zinc or aluminum. The abrasive action of a bed load of transported aggregates acts to expose the iron surface, which then oxidizes and forms a scale that is not highly resistant to further abrasion. The same abrasive action is a concern when loading and unloading the pipe for installation. MoDOT currently uses a front end loader and log chains to load and unload pipe. It is possible for the chains to scratch the steel pipe's coating in a manner similar to the bed load. Therefore, special care should be taken in the transportation, loading and unloading of coated steel pipe. One suggestion is using nylon tie-down ropes instead of log chains.

Structural Strength

The original plastic pipes used were single-walled polyethylene. There were a few problems with the strength and weight of these pipes. The High Density Polyethylene (HDPE) used now is a double-wall polyethylene pipe. Its heavier weight seems to terminate the problem of upwards floating. Steel has a high initial strength, but it becomes weak once it begins to deteriorate. Obviously concrete is the strongest material of the three main types discussed in this report. However, some reinforced concrete pipe (RCP) has failed in Missouri. These failures were due to disjointing at the end sections. Records indicate that there is a database containing 1642 reinforced concrete pipes in Missouri that were inspected in 1989 and 1990. Almost all of these pipes had an excellent structural and material durability rating.

Miscellaneous

Two major concerns with HDPE pipe are fire damage and ultra-violet (UV) degradation. Most manufacturers now add carbon black to the resin mix to resolve degradation problems. Three cases of fire damage to plastic pipe have been reported to RDT. Out of 49 states surveyed for NCHRP Synthesis 254 (2), only three other states reported cases of fire damage. These cases were due to forest or grass fires. Protecting the inlet and outlet of the pipes would guard the pipe from exposure to grass fires and UV degradation. A concern for both polyethylene and metal pipe is mower damage. Using some sort of end protection is the best solution to this problem. However, it is not always economical on the secondary routes. If mower damage has already been done to polyethylene, the damaged end can be cut off. Sometimes it is possible to create a beveled end treatment with what is left of the pipe. Mower damage to metal pipe is more serious. The abrasion to the pipe allows corrosion to begin immediately.

Service Life

Currently, RDT maintains a culvert replacement database containing over 5000 records. This database is continuously growing. As mentioned before, every time a culvert is installed (either replacements or new construction) RDT should receive a report from the district. The information from the report is added to the database. If the report is for the replacement of a culvert, then the service life of the old pipe can be determined. The service life is calculated by subtracting the installation date of the old pipe from the installation date of the new pipe. Sometimes the installation date of the old pipe is not known. This occurs when the pipe is so corroded that the date on the pipe cannot be read or the date tag is no longer attached to the pipe. Appendix B consists of a list of all the pipes in the database in which the service life is known.

High density polyethylene (HDPE) is expected to have a service life of 75 years according to its manufacturers. The Missouri Department of Transportation (MoDOT) has only used HDPE since 1983, and despite its adequate performance to date, the actual service life can not be proven yet. Galvanized steel pipes are expected to last for 50 years. However, as noted in the statistical analysis section (see Appendix C), GSP last less than 50 years in Missouri. From the data contained in the RDT culvert database, a statistical analysis of the service life of metal pipe was determined. The average life of culverts that were installed from 1910 to 1939 was about 60 years. But, culverts installed from 1940 to 1998 only have a service life of approximately 40 years. Data on reinforced concrete pipe indicates that only a few of the large number installed have actually failed. Until more concrete pipes have failed, a statistical analysis to determine service life cannot be performed. However, reinforced concrete pipe (RCP) has been used extensively in Missouri and has demonstrated a service life, to date, of at least 75 years. Based on current performance, it is expected that RCP will last well beyond the current 75 years and very possibly will last for 100 years, as originally predicted.

Coated Pipes

The Department has tested several types of coatings over the years in an attempt to find a coating that would increase the life expectancy of a corrugated steel pipe to a point where it would approach that of RCP. Coatings tested, to date, are aluminum, epoxy, bituminous, and polymer. According to the MR87-1 report, zinc (galvanized) and aluminized Type 2 (aluminum coatings) are the only coatings for steel pipe that are accepted by the department.

In the 1965 investigation, the department concluded to discontinue the use of bituminous coatings. This coating is subject to poor adhesion, abrasion, and salts. The life expectancy of bituminous coating is 0 to 7 years. Epoxy coatings are affected by direct sunlight. This type of coating was found to fail after 5 years of exposure to acidic conditions.

A study initiated in 1980 specifically evaluated and compared the performance of zinc coated (galvanized) to aluminum coated (aluminized) steel pipes. The pipes were actually installed in 1952. A report written after the pipes were in-place approximately 42 years concluded that the aluminized culverts have a longer life expectancy than galvanized culverts in similar environments. Further monitoring would determine the extent of increased life expectancy of aluminized over galvanized steel pipe.

The MR87-1 report states that only one polymer coated pipe had been installed prior to 1987. All the rivets were gone from the invert of this pipe six months after installation due to highly acidic runoff.

In 1990, three more polymer coated pipes were installed and monitored. These pipes were 10' extensions that were added to existing pipes. One of the extensions was added to a concrete pipe on Route O in St. Clair County. The location was chosen for its acidic environment. Previously, metal pipes only lasted up to six months at this location. When this pipe was investigated in 1998, there was no corrosion on the polymer end and excessive corrosion on the concrete portion. The other two extensions were added to galvanized steel pipe. The pipe installed in Monroe County on Route V is still in good condition (inlet and outlet). The placing for this pipe was chosen because of the agricultural runoff. The pH is fairly neutral. The other pipe, located in Howell County on Route K, had slight dings and scratches but has not begun to rust. The galvanized steel end of the pipe is beginning to rust. This location was selected because of the abrasive runoff. The most recent polymer coated pipe installation was in 1997 on Route B in St. Clair County. It has begun to rust after one year. The soil pH at the pipe location was 5.7 in 1998. There was not any water present, so water pH was not taken. Continued monitoring of coated pipes should be carried out in order to determine their field performance and service life.

CONCLUSIONS

Very similar to the conclusion noted in the report MR91-1, correlating field performance and service life of pipes to field testing, such as pH and soil resistivity, has also proved inconclusive in this study. Other field testing conducted in this study, as well, identified no notable trends nor provided little correlation to performance. Some of these issues should be addressed in a pending NCHRP project, "Corrosion in the Soil Environment: Soil Resistivity and pH Measurements."

Culvert data collected over the years has determined that, on average, steel pipe will last 40 years. Many factors affect corrosion of metal pipe, such as soil pH, water pH, soil resistivity, fertilizers, herbicides, coal cinders, and deicing salts. Seventy-six percent of the galvanized steel pipes in this study were replaced because the invert was rusted out.

There is not enough information in RDT's culvert database to form any statistical conclusions about the life span of plastic pipe, which is expected to last 75 years, according to its manufacturers. However, continued monitoring of plastic pipe will allow for statistical analysis in the future. MoDOT has had some problems, mostly bowing in the middle, with the original single-wall polyethylene pipe. The double-wall polyethylene (or HDPE) pipe seems to be much stronger. The advantage of the HDPE is its resistance to corrosion and abrasion. Ultra-violet degradation is an issue and is addressed by most pipe manufacturers. They now add carbon black to the resin mix to resolve degradation problems. RDT has received three reports of fire damage to plastic pipe. However, the overall risk of fire damage with polyethylene pipe is minimal. To be safe, plastic pipe should be protected at the inlet and outlet from exposure to grass and UV degradation.

The third type of pipe discussed in this report is concrete. Like steel, concrete is susceptible to corrosion and abrasion. Low pH levels, high levels of sulfates in the soil or water, and acid run-off from mining areas can be a concern with concrete. While Missouri has reported no problems with RCP due to low pH or the presences of sulfates, there have been some RCP's replaced in locations of mining operations. A total of 1,642 reinforced concrete pipes were inspected during 1989 and 1990. The majority of the pipes inspected had a high structural and material durability rating. Based on current performance to date, reinforced concrete pipe in Missouri has demonstrated a service like of at least 75 years and very well may last 100 years, as originally predicted.

While the culvert study has allowed close performance monitoring of a specified number and type of pipe materials, it appears that limited applicable information has resulted from its field testing efforts. Most of the useful information has been provided by visual examination of pipe condition and familiarity of surrounding conditions. Additional useful information, being the service life of the various pipe materials, has been determined from the information compiled in the culvert inventory database.

RECOMMENDATIONS

Tracking and monitoring the performance of the different pipe materials used throughout Missouri is felt to be a worthwhile effort. With new materials emerging in more recent years, such as polyethylene pipe materials and pipe liners, it's important that some sort of continued evaluation take place so that a determination can be made with regards to the most cost-effective culvert installation, given the location and conditions. While culvert materials have been studied for years in Missouri, some of these efforts have simply been more effective than others. Hence, it is vital that any further monitoring efforts be carried out with the intentions and design of providing effective results.

It is recommended that the culvert study continue, but that it be re-designed for improved efficiency. The following is a summary of proposed changes or additions to the current culvert study:

1) Revise the current list of pipe materials under evaluation to include a comprehensive list of materials both which have been used for years and newer materials installed in Missouri. The number of pipes representing each material should reflect a statistically valid quantity, which is also evenly distributed throughout the state as much as possible. Therefore, the study should take into account the different geographical locations and conditions in Missouri and how these influence material performance. Pipe materials recommended to be included in the study, but not limited to, are as follows:

galvanized steel	poly vinyl chloride
aluminized steel	single wall poly
aluminum clad	double wall poly
reinforced concrete	poly liner
polymer coated	poly vinyl chloride liner

2) Eliminate the following field testing: soil and water pH, 4 pin resistance, soil box resistance, soil to pipe resistance, water hardness, and pipe thickness.

3) Continue field observations of pipe materials to determine performance. Establish an evaluation system, which would allow quantifying performance with regards to pipe durability and structural aspects.

4) Continue the culvert study on an on-going basis with inspections taking place tri-annually. Reports summarizing findings or observations made during field inspections should be completed following the surveys.

5) Implement global positioning system (GPS) technology to locate the exact location of the pipes in the field. This would minimize field personnel needed and provide a more efficient means of locating pipes during field inspections.

REFERENCES

1. *4-Pin Soil Resistance Meter Instruction Manual*, Nilsson Electrical Laboratory, Inc., New York, New York (1984).

2. Gabriel, L. and E. Moran, "Service Life of Drainage Pipe," in *National Cooperative Highway Research Program Synthesis 254*, Transportation Research Board, National Research Council, Washington, D.C. (1998).

3. *Corrosion in the Soil Environment: Soil Resistivity and pH Measurements*. National Cooperative Highway Research Program. 2 Mar. 1999 <http://www2.nas.edu/trbcrp/6412.html>.

APPENDIX A

Table 2 - Itemized List of the 230 Pipes Inspected

Double Walled Polyethylene	51.00
Single Walled Polyethylene	10.00
Polyethylene Liner	30.00
Aluminized	25.00
Aluminum	5.00
Polymer Coated	4.00
Concrete Box	8.00
Poly-Vinyl Chloride	3.00
Poly-Vinyl Chloride Liner	1.00
Insituform	1.00
Fiberglass	2.00
Slotted Drain	7.00
Galvanized	1.00
Reinforced Concrete	82
Total	**230**

APPENDIX B

County	Route	Location	Type	Install date	Soil PH 94	Soil PH 95	Soil PH 96	Soil PH 98	Water PH 94	Water PH 95	Water PH 96	Water PH 98	4 Pin Resistance ohm-cm 94	4 Pin 95	4 Pin 96	4 Pin 98	Soil Box Resistance ohm-cm 94	Soil Box 95	Soil Box 96	Soil Box 98	Soilpipe Resistance ohm-cm 94	Soilpipe 95	Soilpipe 96	Soilpipe 98	Water Hardness 94	Water Hardness 95	Water Hardness 96	Water Hardness 98	Pipe Thickness inch position 12-3-6-9: 94				95				96			
Dist 1																																								
Buch	H	0.9 E RT E	DWP	08/01/89	6.9	7.6	6.8						2527.93	2183.21	1646.99	1991.70	2700	4700	4600	27007																	0.23	0.27	0.23	0.30
Davi	E	2.85 E DEKA CO LN	DWP	04/16/92	7.3	7.5	7.1	7.1					26811.40	6894.36	5362.28	4596.24	3800	4400	3200	4000																	0.22	0.25	0.24	0.26
Deka	D	1.55 N RT 6	DWP	04/14/92	7.2	6.7	6.6	6.8					14937.78	2681.14	72.77	1761.89	3050	3500		2200																	0.16	0.13		0.13
Deka	D	2.1 N RT 6	DWP	04/13/92	7.1	6.8	6.9	7.1					65113.40	6894.36	1915.10	1800.19	2200	2200	3300	1400																	0.09	0.09	0.09	0.09
Deka	D	3.75 N RT 6	DWP	04/13/92	6.6	7	7.1	6.7		7.3	6.7		41749.18	3753.60	4596.24	2259.82	3100	2900	2200	2500						306	186										0.20	0.21		0.21
Deka	E	0.05 E RT D	DWP	04/16/92	7.1	7.6	7.1	7			7.2		22981.20	1991.70	1646.99	1608.68	1500	1600	2400	3400						690											0.13	0.17	0.13	0.13
Deka	E	0.4 E RT D	DWP	04/16/92		6.7	7.2	7.1					28726.50	8809.46	4596.24	3868.50	4700	4500	2800	3300									0.49			0.47					0.20	0.31	0.28	0.28
Deka	E	0.7 W RT D	DWP	04/15/92	7.1	7	6.9	6.8	7.8	7.1			41366.16	2183.21	1493.78	1340.57	2900	2200	2400	4200					424	448			0.39	0.17			0.12	0.16	0.15	0.15	0.11	0.11		0.11
Deka	E	3.45 W RT D	DWP	04/15/92		7	7	6.9		7.2				12256.64	2566.23	4596.24		2500	2700	3300						224							0.12	0.13	0.15	0.10	0.15	0.15	0.15	0.14
Deka	E	3.55 W RT D	DWP	03/15/92		6.9	7.1	7.1						6511.34	3179.07	3830.20		4200	3050	3500													0.19	0.15	0.14	0.15	0.16	0.16	0.16	0.15
Holt	111	4.1 N RT 111 S	ALZ	10/14/93	6.7	7.4	7.1	7					2642.84	2183.21	1570.38	1761.89	3300	2100	2600	3100		1050	120	305					0.07	0.07		0.07	0.05	0.05	0.06	0.05	0.07	0.08		0.07
Holt	111	4.9 N RT 111 S	ALZ	10/07/93	6.9	7.8	7.1	7.1					2298.12	1991.70	1953.40	1378.87	3100	2700	800	3100		420	150	140					0.10	0.07		0.07	0.07	0.03	0.05	0.05	0.06	0.08		0.09
Noda	246	3.24 E RT 148	ALZ	01/01/52	6.8	7	7.3	6.9	7.3	6.9	7	6.7	29492.54	7277.38	1570.38	2336.42	7200	10	1600	1500	520	2600	245	1100		352	170	225	0.11	0.12	0.12	0.12	0.11	0.11	0.11	0.11	0.12	0.12		0.12
Dist 2																																								
Adai	6	4.8 E SULL CO	PLI	04/15/94	4.9	6.5	6.8	6.7					1187.36	1532.08	1493.78	3102.46	1800	2700	2050	1700													0.73	0.79	0.80	0.83				
Adai	6	4.9 E SULL CO	PLI	04/15/94	5.3	6.9	6.6	6.9					3523.78	2872.65	2566.23	1302.27	2300	3000	2200	1600																				
Adai	6	5.05 E SULL CO	PLI	04/19/94	5.7	7.6	7	7					1378.87	1302.27	1608.68	3830.20	2200	2500	2000	1600																				
Char	JJ	0.4 S LINN CO	DWP	06/01/92	6.5	7.3	7.2			6.9			2681.14	2068.31	3447.18	2068.31	4000	2700	5200	2700						764		764	0.20	0.22		0.21	0.18	0.17		0.21	0.20	0.17		0.17
Linn	5	1.55 S RT JJ	DWP	06/01/92	6.9	6.7	6.8	7					957.55	1072.46	1034.15	1417.17	1400	1400	1300	2800									0.38	0.36		0.36	0.11	0.14		0.13	0.14	0.16	0.14	0.14
Sali	C	7.8 E RT 41	DWP	01/01/94	7.4	6.9	7	7.2	7	7	7.1	7	1417.17	1493.78	1493.78	1646.99	3700	1850	2600	2500						300	426						0.15	0.17	0.11	0.16	0.05	0.05		0.05
Sali	EE	2.1 N I-70	CPE	05/15/97	5.7	6.6	7	7					1149.06	2681.14	1455.48	766.04	3500	2800	2100	5800													0.24	0.26	0.23	0.20	0.15	0.14	0.15	0.15
Sull	6	0.7 E RT 129	PLI	01/01/93	7.4	7.1	7.1	7			7.2		3562.09	3102.46	2336.42	1570.38	2200	1700	1900	2500													0.23	0.23	0.23	0.24	0.30	0.29		0.29
Dist 3																																								
Lewi	81	1.9 N RT 16	DWP	10/12/93	6.9	7	6.9	6.6	7		6.3		2872.65	4213.22	1953.40	1263.97	4200	4600	1900	2100					140	581							0.35	0.29	0.33	0.38	0.10	0.09		0.10
Linc	U	2.8 W RT J	DWP	05/03/94	5.6	7.2	7	7.1					1263.97	8043.42	3025.86	1187.36	7500	3300	3600	2500																	0.12	0.14	0.15	0.14
Linc	W	4.8 S RT B	DWP	06/01/95	5	4.6	7	7.2				7	1340.57	9192.48	4596.24	1149.06	3700	2850	2700	5000								70									0.17	0.16		0.18
Mari	A	0.8 N RT 168	DWP	01/01/94	5.6	7	6.6	6.8				6.7	5362.28	1646.99	5745.30	957.55	3800	5500	2600	4100								109					0.08	0.07	0.10	0.07	0.11	0.14	0.12	0.11
Mari	C	0.15 S RT 168	DWP	01/01/94	6.8	7.2	6.6	7.1					6128.32	6894.36	4213.22	574.53	3500	7100	1700	3200																				
Mari	P	3.3 N RT A	CPE	01/01/94	6.8	6.8	6.9	7.1	7.1	6.5		6.8	1378.87	2757.74	766.04	880.95	1600	3400	1800	2200						416		66					0.16	0.17	0.18	0.17	0.18	0.20		0.19
Monr	151	1.2 S RT K	DWP	11/17/92	6.6	7.1	6.8	6.8					12639.66	6511.34	2106.61	2566.23	2800	3500	2100	3500													0.17	0.16	0.15	0.15	0.17	0.16	0.19	0.16
Monr	K	1.3 W RT 151	DWP	04/03/92	7.1	7.2	6.6	6.9					107245.60	2681.14	1991.70	689.44	1500	4900	2500	4500													0.13	0.12	0.14	0.15	0.15	0.15	0.13	
Monr	K	5.6 W RT 151	DWP	04/02/92	6.7	6.8	6.4	7					12639.66	1800.19	1493.78	1761.89	2800	5600	2400	3500													0.14	0.13	0.12	0.13	0.15	0.17	0.13	0.16
Monr	V	2.45 S SHEL CO LN	DWP	04/06/92	6.8	7.3	6.2	6.9					26811.40	2757.74	15320.80	1225.66		2400	2700	1700													0.16	0.15	0.17	0.15	0.16	0.20	0.16	0.17
Monr	V	2.8 S SHEL CO LN	DWP	04/06/92	8.1	7.4	7.2	7.4					38302.00	1455.48	2719.44	1302.27	2300	4000	2600	2300													0.13	0.13	0.18	0.14	0.15	0.14	0.16	0.16
Monr	V	3.0 S SHEL CO LN	DWP	04/06/92	7.1	6.9	7.2	7.6					80434.20	2642.84	1915.10	1532.08	1600	3900	2000	1900													0.15	0.32	0.30	0.11				
Monr	V	3.2 S SHEL CO LN	PCO	10/04/90	7.2	7.1	6.8	7.3		7.1	6.6		49792.60	3370.58	2068.31	2527.93	2500	2800	1200	2100		170	155	1100		500	680						0.11	0.11	0.11	0.11				
Mont	161	3.1 S RT CC	ALU	01/01/74	6.9	7.2	6.9	7.2		7.1	6.6	6.9	24513.28	5745.30	2872.65	919.25	1500	3000	4000	4300		130		350		278	496	340					0.07	0.08	0.07	0.07	0.07	0.08	0.07	0.07
Mont	CC	0.7 E RT 161	DWP	05/24/94	7.6	7	6.7	7.4	6.7	7.1	6.7	7.7	42132.20	6894.36	3830.20	1991.70	1800	4100	1280	2600					548	326	500	222					1.83	0.18	0.19	0.18	0.15	0.16	0.15	0.15
Mont	P	0.7 S RT K	PLI	12/15/91	5.2	5.8	6.9	6.4					11490.60	6894.36	3064.16	1723.59	2200	1700	6400	7100									1.29	1.23	1.24	1.25								
Shel	151	6.0 S RT 36	DWP	04/15/92	6.9	7.2	7.3	6.8		6.8	6.6	7.3	2489.63	7277.38	2834.35	1761.89	8500	2500	4300	1600						304	500	149												
Shel	151	6.3 S RT 36	DWP	04/21/92		6.8	6.8	7			6.3		68943.60	3523.78	3370.58	2106.61	3700	4900	3300	3200																				
Warr	WW	1.05 E RT J	PLI	05/10/93		7	6.8	7.2						4596.24	2106.61	4979.26		7700	8100	4400																				
Dist 4																																								
John	13	3.3 N RT H	PLI	01/01/94	6.9	7.2	7.3	6.5					1532.08	3064.16	1493.78	1072.46	5600	6700	2900	2550																				
Lafa	FF	1.07 W RT 13	ALZ	01/01/52	6.6	6.7	6.5	6.6			7	5.5	30641.60	2144.91	2374.72	2106.61	2200	1550	3000	2700	1100	135	160	92			780	100	0.03	0.03		0.03								
Lafa	FF	1.46 W RT 13	ALZ	01/01/52		7	6.5	7				6.7		2949.25	1608.68	3293.97		4000	2500	2350		75		76			266	132									0.13	0.12		0.11
Lafa	FF	1.5 W RT 13	ALZ	01/01/52		6.8	6.5				6.6			3293.97	1915.10	0.00		2300	1300			505	350				266		0.04	0.04		0.04					0.12	0.12		0.11
Dist 5																																								
Boon	Z	2.45 N RT FF	CPE	03/01/87	4.2			6.3	6				11490.60			1417.17	1700			2200					470															
Boon	Z	3.8 S RT HH	CPE	03/01/87	5.1			6.7	5.5				21832.14			1685.29	1400			2300					520															
Boon	Z	6.0 N RT OO	CPE	03/01/87				6.7	5.4				14554.76			651.13	2000			8800					292															
Call	54	4.2 N RT J	CON	10/24/92	6.9	7				7			6511.34	6894.36		0.00	4600	2400								340														
Call	94	6.9 E RT 54	PLI	03/01/94	7.5			6.8				6.9	7277.38			17235.90	5100			2200																	0.10	0.10		0.10
Call	94	7.1 E RT 54	PLI	03/01/94	6.8			6.7					6511.34			1417.17	4200			4300																				
Call	94	7.2 E RT 54	PLI	03/01/94	6.9			6.8					6894.36			1340.57	7800			3700																				
Call	94	7.5E RT 54	PLI	03/01/94	7.2			6.5					5745.30			1991.70	6500			3800																				
Call	94	7.7 E RT 54	PLI	03/01/94	7.1			6.6					6511.34			2796.05	5600			2400																	0.09	0.08	0.08	0.09
Call	DD	2.3 S RT E S J	DWP	05/01/94	7.2	7.3		6.9				7	3064.16	5745.30		9575.50	5600	2700		3300								122									0.12	0.11	0.10	0.11
Camd	54	1.3 E RT KK	PVC	11/01/91	7.5		7	6.9			6.5		9192.48		6894.36	6894.36	7600		6700	3300							318													
Camd	54	2.6 E RT KK	PLI	11/30/93		5.5								12256.64		0.00		1500																						
Cole	50	1.2 W RT Z	DWP	09/01/93	6.6	7	7.1	7.1					8426.44	9958.52	9575.50	34854.82	5700	3600	11	5000																				
Cole	U	0.2 N RT C	ALZ	06/03/94	7.2		6.8	7					30258.58		2681.14	2030.01	43000		4000	5400			200	160													0.07	0.06	0.06	0.06
Gasc	100	2.7 W RT J	PLI	10/02/92	5.4	6.7		6.8					14554.76	13022.68		1800.19	4500	2600		7200																				
Gasc	100	3.2 E RT J	PLI	06/21/93	6	7		7		6.7			6128.32	16852.88		5362.28	5000	4000		4600																				
Gasc	28	0.2 W RT19 N J	PLI	09/02/94		7.1		6.7						26428.38		3753.60		5100		4800																				
Gasc	28	1.6 E RT19 N J	PLI	01/01/89		6.8		7	7					5745.30		1378.87		2000		4200																				
Gasc	EE	11.55 S RT 28	PLI	09/21/94	5.7	7.2	5.3	6.4			7		18001.94	18767.98	16469.86	13788.72	26000	1100	13	11000																				
Marie	N	2.9 N RT 28	PLI	08/23/89	6.9			6.8	7				6894.36			4174.92	4100			3200					520															
Marie	N	3.0 N RT 28	PLI	08/23/89	6.5			6.8					2796.05			2489.63	2900			2500																				
Mill	AA	1.2 N RT 54	DWP	06/07/94	7	6.8	6.7	6.6					8426.44	5745.30	4979.26	2681.14	3500	8000	8700	5500													0.07	0.09	0.08	0.09				
Mill	AA	2.6 N RT 54	DWP	06/02/94	7.3	6.8	6.7	6.8					14554.76	3830.20	6128.32	1800.19	9200	5400	5900	4800													1.25	1.25	1.11	1.38				
Mill	AA	3.1 N RT 54	DWP	06/13/94	6.6	6.6	6.8	6.7					14171.74	12639.66	7660.40	6511.34	10	4800	16	3200													1.90	1.64	1.74	1.79				
Osag	133	1.05 N MARI CO LN	PLI	10/20/93	6.8	6.8		6.6					31024.62	38302.00		7277.38	20000	7000		12000													7.10	6.48	3.63	9.46				
Osag	89	2.05 N RT E	PLI	05/01/94	6	6.8	6.7	6.6					1149.06	6511.34	3064.16	4596.24	17000	6100	17	7800													0.77	0.80	0.83	0.80	0.41	0.45	0.49	0.43
Osag	89	2.6 N RT E	PLI	05/01/94	6	6.6	6.4	6.7					3064.16	4596.24	3447.18	1608.68	8300	3000	5900	3100																	0.82	0.82	0.85	0.84
Osag	M	0.5 N MARI CO LN	DWP	06/20/95	6.6	7	6.4	6.6	6.7		6.6		3830.20	37152.94	3830.20	12256.64	6600	6800	25	9300							204										0.45	0.45	0.45	0.44
Osag	M	0.8 N MARI CO LN	DWP	06/09/95	6.9	7	6.6	6.8	6.5	7	6.7		1149.06	6511.34	25279.32	9575.50	8100	5500	15	17000							324										0.45	0.46	0.47	0.46

Count	Route	Location	Type	Install date	Soil PH				Water PH				4 Pin Resistance ohm-cm				Soil Box Resistance ohm-cm				Soilpipe Resistance ohm-cm				Water Hardness				Pipe Thickness inch position 12-3-6-9		
					94	95	96	98	94	95	96	98	94	95	96	98	94	95	96	98	94	95	96	98	94	95	96	98	94	95	96
Osag	N	3.4 N RT 50	PLI	06/04/93	5.9	6.8	6.7	6.8			6.9		5745.30	6511.34	7277.38	2489.63	13000	6700	12	5800							340			0.28 0.62 0.63 0.55	
Pett	127	0.6 N RT 50	CON	01/01/63	7.9	5.9		6.7		6.6			95755.00	6511.34		2489.63	23000	4200		3000						492					
Pett	W	8.4 S RT 50	CON	01/01/63	7.3	6.5		6.6	7.1	6.9		6.7	11490.60	15703.82		5745.30	64000	3100		2400					770			248			
Dist 6																															
Jeff	B	8.5 W RT 21	FGL	06/01/75		6.9		6.8						1493.78		842.64		5100		1900											
Jeff	B	8.55 W RT 21	FGL	06/01/75		6.9		7.3						919.25		689.44		4000		3200											
StCh	D	1.6 W RT DD	PLI	07/20/92	6.9	7.4		6.8		7.1		6.5	33322.74	4596.24		2604.54	6400	7700		4700					204	254		264			
StCh	P	1.6 E RT 61	PLI	08/01/88	5.7	7.3	7	7					24896.30	1876.80	1953.40	1532.08	3600	5700	12	2000										0.18 0.18 0.18 0.18	
StCh	W	4.5 N I-70	PLI	06/01/94	5.6	7	6.8	7.1					957.55	3523.78	2604.54	2757.74	5100	3600	8600	4200										0.89 0.84 0.87 0.90	
Dist 7																															
Barr	37	700' N AR LINE	CON	02/01/92	7.9	7.3		6.5		6.9				5745.30	65113.40	3830.20		9100	2200	5800						320					
Bart	C	1.0 E RT F	ALU	02/09/62	7.1	6.8	6.8	6.5			6.9		42132.20	19917.04	9575.50	4596.24	7200	4100	7800	2800		845	600	360			140		0.01 0.01 0.01		
Bart	J	0.3 S RT 126	DWP	05/09/89	6.8	6.5	7	6			7		1915.10	4596.24	3064.16	3447.18	2400	2200	7200	2300							325	325	0.01 0.01 0.01		
Bart	NN	0.5 S RT K	ALU	12/18/62	6.8	6.8	6.9	5.9		6.8	6.8		13405.70	1570.38	4596.24	1608.68	1700	2100	4800	1200		62	250	48		774	250				
Bate	H	1.5 E RT VV	DWP	02/09/95	7.2	6.5	7	6.6	7.6		7.1		6894.36	8043.42	3830.20	24513.28	2700	3600	3500	2000					296		458				
Bate	H	2.7 E RT VV	DWP	02/08/95	7	6.2	7.1	4.5	7.2		6.6		3447.18	8809.46	2298.12	1455.48	5000	1700	4800	2100					254		418				
Bate	O	5.4 S RT 52	DWP	07/08/92	7.2	6.4	7.1	5.8			7		24130.26	7660.40	5745.30	1838.50	7200	4500	8400	1800							220		0.03 0.04 0.03		
Bate	W	2.9 S RT 52	DWP	10/11/93	6.4	7	6.8	6.4			6.6		22215.16	3064.16	3830.20	2489.63	1300	3100	1600	4800							430		0.03 0.02 0.02 0.02		
Ceda	32	5.2 S RT 54	CON	06/27/90	7.7	6.6	6.8	7	7		6.9	6.5	42132.20	6511.34	3830.20	4979.26	3200	5050	9400	4700					318	280	244	356			
Jasp	A-71	0.55 S I-44	CON	08/15/94		6.8	6.9	6.1		6.7	6.9			6128.32	11490.60	6511.34		9300	19	4900						276	250				
Jasp	H	1.4 W RT Y	ALU	03/09/62	6.9	6.9	6.9	5.4			6.9		574.53	25662.34	9575.50	8426.44	6900	2800	11	2300		590	340	950							
Newt	I-44	E/B WEIGHST.	SLD	03/10/88																											
StCl	A	3.45 W RT 13	CPE	05/01/93	5.9	6.5	6.9	6.4		6.8	6.8		45962.40	2834.35	10724.56	6894.36	3900	3700	5200	2800						778	402		0.01 0.01 0.01		
StCl	A	4.1 W RT 13	CPE	05/01/93	4.7	7.1	5.8	6			6.6		76604.00	6128.32	6511.34	2144.91	2450	3250	4100	2325									0.01 0.01 0.02		
StCl	AA	5.9 N RT 54	PVL	05/11/94				6.8								2719.44				3200											
StCl	B	4.5 W RT 13	PCO					5.7								4979.26				6700				220				280			
StCl	D	2.45 S RT A	PVC					6.2								4596.24				5000								112			
StCl	O	0.7 E RT H	PCO	10/24/90	7.4	6.9	7.1	3.5	7.2	6.9	3.2	2.7	53622.80	8426.44	57453.00	6511.34	2200	3600	5800	4400		225			640	566	350	112			0.15 0.14 0.13 0.14
Vern	F	2.5 W RT 43	ALU	04/03/62	7.2	7.1	6.8	5.2			6.9		76604.00	38302.00	12256.64	21449.12	7900	5200	9400	5500		690	700	1100			222		0.01 0.01 0.01		
Dist 8																															
Chri	NN	1.05 N RT 14.	DWP	09/30/94	5.6	6.8	6	6.7					17235.90	19151.00	2527.93	16086.84	8200	2300	1500	2700										0.21 0.26 0.18 0.18	0.19 0.18 0.21 0.19
Chri	NN	2.39 S RT 14	DWP	09/30/94	7.5	6.8	6.2	6.7					4596.24	3753.60	57453.00	12639.66	780	2700	3400	3200											0.15 0.11 0.14 0.13
Chri	NN	2.5 N RT 14 ES	DWP	09/30/94	5.2	6.9	6.9	6.2					6128.32	6894.36	20683.08	24130.26	11	2400	3200	2400											0.12 0.13 0.14 0.11
Chri	NN	2.5 N RT 14 WS	DWP	09/30/94	5.2	6.7	6.5	6.7					12639.66	9958.52	2298.12	29109.52	24	2400	2100	3100											
Lacl	Z	2.3 N RT O	CPE	03/02/87	7.6	5.7	6.5	6.5		6.3	6.4	7	65113.40	5745.30	21066.10	4979.26	11	12	3600	9900						1200	1000	54		0.27 0.29 0.29 0.28	0.14 0.14 0.14 0.13
Lacl	Z	4.3 N RT O	CPE	03/02/87	6.5	5.9	6.4	6.7				5.9	72773.80	10341.54	6128.32	5362.28	10	9800	3600	3400								63		0.49 0.49 0.49 0.49	
Wrig	M	0.3 W RT 5	PLI	09/25/94	6.5	6.3	6.5	7		6.9		7	7660.40	7277.38	7277.38	9958.52	10	5300	3700	6100						1000	850	150		1.25 1.25 1.25 1.00	
Dist 9																															
Cart	60	0.1 N BL 60 E	CON	06/11/92	6		6.9	6.2			6.6		8426.44		18767.98	5745.30	6800		4400	4800						249					
Cart	60	0.45 W RT M	CON	07/09/92	6.2		6.3	6.8					12639.66		8043.42	30641.60	6500		4500	2000											
Cart	D	1.5 S REYN CO LN	ALZ	01/01/52		6.9	6.3	7						3102.46	95755.00	6511.34		7700	120	5100		518	7600	570							0.12 0.12 0.12
Cart	D	1.7 S REYN CO LN	ALZ	01/01/52		6.8	6.1			6.5				9575.50	32556.70	0.00		2800	29			100	1300								0.09 0.09 0.09 0.09
Craw	8	1.2 W RT 19	PLI	01/01/89	6	7	6.6	6.8		6.9	6.8		11490.60	17235.90	4979.26	10150.03	14	16	16	5700					500	428				0.51 0.57 0.57 0.58	0.38 0.46 0.39
Craw	8	1.7 W RT 19	PLI	01/01/89	5.9	6	6.9	6.8			6.8		23364.22	1532.08	15320.80	18767.98	71	3400	24	2300						572				0.48 0.48 0.57 0.53	0.35 0.37 0.37
Howe	K	8.8 W RT 63	PCO	04/19/90		6.9	6.2	5.3		6.4	6.6			11873.62	11873.62	6894.36		7900	23	11000		520	710	1300	216	402					0.06 0.06 0.07
Phel	63	0.11 N I-44	SLD	08/17/87																											
Phel	63	0.15 S I-44	SLD	08/17/87																											
Phel	63	N PINE ST & 63	SLD	08/17/87																											
Phel	63	0.05 N PINE ST	SLD	08/17/87																											
Phel	63	0.54 N I-44	SLD	08/17/87		6.6	6.7	7.1			6.5			8043.42	########	13022.68		3400	100	9300											
Phel	63	0.55 N I-44	SLD	08/17/87		6.8																									
Reyn	21	3.6 S RT D	PLI	05/01/89	4.8		5.3	6.4			6.6		134057.00		########	149377.80	89		21	2100						236					
Ripl	142	0.75 N RT H	DWP	06/30/92	5.9		7.1	5.4			6.7		9575.50		4213.22	1455.48	7200		12	1050						340					
Ripl	H	0.8 W RT 142	ALZ	06/01/92	5.6		6.1	5.7	6.6		6.6		7660.40		10724.56	8043.42	15		25	5200		52	425	440		338					
Texas	38	0.6 E RT M	CPE					6.7								8809.46				3700											
Dist 10																															
Butl	51	3.7 N RT 53	ALZ	07/26/94	1.8	7.3	6.1	6.7	2.5		6.9	6.5	3064.16	29875.56	23747.24	5745.30	12	5400	2500	9300	2000			460			336	141	0.01 0.01 0.01 0.01		
Butl	HH	8.9 S RT 53	DWP	04/25/94		6.9	6.9				7			42132.20	12639.66	0.00		3200	2100								320				
Madi	C	1.3 W RT 67	ALZ	01/05/94	5.5		6.2	6.6			6.4		88094.60		91924.80	29492.54	32		28	99999			1100	2000			310		0.05 0.05 0.05		
Madi	C	1.4 W RT 67	ALZ	01/06/94	4.8		6.2	7.1			6.4	6.8	8426.44		9192.48	2604.54	12		17	4600			470	335			202	146	0.05 0.05 0.02		
Madi	C	4.7 W RT 67	ALZ	02/24/94	5.4		6.2	6.4			6.5		18767.98		14554.76	6511.34	21		37	9900			300	200			480		0.06 0.05 0.05		
Madi	C	4.9 W RT 67	ALZ	01/11/94	5.3		6.3	6.6				6.9	24513.28		14171.74	4213.22	22		32	8900			680	320							
Madi	C	6.3 W RT 67	ALZ	12/08/93	4.9		6.1	6.6			6.3		21066.10		31407.64	8426.44	30		22	5300			1850	340			198				
Madi	C	6.4 W RT 67	ALZ	12/08/93	5.4		6.6	6.5					13405.70		13022.68	6511.34	20		4700	5000			770	220							
Perr	61	0.3 N RT D	PVC	06/01/89	7.3		6.8	6.6					3064.16		68943.60	2604.54	9100		1560	8500											
Ste.G	V	0.05 E RT 61	DWP	04/02/96				7								1149.06				12000											
Scot	W	0.85 E RT CC	DWP	05/06/92	2.5		6	5.7	2.7		6.6		5745.30		12639.66	8809.46	8000		14	6900					290		200				
Scot	ZZ	1.7 E RT Z	DWP	01/01/92	5.5		6.9	6.6	8.8		6.6		34471.80		18767.98	5362.28	5400		29	9000					62		190				
Stod	51	0.3 S RT K	DWP	08/01/93	1.2		6.6	6.7	1.7		6.6	6.5	18001.94		5745.30	1876.80	2800		5000	2300					244		254	206			0.10 0.10 0.10
Stod	N	2.0 S RT Y	DWP	07/02/90	6.8		6.2				7		9192.48		8426.44	0.00	10		1300								244				
Stod	TT	0.95 S RT 60	DWP	01/01/94	2.4		6.8	7	6.9		6.9	6.7	14554.76		7660.40	1149.06	3500		11	2500					186		214	218			0.10 0.09 0.10
Wayn	172	0.05 E RT 67	ALZ	03/22/94	5.3		4.5	6.8			6.5		11873.62		22981.20	8809.46	2000		8200	5600			900	260			288				
Wayn	172	2.4 E RT 67	ALZ	03/22/94	5		4.9	6.8			6.8		42898.24		42132.20	32173.68	3200		25	15000			1600	1300			428				
Wayn	172	3.2 E RT 67	ALZ	03/28/94	5.3		4.4	4.4			6.7		31024.62		42132.20	20300.06	49		35	21000			1600	910			318				
Wayn	172	6.2 E RT 67	ALZ	03/28/94	5.5		6.7	6.5			6.7		42898.24		57453.00	23364.22	39		42	35000	6300		1600	1200			174				
Wayn	C	2.0 S RT 34	ALZ	04/01/93	2.3		5.5	6.4	8.2		6.5	6.8	137887.20		84264.40	11490.60	12		120	10000	4600		5100	2700	484		258	168	0.00 0.00 0.00 0.00		
Wayn	D	14.45 E RT 67	ALZ	10/01/93	3.5		5.8	7	8.4		6.3		91924.80		11873.62	4979.26	2700		11	5200			280	140	480		350		0.00 0.00 0.00 0.00		
Wayn	D	14.6 E RT 67	ALZ	10/01/93	1.2		6.4	6.8	3.1		6.6	6.7	118736.20		23364.22	12639.66	4400		13	7800	4400		490	690	326		290	45	0.00 0.00 0.00 0.00		
Wayn	D	14.65 E RT 67	ALZ	10/01/93	2.9		6.2	6.8	2.6		6.7	6.4	99585.20		8809.46	8809.46	4700		7200	9500	1300		2500	170	362		258	94	0.00 0.00 0.00 0.00		

APPENDIX C

STATISTICAL ANALYSIS

The life span of galvanized steel pipe (GSP) was found to follow a normal distribution. The data was separated by age and how many were replaced at that particular age. Then each age was divided by the total number of GSP replaced thus giving a probability of a pipe being replaced at that age. The mean and standard deviation were found using this binomial approximation, and this was used to find the normal approximation. This may be useful in the future for quality control, approximating when specific culverts need to be replaced, the reliability of a specific culvert at a certain age, and other analysis of general or specific culverts.

The charts on the following pages show graphically how the separate distributions fit the data from their particular time period and how the time periods relate to each other. The purpose of the diagnostic plot analysis is to test the validity of the approximations. This is accomplished by plotting the residuals (the actual value minus the expected value) to check for any distinct patterns (see figures 3 and 4). Since there exist no contradicting evidence we will assume the data fits the normal approximation. The analysis will focus on the approximation for the time period from 1940 to the present because most of the culverts in place and those being installed will fall into this category.

It was assumed that GSP would last 50 years. Given our data, there is strong evidence to show that GSP does not last 50 years.

The probability that the life span of a GSP is 50 years or more is **0.4%**.

A 90% Confidence Interval that the life span is **[32.49,46.29]** years which does not contain 50 years.

If a culvert does last 50 years, the probability it will fail at 50 years is **72.5%**

A better assumption is that GSP will last 40 years. 40 does fall within the above noted 90% Confidence Interval.

If a culvert lasts 40 years, the probability it will fail at 40 years is only **22.8%.**

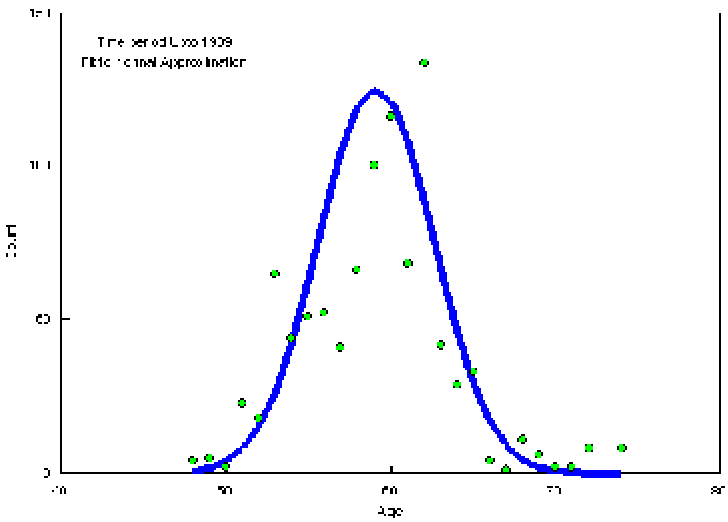

Figure 1 - Useful Life of GSP from 1900 – 1939

Figure 1 shows the normal distribution curve for GSP replaced from 1900 to 1939. The curve indicates that the average life is approximately 60 years.

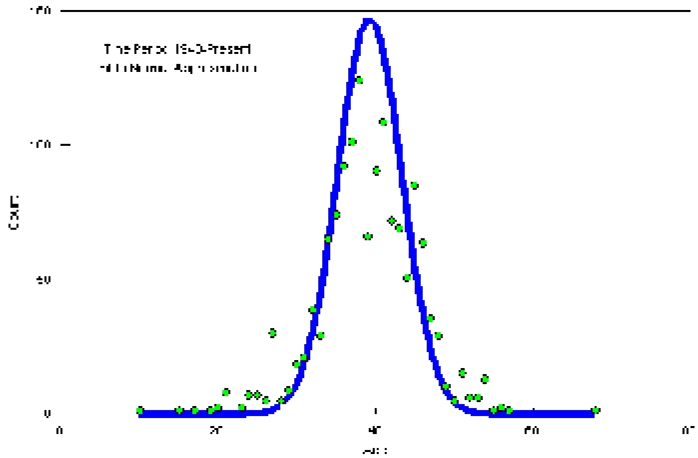

Figure 2 - Useful Life for GSP from 1940 - 1998

Figure 2 covers the time period of 1940 to the present. The useful life for this time interval is about 40 years.

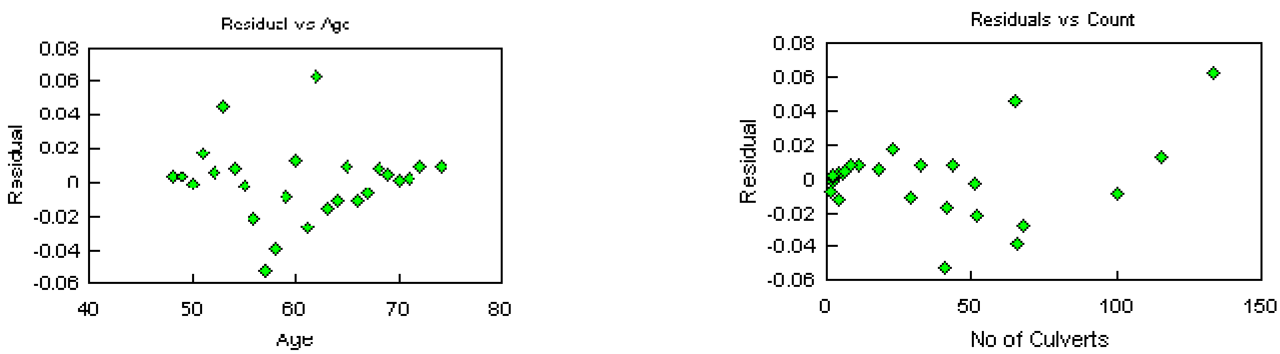

Figure 3: Time period: Up to 1939

Summary: There is no evidence the data does not fit the normal approximation because no patterns are evident in the residual plots for this time period.

Conclusion: The life span of culverts during this time period is distributed normally with: Mean life time = **59.10** years

Standard deviation = **3.450** years

Figure 4: Time period: 1940 - Present

Summary: There is no evidence the data does not fit the normal approximation because no patterns are evident in the residual plots for this time period.

Conclusion: The life span of culverts during this time period is distributed normally with: Mean life time = **39.19** years

Standard deviation = **4.075** years

Equality of means: Does the mean for pipes made before 1940 equal those made after?

No. Hypothesis testing showed approximately zero probability that they are equal.