BURIED facts

CULVERT DURABILITY STUDY

REVIEW AND IMPLEMENTATION

INTRODUCTION

The Ohio Department of Transportation (ODOT) has published a 173 page report on the corrosion and abrasion resistance of various types of pipe and pipe protection used for culverts in the State of Ohio. The "Ohio Culvert Durability Study" is a compilation of a ten year investigation of 1616 corrugated steel, structural steel plate and concrete pipe culverts in all 88 Ohio counties and 21 asbestos bonded bituminous coated and paved corrugated steel pipe (CSP) culverts in the States of Kentucky and Indiana. Also included in the report is a qualitative evaluation of thermoplastic coated CSP based on investigation of 53 culverts protected with this type of coating. This article reviews the Ohio report and presents a procedure for evaluating service life and life cycle cost analysis to enable consideration of pipe durability as a design criterion.

DURABILITY SURVEYS

The Federal Highway Administration (FHWA) recognized that the service life of corrugated metal pipe may be seriously affected by corrosion and/or abrasion and that the trend of designing the minimum thickness (gage) of corrugated metal pipe based solely on structural considerations could adversely affect both structural and durability performance. As a result, FHWA by circular memorandum, dated June 10, 1970, requested state departments of transportation to conduct statewide surveys to determine appropriate protection and minimum thickness of metal. Several state and federal specifying agencies conducted culvert condition surveys and established that CSP and all of the currently available protective coatings have durability problems but the survey reports did not develop appropriate design procedures to account for all of the various environmental factors affecting CSP culvert deterioration. Therefore, ODOT decided it was necessary to evaluate the various environmental factors that occur in the state and to determine their effect on culverts installed in Ohio. A preliminary study was made in the fall of 1971 to determine the feasibility and scope of an in-depth study into culvert durability. An in-house report describing the preliminary study was made in January 1972, and authority was subsequently obtained to undertake a comprehensive study. The study was coordinated through the ODOT Hydraulics Section in cooperation with the Bureau of Location and Design, Bureau of Bridges, Bureau of Data Control, District Offices and the Ohio Department of Natural Resources.

The purposes of the study were to investigate the significance and interrelations of the various soil and water parameters affecting culvert corrosion, evaluate the incremental effects of each parameter in the corrosion process, and relate observed corrosion to the geologic environment. Practical field methods for detecting corrosive environments and procedures for determining the type of culvert material and protection to be used at a proposed site were also established. In addition, the structural and hydraulic behavior of culverts were investigated, with the findings being incorporated into ODOT's culvert design procedures. Finally, to improve culvert performance and longevity, the report recommends changes in design and maintenance procedures, more restrictive specifications, increased galvanizing thickness and modifications to AASHTO and ODOT specifications for corrugated steel pipe.

SERVICE LIFE

According to the FHWA Technical Advisory T5040.2 on "Corrugated Metal Pipe Durability Guidelines," dated March 21, 1978:

> "In order to specify and take bids on alternate materials, the designer must make a determination that two or more products or materials are equal in their ability to perform their intended function for the design life of the product."

When two pipe materials of different performance capabilities are being considered, an overall economic comparison of relative costs requires establishing a service life. The National Cooperative Highway Research Program Synthesis of Highway Practice "Durability of Drainage Pipe" presents the following as a guide:

> "One way of defining the service life of a culvert is by the number of years of relatively maintenance-free performance. Although a culvert may have reached its service life, there may be many more years until failure. However, the level of maintenance required after reaching service life may be such that replacement is justified, well before failure occurs."

Based on this guide recommendation, a maintenance-free service life of 50 to 100 years should be expected of any permanent hydraulic structure, depending on the particular facility. A minimum of 50 years of relatively maintenance-free performance should be expected of culverts on secondary road facilities with up to 100 years for high type facilities such as primary and interstate highways and all sewer applications.

The Ohio Culvert Durability Study evaluates the durability of both concrete pipe and corrugated steel pipe under the same conditions and develops predictive equations and graphs for culvert service life. Many times designers only consider first costs and first costs are important; however, lower first cost does not necessarily mean the most economical product when service lives of alternate pipe materials are considered through a life cycle cost analysis. By utilizing the predictive performance graphs included in the report to establish appropriate service lives, the principles of engineering economics can be applied so the owner is assured of purchasing the most economical and cost effective pipe material.

The predictive performance graphs and applicable equations are reproduced from the report for:

- *Figure 1. Bituminous Coated CSP.*
- *Figure 2. Bituminous Coated and Paved CSP.*
- *Figure 3. Corrugated Steel Pipe Metal Loss.*
- *Figure 4. Structural Steel Plate Metal Loss.*
- *Figure 5. Percent of Abrasion.*
- *Figure 6. Concrete Pipe Culvert Life.*

FIELD INSPECTION

To enable a statistically representative inspection of both concrete pipe culverts and CSP culverts, a computer program was developed to establish a random sampling technique based on total inventory per county and state and age groups. This selection method was then supplemented by inspection of specific culverts over a three year period for collection of additional information. The statewide breakdown is listed in *Table I.*

The field inspection phase of the study involved several functions and data collection, including a visual rating system which proved to be a generally accurate and acceptable method of evaluating the condition of the pipe material and/or protective coating. Five rating classifications were established with each classification further defined as explained in *Table II.*

BITUMINOUS COATED CORRUGATED STEEL PIPE

Figure 1 presents the percentage of bituminous coating not in poor condition on the vertical scale and age in years on the horizontal scale. The predictive graph is based on the investigation of 121 culverts with bituminous coating in which 93.4% did not perform satisfactorily with the majority rated as being in *poor* condition.

Rating	No.	Percent	
Poor	96	79.3	93.4% (Poor, Fair, Good)
Fair	10	8.3	
Good	7	5.8	
Very Good	7	5.8	
Excellent	1	0.8	
	121	100.0	

As indicated by the predictive graph, the additional service life of CSP provided by bituminous coatings is negligible and as stated in the Conclusions and Recommendations of the report, "Therefore, bituminous coating, without invert paving, appears to be of little value . . . this type of protection should be discontinued."

Table I. State Culvert Inventory.

Type	Inventory	Inspected	Percent Inspected
Concrete	4170	545 (519)	13
Corrugated Steel	2193	685 (613)	31
Sectional Plate	1600	386 (379)	24
Total	7963	1616 (1511)	20

Number in parenthesis indicate number of culverts inspected on a random selection basis.

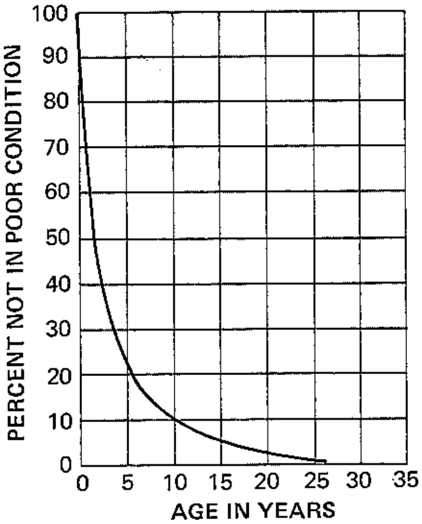


Figure 1. Percentage of Bituminous Coated Culverts With Protection Not Rated Poor.

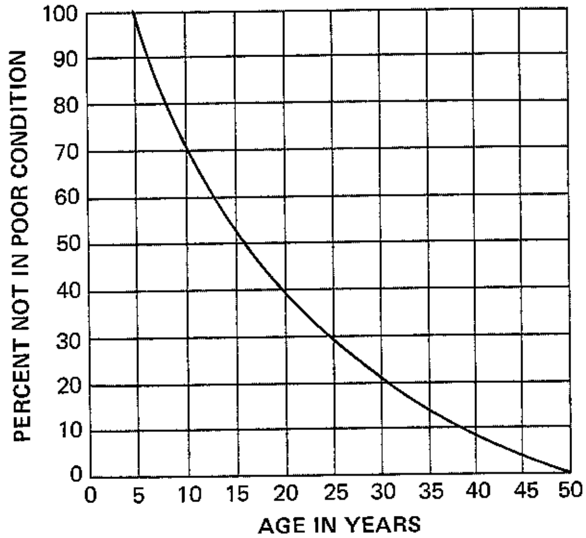


Figure 2. Percentage of Bituminous Coated and Paved Culverts With Protection Not Rated Poor.

Table II. Visual Rating Classification.

	Corrugated Steel Pipe Protection	Corrugated Steel Pipe	Concrete Pipe
EXCELLENT	Condition as constructed. Slight exterior checking permitted.	Condition as constructed. No apparent loss of galvanizing.	Condition of concrete as constructed.
VERY GOOD	Exterior protection checking or loss. Slight erosion of paving and/or interior checking. No significant loss of interior protection. (95% area intact)	Discoloration but no scaling or corrosion.	Discoloration but no loss, corrosion, or softening.
GOOD	Interior protection could be checked throughout. Slight loss of interior protection. Erosion of paving to top of corrugations but no exposed corrugations. Manufacture control problems.	Slight to moderate scale and/or rust. Pitting just started. Isolated spots of moderate corrosion permitted.	Slight loss of mortar leaving aggregate exposed.
FAIR	Paving or coating gone for strip 25% of length. Areas of coating and or paving gone. (approximately 10%)	Moderate to heavy scale and or rust.	Moderate loss of mortar and aggregate. Slight softening of concrete.
POOR	Paving or coating gone for strip 50% of length. Large areas of coating and or paving gone. (approximately 25%)	Penetration with geologist's hammer. Perforation. Loss of invert.	Significant loss of mortar and aggregate. Concrete in softened condition.

BITUMINOUS COATED AND PAVED CORRUGATED STEEL PIPE

Figure 2 presents the percentage of bituminous coating and paving not in poor condition on the vertical scale and age in years on the horizontal scale. The predictive graph is based on the investigation of 267 culverts with bituminous coating and paving in which 71.2% did not perform satisfactorily with the majority rated as being in *poor* condition.

Rating	No.	Percent	
Poor	105	39.4	71.2%
Fair	30	11.2	
Good	55	20.6	
Very Good	73	27.3	
Excellent	4	1.5	
	267	100.0	

The average age of the bituminous coated and paved protective coatings for CSP which were rated in the *very good* and *excellent* categories was less than 10 years.

Based on the predictive graph, the following percentage of installations with protective paving will be in poor condition at the given number of years.

Age	% Poor
5	0
10	30
15	48
20	68
25	72

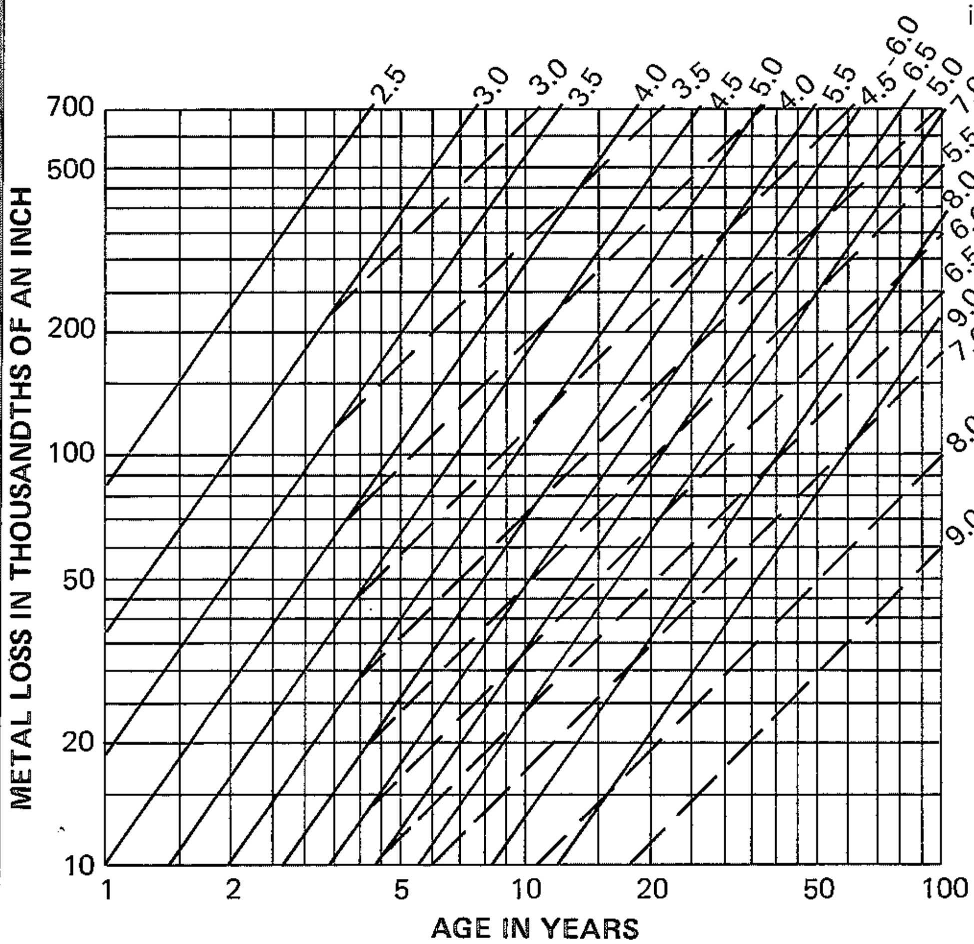
Age	% Poor
30	80
35	87
40	92
45	97
50	100

Based on a risk factor as to how many bituminous coated and paved failures can be tolerated, a five year minimum to a 10 year maximum service life can be assigned to this type of protection. A minimum protection of bituminous coating and paving should be required for all CSP culverts. However, because of the high probability of this type of protection failing before the desired coating and paving service life is reached, the bituminous coating and paving should only be considered as a limited durability safety factor. In fact, at 10 years, 30% of all bituminous coatings and pavings can be expected to have failed before this age. At the average age of 18.71 years for all bituminous coated and paved culverts surveyed, 58.2% were found to be in poor condition. Since a large percentage of bituminous coated and paved protective coatings for CSP can be expected to be in a deteriorated condition within a 5 to 10 year period hydraulic design should be based on uncoated pipe.

Corrugated Steel Culvert, Bituminous Coating and Paving Rated Very Good.

THERMOPLASTIC COATED CORRUGATED STEEL PIPE

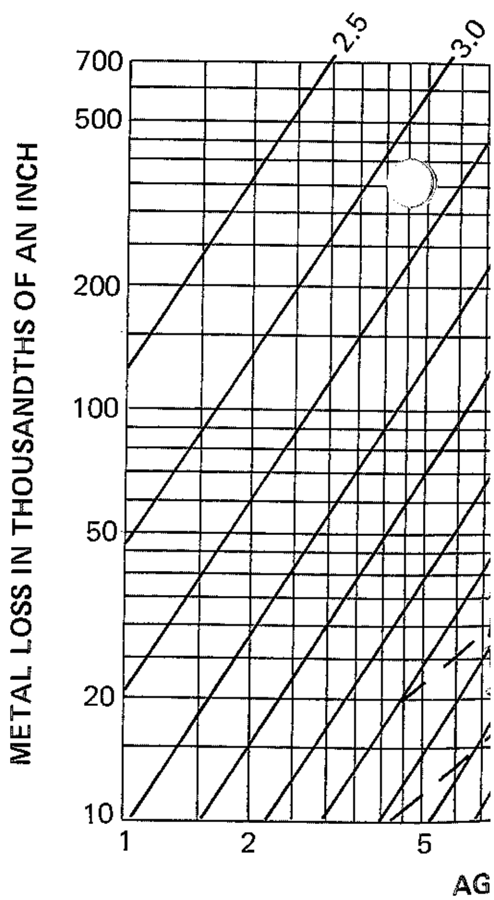
A total of 53 thermoplastic coated CSP culverts were inspected one or more times. Although an in-depth analysis was not included in the report, several problems unique to these types of protective coatings were reported. These included delamination, pocking, suscepibility to peeling and poor resistance to abrasive flow. These problems are substantiated by investigations by other major specifying agencies. The report concluded, "The use of thermoplastic coatings is not recommended for sites with abrasive flow unless a bituminous paved invert with adherence properties similar to asbestos bonding can be provided."



—— CMP WITH ABRASION $ML = 5040\ (AGE)^{1.4569}\ (pH)^{-4.4691}$

– – CMP WITHOUT ABRASION $ML = 7210\ (AGE)^{1.0164}\ (pH)^{-4.3076}$

Figure 3. Predicted Metal Loss for Corrugated Metal Pipe (CMP) Culverts.



—— SPP WITH ABRASION ML

– – SPP WITHOUT ABRASION ML

Figure 4. Predicted Me
Plate Pipe (S

CORRUGATED STEEL PIPE METAL LOSS

Figures 3 and *4* present metal loss in thousandths of an inch on the vertical scale and age in years on the horizontal scale. The solid diagonal lines represent pH of the water for use when there is a potential for abrasive flow and the dashed diagonal lines represent pH of the water for use when there is no potential for abrasive flow.

The predictive metal loss graphs are based on laboratory metal loss analysis of coupons obtained from 38% of the CSP culverts and 20% of the structural steel plate culverts which were included in the investigation and had exposed metal. Culverts with the inverts completely corroded away were not included in the analysis unless the time of failure could be estimated. Of the 613 CSP culverts, with and without protective coatings, which were included in the random sampling investigation, over 53% were observed to have experienced corrosion anywhere from pitting to complete loss of invert. For the plain galvanized CSP, this corrosion percentage increased to 76% with one third rated as being in *poor* condition.

Rating	No.	Percent	
Poor	80	33.1	76%
Fair	41	16.9	
Good	63	26.0	
Very Good	46	19.0	
Excellent	12	5.0	
	242	100.0	

For any given metal thickness and pH value of the water, the number of years for the pipe invert to be completely corroded away can be readily determined by projecting a horizontal line from the given metal thickness on the vertical scale to the diagonal line representing pH and then projecting a vertical line down to the age in years on the horizontal scale. *Tables III* and *IV* were prepared from *Figure 3* and present years to complete metal loss for available corrugated steel pipe gage thicknesses and various pH levels. The tables illustrate that plain galvanized CSP has very limited service life over the full range of environmental conditions. When potential for abrasion is present, plain galvanized CSP should not be used and for the limited installations where potential for abrasion does not exist, plain galvanized CSP should only be considered under neutral environments with the heavier gage thicknesses.

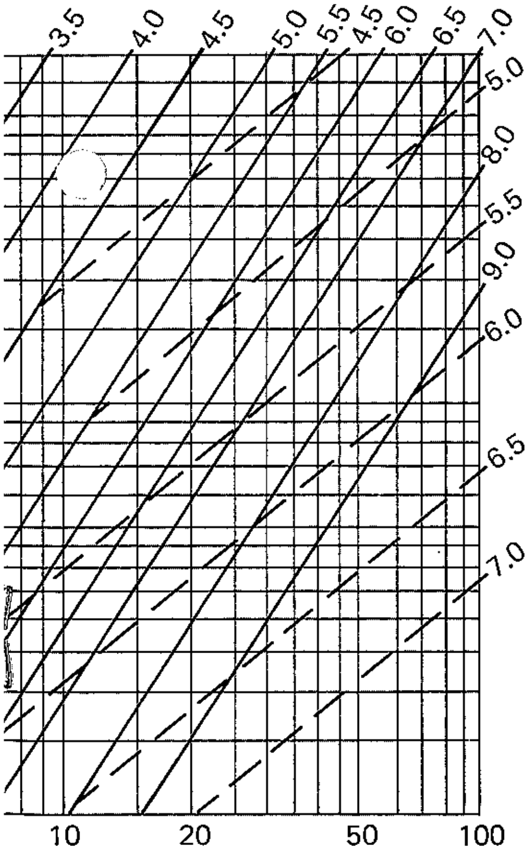
Appropriate guidelines for the determination of whether or not abrasion was a factor contributing to the condition of the culvert were not established for the field investigation phase. However, the presence of abrasive material in the culvert at the time of the investigation was noted and the percentage of culverts with abrasive material present is presented in *Figure 5*. Of the culverts inspected, only four counties included culverts which did not have any abrasive material present at the time of the inspection. These

Table III. Years to Complete Metal Loss With Abrasion.

Gage Thickness Ins.	pH 3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
16(0.064)	1.5	2.3	3.5	5.0	7.0	9.3	12	16	20	24	29
14(0.079)	1.7	2.7	4.1	5.8	8.0	11	14	18	23	28	34
12(0.109)	2.1	3.4	5.1	7.3	10	13	18	22	28	35	42
10(0.138)	2.5	3.9	5.9	8.6	12	16	21	26	33	41	50
8(0.168)	2.8	4.5	6.8	9.8	13	18	24	30	38	47	57
7(0.188)	3.0	4.9	7.4	11	15	20	26	33	41	56	62
5(0.218)	3.4	5.4	8.1	12	16	22	28	36	45	56	68
3(0.249)	3.7	5.9	8.9	13	18	24	31	40	50	61	75
1(0.280)	4.0	6.4	9.7	14	19	26	34	43	54	66	81

Table IV. Years to Complete Metal Loss Without Abrasion.

Gage Thickness Ins.	pH 3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
16(0.064)	1.5	2.3	3.5	5.6	8.8	13	19	27	37	49	64
14(0.079)	1.7	2.7	4.2	6.9	11	16	23	33	45	60	79
12(0.109)	2.1	3.4	5.8	9.5	15	22	32	45	62	83	100+
10(0.138)	2.5	4.1	7.3	12	19	28	41	57	78	100+	100+
8(0.168)	2.8	5.0	8.8	15	23	34	49	69	94	100+	100+
7(0.188)	3.0	5.6	9.8	16	25	38	55	77	100+	100+	100+
5(0.218)	3.4	6.5	11	19	29	44	64	89	100+	100+	100+
3(0.249)	3.8	7.4	13	21	33	50	72	100+	100+	100+	100+
1(0.280)	4.3	8.3	15	24	38	56	81	100+	100+	100+	100+



GE IN YEARS

. = 18300 $(AGE)^{1.6042}$ $(pH)^{-5.4446}$

. = 4,995,000 $(AGE)^{0.8427}$ $(pH)^{-8.0583}$

etal Loss for Structural
SPP) Culverts.

four counties are located in an area characterized by extreme flatness and fine soils such that hydraulic design factors are the prime consideration. Analysis of the corrosion rate from the rating classification data and the measured metal loss data indicates that the predictive equations and graphs for "abrasion" more accurately predict the durability performance of CSP actually observed and substantiated by the laboratory metal loss measurements.

CONCRETE PIPE CULVERT LIFE

Figure 6 presents years to poor on the vertical scale and "pH" of the water on the horizontal scale. The diagonal lines represent the culvert slope in percent. The predictive graph for concrete pipe culvert life is based on the investigation of 519 concrete pipe culverts in which only 1.7% of the culverts were rated in poor condition.

Rating	No.	Percent
Poor	9	1.7
Fair	33	6.3
Good	115	22.2
Very Good	302	58.2
Excellent	60	11.6
	519	100.0

Because of the extremely long service life of concrete pipe, it was necessary to develop the predictive equation and graph from data obtained from only those concrete pipe culverts subjected to acid flow and these culverts were primarily located in the acid coal mine drainage areas of the Eastern and Southeastern part of the state.

The results of the investigation and the predictive graph illustrates the excellent performance of concrete pipe with a service life expectancy in excess of 300 years for water pH levels of 7.0. For all water pH levels of 4.0 and above, a service life in excess of 100 years can be expected from concrete pipe without any need for protective coatings.

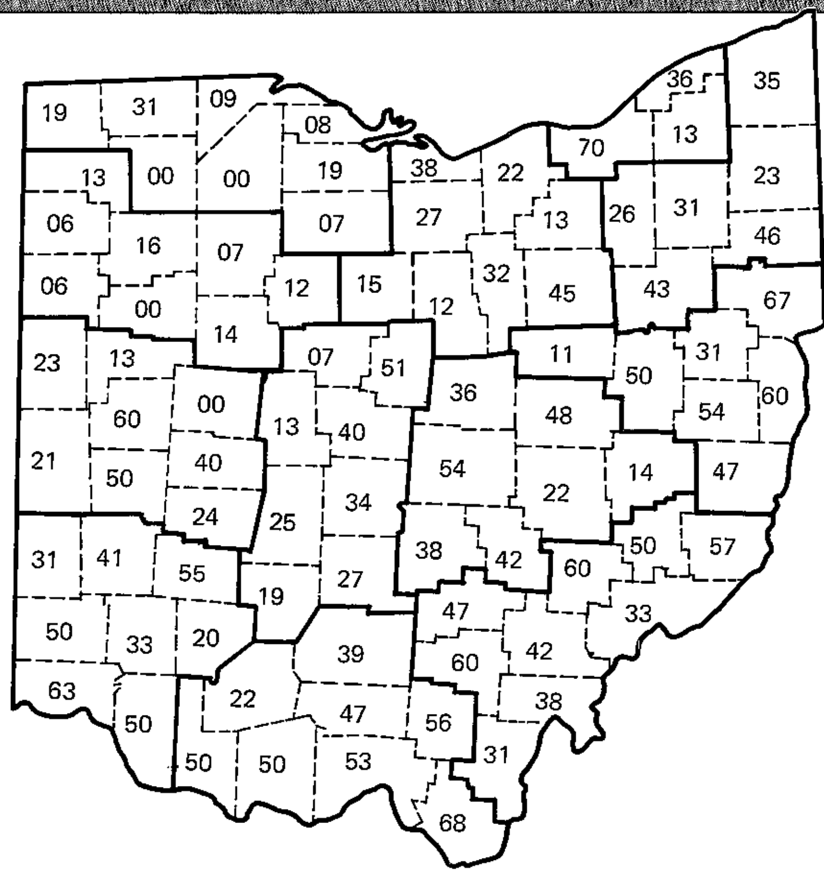


Figure 5. Percent of Culverts With Abrasive Material Present by County.

RATING SUMMARY

Table V presents the rating summary by age groups for concrete pipe, corrugated steel pipe and structural steel plate pipe. As indicated by the percentage figures in each five year age grouping, the percentage of CSP in the *excellent* category is relatively high for culverts less than 10 years old and then rapidly approaches zero at about 20 years. On the other hand, the percentage of CSP culverts in the *fair* and *poor* categories is relatively low for culverts less than 10 years old, and then rapidly approaches 40% at about 20 to 25 years. The rating summary by age groups for concrete substantiates the outstanding performance of concrete pipe. Only 1.7% were rated in *poor* condition with the majority of the culverts rated in the *excellent* and *very good* categories, the direct opposite of CSP rating results.

$$\text{YEARS TO POOR} = \frac{(0.349\,(\text{pH})^{1.204})^{7.758}}{(\text{Slope})^{0.824}}$$

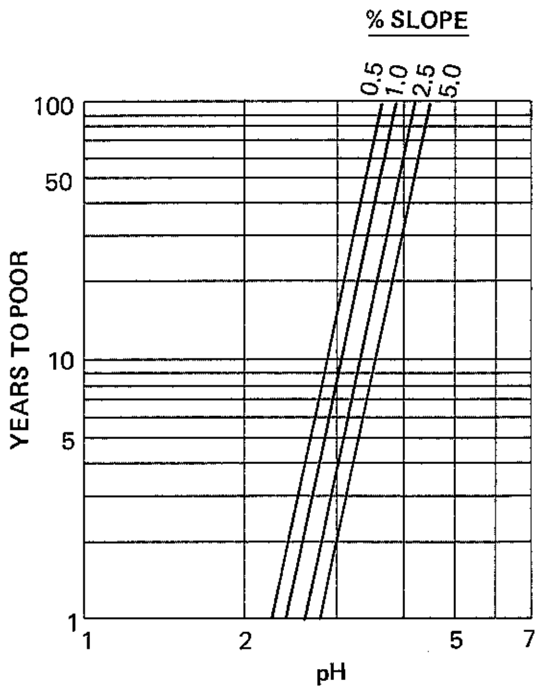


Figure 6. Concrete Pipe Culvert Life.

Table V. Rating Summary by Age Groups.

CONCRETE PIPE

	YEAR BUILT	AFTER 1965	1960-64	1955-59	1950-54	1945-49	1940-44	1935-39	BEFORE 1935	ALL AGES
	NUMBER	102	82	96	57	73	37	37	35	519
	PERCENT	19.6	15.7	18.4	10.9	14.0	7.1	7.1	6.7	100.0
RATING	EXCELLENT	25.5	14.6	10.4	7.0	6.8	5.4	0.0	2.9	11.6
RATING	VERY GOOD	61.8	73.2	70.8	57.9	46.6	56.8	29.7	34.3	58.2
RATING	GOOD	8.8	8.5	15.6	31.6	34.2	27.0	43.2	42.9	22.2
RATING	FAIR	2.9	2.4	3.1	3.5	12.3	5.4	16.2	17.1	6.4
RATING	POOR	1.0	1.2	0.0	0.0	0.0	5.4	10.8	2.9	1.7

CORRUGATED METAL PIPE

	YEAR BUILT	AFTER 1965	1960-64	1955-59	1950-54	1945-49	1940-44	1935-39	BEFORE 1935	ALL AGES
	NUMBER	73	152	136	58	65	56	31	42	613
RATING	EXCELLENT	41.1	25.7	18.4	1.7	3.1	0.0	0.0	0.0	15.8
RATING	VERY GOOD	53.4	42.1	27.2	29.3	29.2	12.5	12.9	7.1	31.0
RATING	GOOD	4.1	27.0	33.8	25.9	27.7	17.9	9.7	35.7	24.6
RATING	FAIR	1.4	5.3	14.7	20.7	20.0	23.2	22.6	7.1	12.6
RATING	POOR	0.0	0.0	5.9	22.4	20.0	46.4	54.8	50.0	16.0

SECTIONAL PLATE PIPE

	YEAR BUILT	AFTER 1965	1960-64	1955-59	1950-54	1945-49	1940-44	1935-39	BEFORE 1935	ALL AGES
	NUMBER	73	83	131	36	25	13	10	8	379
	PERCENT	19.2	21.8	34.5	9.4	6.5	3.4	2.6	2.1	100.0
RATING	EXCELLENT	21.9	12.0	3.8	0.0	4.0	0.0	0.0	0.0	8.4
RATING	VERY GOOD	47.9	62.7	46.6	38.9	28.0	30.8	20.0	37.5	47.0
RATING	GOOD	30.1	22.9	37.4	47.2	44.0	46.2	30.0	37.5	34.3
RATING	FAIR	0.0	1.2	10.7	13.9	12.0	23.1	50.0	12.5	8.4
RATING	POOR	0.0	1.2	1.5	0.0	12.0	0.0	0.0	12.5	1.8

LIFE CYCLE COST ANALYSIS

Life cycle cost analysis is based on the principles of engineering economics, and the most important parameters are: service life, bid price, interest rate, and inflation rate.

Any decision to be made between alternative pipe materials with different service lives involves different money receipts and disbursements at different times and, therefore, an economic comparison of relative costs must take these differences into account. There are several methods of analysis which could be used, including present worth, annual equivalent cost and rate of return on extra investment. An approach which enables evaluation at the design stage, is to determine how much lower the bid price of CSP must be than the bid price of concrete pipe based on differences between interest and inflation rates over the study period.* This can be determined by equating the present worth of CSP to the present worth of concrete pipe. The present worth of the shorter lived CSP would be the bid price (P_S). The present worth of the longer lived concrete pipe would be the bid price (P_C) minus a salvage life factor, times an interest factor, times an inflation factor. The general expression is:

Salvage Life Factor — Interest Factor — Inflation Factor

$$P_s = P_c - P_c \times \left[\frac{n_c - n_s}{n_c}\right] \times \left[\frac{1.0}{(1.0+i)^{n_s}}\right] \times \left[(1.0+I)^{n_s}\right]$$

or

$$\frac{P_s}{P_c} = 1.0 - \left[\frac{n_c - n_s}{n_c}\right] \times \left[\frac{1.0}{(1.0+i)^{n_s}}\right] \times \left[(1.0+I)^{n_s}\right]$$

where: P_s = bid price of CSP
P_c = bid price of concrete pipe
n_c = service life of concrete pipe
n_s = service life of CSP
i = interest rate (8.25% recommended by U.S. Government)
I = Inflation rate

*If installation costs are not included in the bid prices, then an additional analysis must be made to account for the differences in initial installation costs between concrete pipe and CSP and replacement costs of CSP at the end of its service life.

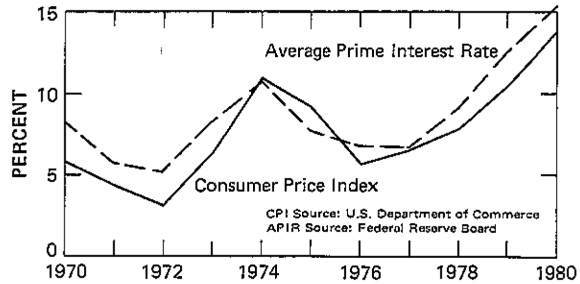
Following is a summary of the bid price ratios between CSP and concrete pipe to produce equal present worth values for differences in interest and inflation rates varying from 1% through 5% and service lives as indicated. The interest rate was assumed to be 8.25% as recommended by the U.S. Government.

i-I	n_c=100 n_s=10	n_c=100 n_s=20	n_c=100 n_s=30	n_c=100 n_s=40	n_c=100 n_s=50
1	0.18	0.34	0.47	0.59	0.69
2	0.25	0.45	0.60	0.72	0.80
3	0.32	0.54	0.70	0.80	0.88
4	0.38	0.62	0.77	0.87	0.92
5	0.43	0.69	0.83	0.91	0.95

By taking this approach, the absolute interest and inflation rates over a considerable period of time do not have to be assumed, but rather, the difference between the two rates can be selected and then the bid price ratio readily selected. The base interest rate used in the analysis will not significantly affect the results.

Generally, interest rates will be a few percentage points higher than the inflation rates and a comparison of the two rates since 1970 is presented below.

Comparison of Interest and Inflation Rates



The following examples illustrate use of the predictive graphs to determine service life and application of life cycle cost analysis.

EXAMPLES

Example 1

Given: A 16 gage (0.064") corrugated steel pipe and a reinforced concrete pipe are to be installed in a neutral environment with a water pH of 7.0 and a potential for abrasion.

Find: The predictive service life of both pipe materials and the bid price differential for an interest rate of 8.25% and an average difference between interest and inflation rates of 2% over the study period.

Solution: From *Figure 3* at 64 thousandth of an inch on the vertical scale for a 16 gage metal thickness, project a horizontal line to the solid diagonal line representing a pH of 7.0 with abrasion and then down to the horizontal scale and read 20 years. Total metal loss can be expected in 20 years and, if a durability factor of safety is not applied, the maximum service life of the CSP would be 20 years.

From *Figure 6* at a pH value of 7.0 on the horizontal scale project a vertical line to any of the diagonal slope lines and by extrapolation, the years to poor for concrete pipe would be in excess of 300 years. Use a conservative service life of 100 years with the understanding a substantial durability factor of safety will be incorporated into the design.

For n_c=100 years n_s=20 years, i=8.25%, I=6.25%

$$\frac{P_s}{P_c}=1.0-\left[\frac{100-20}{100}\right]\times\left[\frac{1.0}{(1.0+0.0825)^{20}}\right]\times\left[(1.0+0.0625)^{20}\right]=0.45$$

Answer: The bid price of a 16 gage CSP with a 20 year service life must be 55% lower than the bid price of concrete pipe with a 100 year service life.

Example 2

Given: The same as *Example 1* except that a 20 year service life for CSP is considered to be inadequate and, therefore, the service life is to be increased to at least 50 years by increasing the steel gage thickness and adding bituminous coating and paving.

Find: The required steel gage thickness and bid price differential.

Solution: From *Figure 2*, projecting a vertical line from an age of 10 years on the horizontal scale to the curve and then projecting horizontally to the vertical scale, read 70% not in poor condition. This means that under normal conditions, 30% of bituminous coatings and pavings can be expected to be in poor condition at 10 years. Although a 30% failure rate is relatively high, a 10 year service life will be assumed for the protective coating and paving, requiring a metal thickness to give a 40 year service life.

From *Figure 3*, projecting a vertical line from an age of 40 years on the horizontal scale to the solid diagonal line representing a pH value of 7.0 with potential for abrasion, and then across to the vertical scale, read a metal thickness of 182 thousandths of an inch. A 7 gage CSP has a wall thickness of 0.188 inches.

$$\frac{P_s}{P_c}=1.0-\left[\frac{100-50}{100}\right]\times\left[\frac{1.0}{(1.0+0.0825)^{50}}\right]\times\left[(1.0+0.0625)^{50}\right]=0.80$$

Answer: The bid price of a 7 gage CSP bituminous coated and paved, with a 50 year service life must be 20% lower than the bid price of concrete pipe with a 100 year service life.