254

National Cooperative Highway Research Program

NCHRP Synthesis 254

Service Life of Drainage Pipe

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

National Cooperative Highway Research Program

Synthesis of Highway Practice 254

Service Life of Drainage Pipe

LESTER H. GABRIEL, Ph.D., P.E.
Professor Emeritus,
California State University, Sacramento

and

ERIC T. MORAN, MSCE, P.E.
Sacramento, California

Topic Panel

D.W. (BILL) DEARASAUGH, *Transportation Research Board*
WILLIAM D. DRAKE, JR., *Louisiana Department of Transportation & Development*
WILLIAM A. GROTTKAU, *Carmichael, California*
JOHN HURD, *Ohio Department of Transportation (Retired)*
PAUL L. KOKOS, *Pennsylvania Department of Transportation*
THOMAS KRYLOWSKI, *Federal Highway Administration*
MICHAEL MATHIOUDAKIS, *New York Department of Transportation*
WILLIAM M. MEDFORD, *North Carolina Department of Transportation*
WILLIAM H. PARCELLS, JR., *Kansas Department of Transportation*
TONY WELSCH, *Federal Highway Administration*

Transportation Research Board
National Research Council

Research Sponsored by the American Association of State Highway and Transportation Officials in Cooperation with the Federal Highway Administration

NATIONAL ACADEMY PRESS
Washington, D.C. 1998

Subject Areas
Bridges, Other Structures and Hydraulics and Hydrology; Soils, Geology, and Foundations; and Materials and Construction

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communication and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

NOTE: The Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials, and the individual states participating in the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

NCHRP SYNTHESIS 254

Project 20-5 FY 1993 (Topic 25-21)
ISSN 0547-5570
ISBN 0-309-06111-3
Library of Congress Catalog Card No. 97-62281

Price $16.00

NOTICE

The project that is the subject of this report was a part of the National Cooperative Highway Research Program conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council. Such approval reflects the Governing Board's judgment that the program concerned is of national importance and appropriate with respect to both the purposes and resources of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation Officials, or the Federal Highway Administration of the U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

The National Research Council was established by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and of advising the Federal Government. The Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in the conduct of their services to the government, the public, and the scientific and engineering communities. It is administered jointly by both Academies and the Institute of Medicine. The National Academy of Engineering and the Institute of Medicine were established in 1964 and 1970, respectively, under the charter of the National Academy of Sciences.

The Transportation Research Board evolved in 1974 from the Highway Research Board, which was established in 1920. The TRB incorporates all former HRB activities and also performs additional functions under a broader scope involving all modes of transportation and the interactions of transportation with society.

Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

and can be ordered through the Internet at:

http://www.nas.edu/trb/index.html

Printed in the United States of America

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to state DOT highway and roadway design and materials engineers, including specifications and standards, geotechnical, chemical, pavement, construction, and maintenance specialists; engineering geologists and geologists; product manufacturers and suppliers; and researchers. The synthesis describes the current state of the practice regarding state transportation agency standards and strategies that determine and define the service life of drainage pipe. Information for the synthesis was collected by surveying state transportation agencies and by conducting a literature search.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board is an update of *NCHRP Synthesis 50: Durability of Drainage Pipe* (1978). The synthesis provides detail on the elements influencing material durability considered in the selection of drainage pipe. These elements include the definitions of useful service life and life expectancies of various types of pipe protection systems in differing environments based on such facts as pH, resistivity, abrasion, flow conditions, etc. Protection strategies that influence material durability are also addressed.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

Lester H. Gabriel, Ph.D., P.E., Professor Emeritus, California State University, Sacramento, and Eric T. Moran, MSCE, P.E., of Sacramento, California were responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of D.W. (Bill) Dearasaugh, Engineer of Design, Transportation Research Board; William D. Drake, Jr., Specifications & Standards Engineer, Louisiana Department of Transportation & Development; William A. Grottkau, Carmichael, California; John Hurd, Ohio Department of Transportation (retired), now Regional Engineer, Advanced Drainage Systems, Inc.; Paul L. Kokos, Standards & Criteria Engineer, Pennsylvania Department of Transportation; Thomas Krylowski, Highway Engineer, Federal Highway Administration; Michael Mathioudakis, Ph.D., Engineering Research Specialist 1, Transportation Research and Development Bureau, New York Department of Transportation; William M. Medford, Chemical Testing Engineer, North Carolina Department of Transportation; William H. Parcells, Jr., Pavement Surface Research Engineer, Bureau of Materials and Research, Kansas Department of Transportation; and Tony Welsch, Highway Engineer, Federal Lands Highway Office, Federal Highway Administration.

This study was managed by Stephen F. Maher, P.E., Senior Program Officer, who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in Topic Panel selection and project scope development was provided by Sally D. Liff, Senior Program Officer. Linda S. Mason was responsible for editing and production.

Crawford F. Jencks, Manager, National Cooperative Highway Research Program and Lloyd R. Crowther, Senior Program Officer, assisted the NCHRP 20-5 staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

SERVICE LIFE OF DRAINAGE PIPE

SUMMARY

During periods of abnormally high rainfall and floods, efficient and reliable systems of drainage are required to maintain the functions of highway transportation systems. Thus, it is necessary to maintain control and disposal of surface water runoff from the traveled roadway surface, median areas, shoulders and adjacent service areas. In addition, within urban areas, uninterrupted pedestrian traffic on sidewalks and crossings must also be maintained.

The estimate of years of reliable low maintenance service, anticipated in the design phase, is conditioned by service experiences of drainage pipes, choice of pipe materials, environmental considerations, regional construction practice and economic constraints. Soil and water containing acids, alkalis, dissolved salts and organic industrial wastes will act to chemically corrode a buried drainage pipe. These contaminants, which can occur in regions of high rainfall and in arid locations, are carried by surface water, ground water, sanitary effluent, acid rain, marine environments and mine drainage.

Oxygen concentration cells may occur in buried metallic pipelines and culverts. Oxygen-starved and oxygen-rich locations on and in the vicinity of the pipe become anodes and cathodes, respectively. Anodic loss of pipe material results in electrochemical corrosion. Soil and water pH, resistivity, and the nature and concentration of aggressive salts are all indicators of corrosion. Anaerobic bacterial corrosion of metal pipes is most severe in wet, poorly drained soils, swamps, marshes and brackish water. Abrasion, a consequence of heavy bed loads and high velocities, can lead to accelerated corrosion and further degradation.

Highway drainage pipes are built using metal, clay, concrete or plastic. For concrete pipes and culverts, the type of cement, aggregates, additives, water/cement ratio, mix proportions and curing strategies are reportedly adjusted for aggressive chemical effluent, aggressive bed loads, and cyclic freezing and thawing. Acidic conditions, sulfates, carbonates and chlorides are known to degrade concrete. The state departments of transportation responding to a request for information for this synthesis report were inconsistent in their definition of useful service life for pipe of any material. Several agencies reported using regression formulae to predict survivability for reinforced concrete. Representative state practices and requirements for limits of pH, concentrations of aggressive salts and types of cement are included in this synthesis report. Chemical and mechanical properties of thermoplastic pipes are also discussed.

Zinc, aluminum, aluminum-zinc alloy metallic coatings, asphaltic coatings with and without fiber, and polymer coatings protect metal pipes against soil-side and water-side chemical and electrochemical corrosion. Invert pavings of asphalt and concrete protect against bed loads and velocities likely to cause moderate to severe abrasion. Coatings appropriate to the soil and water environments of chemistry, pH and resistivity were also studied and are discussed in this synthesis report.

The desired service life of a drainage system is specified by the agency of jurisdiction. With frequent and periodic inspections by well-trained personnel, the uncertainty of meeting the desired service life requirements can be minimized. Well-defined and timely maintenance is key to achieving the anticipated longevity. Inspection strategies vary, however.

Rehabilitation or replacement is justified when it is unsafe, or uneconomical, to maintain elements of the drainage system in service. Trenchless methods of rehabilitation include sliplining, flexible tube lining and portland cement mortar lining. Methods for replacement of damaged pipelines include cut and cover, jacking and micro-tunneling, the latter two being methods of trenchless rehabilitation. Trenchless rehabilitation in a confined breathing area often requires an appropriate ventilation system; however, the value of minimum disruption of highway and utility services should be included in a cost analysis. Use of preformed linings of plastic is often followed with grouting of the annular space between the liner and the existing pipe. The useful service life of the drainage system may be significantly extended.

A great deal of uncertainty is involved in economic studies that include estimates of future conditions. Life-cycle cost analyses, governed by assumptions of parameters, require an objectivity often difficult to maintain in the face of anecdotal experiences and manufacturer's claims. Expected survival lives, initial cost, discount rate, inspection and maintenance costs, timely repair, rehabilitation or replacement costs, salvage credits and residual value at the end of the design service life are all factors in the calculations for a present-worth study.

Examples of some areas of future study include the determination of improved surety of bond between a liner and a metal pipe, and strategies for predicting loads as a result of active and passive surcharges on pipes.

CHAPTER ONE

INTRODUCTION

BACKGROUND

In 1978, a study sponsored by the American Association of State Highway and Transportation Officials (AASHTO), in cooperation with the Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP), resulted in the publication of *NCHRP Synthesis of Highway Practice 50: Durability of Drainage Pipe.* Synthesis 50 has been reported to be of considerable value to practicing engineers, architects, and to the agencies of local, state and federal government; these agencies shoulder the burdens of choosing the most efficient pipes and culverts for particular drainage applications.

This synthesis report, a result of a study done under NCHRP Project 20-5, Topic 25-21, Service Life of Drainage Pipe, updates Synthesis 50. The state of the art and the state of the practice are woven for purposes of lending definition to concepts of desired service life and useful service life of pipes and culverts of various materials. Protection strategies that influence material durability are addressed. As defined by this study, desired service life (also referred to as design service life) means projected years of reliable low-maintenance service expected of the drainage pipe, or drainage system, from the time of installation; useful service life means years of service relatively free of maintenance. The years assigned for design service life vary from state to state; the number of years assigned is influenced by preferred pipe materials for specific applications, environmental considerations, regional construction practices and economic constraints. Representative state and select federal practices for the selection and preferred use of drainage pipes and culverts, and selected research that has, or may, influence these practices, are reported herein.

As defined by this study, durability describes a material's ability to resist degradation as a result of forces of chemical or electrochemical corrosion and mechanical abrasion. The composite effect is erosion. In culverts and storm drains, durability is a means of stating and comparing useful service lives when limited by the pipe's material performance.

ASPECTS OF HIGHWAY DRAINAGE

Predictably efficient and effective highway drainage is a common goal of state departments of transportation (DOTs). One important requirement of a highway drainage system is to maintain functioning highway transportation during periods of abnormally high rainfall and floods. For motorist safety, surface water runoff from the traveled roadway surface, median areas, shoulders and adjacent service areas must be intercepted and effectively redirected. Streets and roadways within urban areas must be kept drained to permit pedestrian traffic on sidewalks and crossings. Highway storm drain facilities must be compatible with local systems.

Another important requirement of a highway drainage system is to inhibit the destructive forces of pooled waters and the uncontrolled flowing of surface waters because both of these waters could severely limit the desired service life of drainage facilities. For some materials, pooled water in and about drainage pipes will accelerate the corrosion process. Uncontrolled flow is likely to add to abrasion problems within the pipe, and cause bedding support problems outside the pipe and structural stability problems in adjacent cut-and-fill slopes.

Culverts and other drainage facilities must be sufficiently durable to meet the expected longevity of the desired service life. To this end, drainage structure materials must be compatible with local and regional environments. This synthesis addresses this concern. Vulnerabilities of design service life predictions are a result, in part, of changing upstream hydraulic conditions, often a consequence of storm water draining over rooftops, parking lots and pavements associated with urban and industrial development, mine wastes, and agricultural development rather than previously existing undeveloped land.

While considerations of structural and hydraulic performance of drainage pipe are equally important, discussion of them is beyond the scope of this synthesis.

PROBLEMS RELATED TO DURABILITY

The damage done to culverts and drainage pipelines by severe corrosion and/or abrasion is irreversible. For many conditions, opportunities exist for corrective measures that enable the extension of useful service life. Weighed against the costs of replacement are costs related to arresting the degradation and/or repairing the drainage structures. In cases of pipelines and culverts under high fills, and in other situations where replacement must include interruption of traffic flow, replacement costs may be very high. The design service life of highway drainage facilities must include expectations of long-term durability, structural integrity and hydraulic capacity.

While there are many causes of corrosion and abrasion of pipe and culvert materials, especially steel, aluminum and concrete, an understanding of these causes is not fully clear. The science and engineering disciplines of physical chemistry, organic chemistry, polymer chemistry, electrochemistry, materials, hydrology, solid mechanics, fluid mechanics, soil mechanics, geology and mineralogy share in predicting the long-term useful service lives of materials used for pipe and culvert installations.

Based on scientific understandings, engineering studies and empirical observations, state DOTs have sorted out their experiences and developed individual strategies for proper selection of pipe and culvert materials. This synthesis includes discussions of a number of these strategies.

Throughout this synthesis report, references are made to measures of the chemistry and physical chemistry of soil and water environments associated with highway drainage pipelines and culverts. These measures are very sensitive to the associated testing protocols. For efficient extrapolation and application of the information contained herein, it is essential that the compatibility of testing protocols be established.

SOURCES OF INFORMATION

At the outset of the study for this synthesis, a request (Appendix A) was sent to state DOTs asking for information on practices relating to the use and criteria for the selection of drainage products and materials as well as standards, policies, completed research and research in progress, and other miscellaneous aspects. Of the 50 states contacted, 49 responded. Documents, policies and standards of the FHWA, and specifically the Federal Lands Highway Division of FHWA, were secured, and information gained was woven into the report. An acknowledgment of the states providing information is given in Appendix B.

A review of literature revealed a large number of published papers and other documents, all of which provided bases for reviews of state and regional practices. In some regards the drainage pipe and culvert industries are experiencing important change, especially noticeable by the substantial research activity of the recent past and planned for the immediate future. Research reports were used extensively for this synthesis and are documented in the references.

Engineers associated with the various segments of the industry were another source of information. Many provided advice on the application of present standards and on the direction their respective industries are headed.

CHAPTER TWO

THEORY AND MECHANISMS OF CORROSION AND RELATED DEGRADATION

INTRODUCTION TO CORROSION

Corrosion is a cause of deterioration, dissolution or destructive attack on materials resulting in degradation of material properties by chemical or electrochemical reaction with the environment. Chemical corrosion of concrete pipe is discussed chapter 3. The following, in large part, discusses the phenomenon of electrochemical corrosion of metals, which is addressed mainly to metal pipes and, where appropriate, the metal reinforcement of concrete pipes. Corrosion may begin on the inner or outer surfaces of buried metallic drainage pipes. Uniform or general corrosion is corrosion that proceeds at the same rate over the surface. When corrosion occurs at discrete sites, such as pitting corrosion or crevice corrosion, it is called localized corrosion. Pitting corrosion is the loss of material when confined to small points forming indentations on the surface. When these pits form between the narrow space of two facing surfaces, it is termed crevice corrosion.

Corrosion of refined metals is a return to native states as oxides or salts. Only the more noble metals (platinum, gold and silver) and copper exist in nature in the metallic state. Metallic ores are refined by the application of energy, usually in the form of heat. Unless protected from a hostile environment, these metals revert (by the process of an electrochemical reaction) from their temporary metallic state to a more natural state. When corrosion has occurred, it is irreversible.

Corrosion affects all metals and alloys, although at widely varying rates that depend on chemical properties, physical properties and environmental conditions. For example, the well-known end product of corroding iron in the presence of water and air is rust. It consists mainly of an iron oxide (Fe_2O_3), which, in its prerefined natural form, may exist as hematite, the most common iron ore. Several metals form corrosion products that serve as insulating surface layers resistant to further corrosion. Examples of importance to pipelines and culverts are aluminum oxide, zinc oxide and copper carbonate.

In recent years, corrosion has been understood more broadly as affecting many nonmetallic substances such as stone, concrete, ceramics, plastics, wood and leather.

CORROSION AND THE ENVIRONMENT

Metal and concrete culverts and other drainage pipes are subject to corrosion in different soil and water, both of which may contain acids, alkalis, dissolved salts, other chemicals and organic industrial wastes. The contaminants may arise from surface runoff waters, groundwater, sanitary effluent, acid rain, and exposure to marine environmental conditions or mine drainage and may contain dissolved or free gases. The chemicals that have reacted with, become dissolved in, or been transported by water are the main corrosion factors affecting subsurface drainage facilities.

Although most chemical elements and their compounds are present in soil, only limited numbers of such chemicals exert an important influence on corrosion. In areas of high rainfall, the passage of time generally results in leaching of soluble salts and other compounds, thus leaving a residual soil that is acidic. Conversely, in arid locations, through capillary and evaporative processes, soluble salts are brought to upper soil layers, thus causing the soil to be strongly alkaline. The intensity, duration and frequency of rainfall, evaporation and other climatic factors have an important role in establishing the basic chemistry of surface runoff and groundwater flow. The chemistry of the groundwater, with dissolved minerals and salts, is an important determinant of the service life of metal and concrete drainage pipes. A performance study of corrugated metal pipes in Kansas (*1*) concluded that the predicted residual longevity is very site-specific and heavily dependent on accurate knowledge of pH.

Groundwater containing the same chemical content as surface runoff will likely be less hostile to pipes than the surface water. This is because passage of water through the soil intervenes in the passage of these chemicals to the drainage pipe. Because of low permeability, diffusion and capillary action, tight clay soils in the vicinity of drainage pipelines reduce the movement of corrosive chemicals. However, the same inherent low permeability is likely to result in oxygen-starved areas, which, in turn, set the stage for electrochemical corrosion.

Cinders, particularly coal cinders, are likely to carry acid or acid-forming compounds. Coal cinders in backfill are highly corrosive to those pipe materials vulnerable to acid attack. Such cinders also contain unburned carbon, which is cathodic to these pipe materials and, with a high galvanic potential difference, may cause rapid corrosion in metal pipes. Another example, corrosive acid backfill, occurs with the presence of weathering pyrite.

Following is a discussion of the causes and consequences of electrochemical corrosion as it applies to subsurface metal drainage pipes and culverts.

ELECTROLYTIC CORROSION CELLS

When a metal corrodes, it releases the energy gained when it was refined. The energy released is in the form of electrical energy. Every corrosion cell is composed of four basic components:

- Electrolyte—soil moisture in the vicinity of buried pipes, or liquid within the pipe, carrying ionic current between active points on metal surfaces, the anode and the cathode.
- Anode—a region of a metallic surface (perhaps the pipe itself) on which oxidation occurs, giving up electrons with metal ions going into solution or forming an insoluble compound of the metal.
- Cathode—a region of a metallic surface (perhaps the pipe itself) that accepts electrons and does not corrode.
- Conductor—a metallic connection (perhaps the pipe itself) that permits electrical current flow by completing the circuit.

Current flows through an electrolyte because of a voltage difference between the anode and the cathode. This difference in potential may be from a source outside the drainage pipeline, as is the case with stray currents from a nearby direct current source such as electric railways or cathodically protected utility pipelines.

In drainage pipelines and culverts, the potential difference is often associated with two locations on a continuous metal pipe embedded in an electrolyte with each location having different electrical properties. Unfortunately, most chemical differences and some physical differences that exist between locations in the electrolyte, or between locations in the metal of the pipeline, set up a potential difference (or voltage). The amount of the potential difference depends on the nature of the metal, the condition of its surface, the nature and variations of the electrolyte, and the presence of different or foreign materials at the interface of the metal and electrolyte. These materials could be impurities or dissolved gases such as oxygen. Corrosion cells may also be created by variations in the nature of the metal and changes in the condition of the metal's surface.

The extent of corrosion is proportional to the current. At low current densities, corrosion may be in the form of pitting; at high current densities, there may be extensive consumption of metal. Corrosion prevention is accomplished by rendering ineffective one or more of the four components noted above; in drainage practice, there are limited options.

A measure of a metal's electropotential cannot always be readily estimated because of uncontrollable factors affecting corrosion. Such factors include the environment in which the metal is situated, temperature, the chemistry of the soil envelope (which may include metallic ores), fertilizers, the presence of soluble salts and concentrations of oxygen.

Corrosion is accelerated when dissimilar metals are in contact. The rate of this galvanic corrosion depends on the potential difference, the electrical resistance between the metals, the conductivity of the electrolyte, the cathode/anode area ratio and the polarization characteristics of the metals (*2,3*).

Oxygen concentration cells, a major type of corrosion mechanism, commonly develop on buried pipelines and culverts. Pipelines are usually placed on compacted or relatively undisturbed soil at the bottom of a trench. When backfill material is more permeable than the in-situ soil, the backfill provides a shorter pathway to the surface and is more accessible to diffused oxygen. In turn, an oxygen concentration cell is likely to be formed. The oxygen-starved, bottom-outside surface of the pipe becomes the anode; the oxygen-rich top and sides of the pipe form a cathode; the moist soil is the electrolyte; and the metal pipe itself is the connecting electrical circuit.

The portion of a culvert under a highway or other pavement usually has less access to oxygen than those parts under the unpaved shoulders (Figure 1). A cell is formed in which the anode is the oxygen-starved pipe under the pavement, a cathode is formed at the oxygen-rich outer extremity of the pipe, the electrolyte is the moist soil and the metal pipe is the connecting electrical circuit. Although all of the pipe under the pavement is anodic, in this situation most of the corrosion attack occurs on the pipe under the pavement edge.

LOCALIZED CORROSION

The nature and extent of localized attack are of great concern for purposes of design and protection. Four common types of localized corrosion are described below.

- Pitting corrosion—although pitting initiation is caused by oxygen concentration cells, aggressive ions, such as chlorides and sulfides, often accelerate the rate of pitting attack. The pit growth of metal in soil appears to follow a power law equation: $P \propto t^n$, where P is the depth of the deepest pit in time t, n is a constant. For steel, the values of n vary from about 0.1 in well-aerated soil (sand) to 0.9 in poorly aerated soil (clay).
- Crevice corrosion—occluded areas, such as occur at the interface between gaskets and pipe walls, between protective films or liners and pipe walls, or between overlapping plates at pipe wall fastenings, set up a mechanism similar to that of pitting corrosion. The restricted pathways for oxygen diffusion

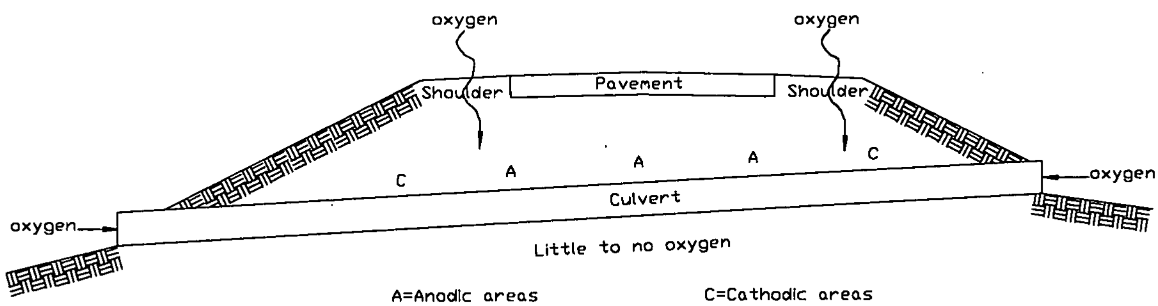

FIGURE 1 Oxidation corrosion cells in pavement drainage structures (after 2).

within the crevice set up oxygen concentration cells, which, in turn, lead to corrosion and subsequent accelerated corrosion. The resulting corrosion products, such as magnetite in the case of steel, may compound the corrosion process by galvanic effects.

- Stress corrosion and cracking—stress corrosion results from a combination of corrosion as described above and tensile stress, including residual tensile stress. Should a steel pipeline or culvert be cathodically protected to inhibit general corrosion, stress corrosion is more likely to occur. This may lead to an accumulation of alkali salts on the surface of the pipe that set up the conditions for cracking the metal, especially where the protective coating has been compromised.
- Microbiologic corrosion—abnormally high corrosion rates of steel in soil with low oxygen may occur in the presence of anaerobic sulfate-reducing bacteria. Wisconsin reported concern with this corrosion mechanism. It is not clear whether the mechanism for the attack is well understood. One theory suggests that these bacteria, which thrive under anaerobic conditions in the range $5.5 < pH < 8.5$, reduce inorganic sulfates to sulfides in the presence of hydrogen or organic matter. The steel surface of a drainage structure normally absorbs the hydrogen that is used by the bacteria in the sulfate reduction process. Biocides may be used to minimize this type of corrosion.

Perforation, the complete penetration of the metal, indicates an impending need for maintenance of a culvert or storm drain. Continuation of this type of deterioration can lead to exfiltration of water and/or infiltration of fine-grained, noncohesive backfill. Loss of subgrade support is often the consequence, followed by structural degradation. Carefully selected backfill can mitigate this danger. For many state DOTs, the time to first perforation of the metal defines the useful service life of the pipe.

EROSION AND ABRASION

The abrasive properties of aggregate bed loads that are harder than the material of the exposed pipe invert or coating and that are traveling at high velocities will erode pipes of metal, concrete, clay and plastic. Invert erosion of drainage pipes is the result of chemical or electrochemical corrosion and abrasion. The erosion of inverts often begins with formation of corrosion products of the parent material in the offending environment. These corrosion products are often more brittle than the parent material from which they were formed. These corrosion products are then carried off by the abrading action of the traveling aggregates thus exposing the surface for subsequent cycles of corrosion and abrasion.

When corrosion and abrasion operate together, they produce far greater deterioration jointly than either would by itself. Abrasion accelerates corrosion by removing protective coatings and passivating films if present. Water flowing at a velocity high enough to create appreciable turbulence can also cause severe localized effects known as impingement and cavitation. Impingement is caused by suspended solid particles or gas bubbles striking the surface or by turbulence alone and occurs at pipe entrances, sharp bends, protrusions (such as rivets and lapped joints) near aggregate or sediment deposits, and at other abrupt changes in flow patterns. The protective layer of a metal or concrete surface is compromised and erosion is the consequence. Cavitation is the result of erosion damage from high-velocity flow in which high pressure and subatmospheric low-pressure areas are developed with bubbles forming and collapsing at the solid-liquid interface. Cavitation damage rarely occurs in culverts or storm drains because of their relatively low operating heads and velocities.

Flow velocities depend on the drainage channel's material, the geometry of its cross-section, its slope and its depth of flowing water. Velocity increases with channel slope and with an increase in discharge, such as during floods. Other things being equal, the steeper the watershed topography, the greater the amount of eroded material carried by runoff into the streams. Abrasion, a function of the square of the velocity, will cause an approximate fourfold increase in its abrasive power when the flow velocity is doubled. Theoretically, doubling the velocity of a stream increases its ability to transport rock fragments of a given size by as much as a factor of 32. The Federal Lands Highway Division of FHWA has, for purposes of design, defined measures of abrasion as follows:

- Nonabrasive—no bed load and very low velocities,
- Low abrasive—minor bed loads of sand and velocities less than 1.5 meters per second (m/s) [feet per second (fps)],
- Moderate abrasive—moderate bed loads of sand and gravel and velocities between 1.5 and 4.5 m/s (5 and 15 fps), and
- Severe abrasive—heavy bed loads of sand, gravel and rock and velocities exceeding 4.5 m/s (15 fps) (*4*). The velocities noted are those of typical flows.

In storm drainage pipelines and culverts, the vulnerable location for corrosion-abrasion damage is most generally the invert. Where organic wastes containing trapped acid-forming gases (such as hydrogen sulfide) are to be drained, the inner crowns of concrete pipes are vulnerable to corrosion. For metal materials, electrolyte corrosion is possible because the invert is host to both an electrolyte and varying concentrations of oxygen. If there are corrosive chemicals in the water, these too are in contact with the invert. Along the inverts of metal and concrete pipes, protective coatings, linings and pavements are at risk of being eroded, cracked or delaminated.

ADDITIONAL EFFECTS

The entrance and exit ends of the culvert invert are often vulnerable to degradation by sunlight (ultraviolet light), ambient temperature changes, and the exposure of both the inner and outer surfaces to dry and wet cycles of air and water.

Backfill settlements and other earth movements, live loads and structural design deficiencies result in movement that can cause joint separation of pipes of all materials. These, in turn, may cause infiltration, exfiltration and migration of the supporting bedding and sidewall trench backfill. The result may be structural failure of the pipeline or culvert. In flexible metal pipes, such movement and joint separation can damage a rigid invert pavement or lining, thus affording the corrosive agent access to underlying unprotected metal surfaces. Repeated cycles of corrosion and progressive structural distress may be expected.

Severe cracking of reinforced concrete drainage structures may result in corrosive attack on the reinforcing steel. Reactive aggregates may cause abnormal expansion, cracking and loss of strength of concrete.

CORROSION INDICATORS FOR METAL PIPES

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

The pH value is defined as the log of the reciprocal of the hydrogen ion concentration (H^+) of a solution. A pH value of 7.0 is neutral, values of less than 7.0 are acid and values of more than 7.0 are alkaline. Soils or waters having a pH = 5.5 or less are considered significantly acid; those of pH = 8.5 or more are considered significantly alkaline. 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.

The pH of soil or water is the most commonly used index of corrosion potential of concrete and metal drainage pipes and culverts. However, as noted below, pH alone is an insufficient indicator as to the likelihood of corrosion potential for metal pipes. A study by Garber and Lin (*5*) informs that at 25°C (77°F), in soil in an aqueous environment and with very poor aeration, iron will corrode in pH environments as high as 8.5. It is at lower pH values that corrosion is more likely to be a problem. The lack of oxygen tends to cause the formation of hydroxide scales that are soluble and, therefore, not protective. The oxide scales that form in a well-aerated environment are insoluble and protective of steel pipe. Aluminum is corrosive in strong acids with pH < 4 and in strong, caustic solutions. In aerated environments, a protective scale forms.

A method favored by some states and the American Iron and Steel Institute (AISI) (*6,7*) to determine pH and resistivity of water and soil and years of service is a form of California Test 643. The most severe exposure would be a continuously flowing low pH (acid) stream with constant replenishment. A similar pH in the soil's groundwater on the pipe's exterior would constitute a less severe exposure because replenishment normally would be low. The use of these values, however, has its limitations.

Several studies find little relationship between pH alone and rates of corrosion of aluminum or steel (*8,9*). Uhlig (*10*) states that, for bare steel within the range of about 4 < pH < 10, the corrosion rate is independent of pH and depends only on how rapidly oxygen diffuses to the metal surface. Oxygen concentration, temperature and velocity of the water alone determine the reaction rate. One should not rely solely on pH, when it is in the middle range, as indicating absence of corrosive soil or water. This is important because almost all natural water, including most conditions of surface runoff of acid rain, falls within the range 4 < pH < 10. In the more significant acid range, pH < 4, as may be expected in drainage areas subjected to mine wastes or acid rain, oxygen diffusion is no longer controlling.

With exceptions, specified limits for the measure of soluble salts and pH of soil and drainage effluent govern the state DOTs' selection of concrete pipes. With the addition of specified limits of soil and drainage effluent resistivity, the efficiency of selecting metal pipes is enhanced. The resistivity of water and soil is another parameter that is central to the states' interest with respect to the likelihood for corrosion of metal pipes. Where soil or effluent conditions fall outside the prescribed bounds, many states will permit the use of protective coatings and/or pavings on susceptible pipes.

Studies of corrugated metal culverts in New York and North Carolina found no correlation with pH, resistivity, concentration of salts, or other soil or water properties. However, the New York study cited pHs for both the water and the soil range from mildly acidic (minimum of 6.2 for water and 6.0 for soil) to moderately alkaline (9.0 for water and 9.4 for soil). As a result, New York has no policy with respect to the measures of pH, chlorides and sulfates in the water or the soil. In general, this strategy is not shared by other states.

It is common for states to define the opportunity for use of galvanized steel and aluminum drainage pipes, with or without coatings of various kinds, by one or more of the following: intended use (cross drains and culverts, side drains, underdrains, slope drains, storm sewers and other less significant drainage pipes); pH and resistivity of soil and water; and concentrations of salts in soil and water. Oregon permits unrestricted use of galvanized steel pipe under driveways only, and the design service life is limited to 25 years. With increase of gauge thickness and a bituminous coat, 10 years of extra service life may be credited. Colorado, Louisiana and Ohio do not permit general use of uncoated galvanized steel pipe. Ohio permits use of galvanized or aluminum-coated steel pipe in a nonabrasive environment; in rare cases in an abrasive environment. In a nonabrasive environment, aluminum-coated Type 2 pipes may be credited with a longer design service life than galvanized steel pipe. Maine (except for subdrains), New Hampshire and New Jersey prohibit use of uncoated galvanized steel pipe near the ocean. Rhode Island rarely uses corrugated steel pipe.

Resistivity and Conductivity

According to the National Institute of Standards and Technology (NITS), formerly the National Bureau of Standards (NBS), the simplest criterion for estimating the corrosivity of a given soil to metals is its resistivity (*10*). [See Table 6 in chapter 4 for a listing of resistivity and corresponding soil corrosiveness, published by the National Corrugated Steel Pipe

Association (NCSPA).] This electrical measurement depends largely on the nature and amount of dissolved salts in the soil and is also affected by the temperature, moisture content, soil compactness and presence of inert materials such as stones and gravel. The greater the resistance of the electrolyte, the less the flow of current associated with corrosion. Conversely, a higher moisture content and temperature may result in lower soil resistivity and a greater prospect of corrosion. For the relationship between soil corrosiveness and soil resistivity, see Table 6. For the relationships of water and soil classifications and resistivity, see Table 7.

Soil resistivity generally decreases as depth increases (*11*). Therefore, it is important that tests be conducted (where practicable) at depths approximating those of the proposed culvert installations. Consideration must also be given to the fact that culverts may be in "imported" fill or structural backfill soil.

Consideration should also be given to seasonal variations in flow and water table position and their impact on soil resistivity and potential for corrosion. Resistivity should be determined under the most critical conditions, such as when the water table is at its seasonally highest level. If not, an allowance should be made for such conditions. California's test method, like that of the NBS, attempts to account for the influence of moisture content on soil resistivity by testing under standardized conditions (*10,12*). In this way, like soils have comparable resistivities independent of seasonal and other causes for variations of soil moisture content.

Resistivity, in ohm-centimeters (Ω-cm), is defined as the electrical resistance at 60°F (15.6°C) between opposite faces of an isolated 1 cm^3 (0.061 $in.^3$) determined experimentally from a larger mass of material from which unit resistivity is calculated. Although there is contention as to the quality of the numbers, typical values of resistivity for various types of soil and water are listed in Table 1. Brackish water may have a resistivity as low as 500 (Ω-cm).

TABLE 1

TYPICAL RESISTIVITY VALUES

Soil		Water	
Classification	Ohm-cm	Source	Ohm-cm
Clay	750–2,000	Seawater	25
Loam	2,000–10,000	Brackish	2,000
Gravel	10,000–30,000	Drinking water	4,000 +
Sand	30,000–50,000	Surface water	5,000 +
Rock	50,000–Infinity*	Distilled water	Infinity*

*Theoretical

Several states rely on soil and water resistivity measurements as an important index of the corrosion potential. The California Test 643 method (*12*) uses the pH and electrical resistivity of soil and water to estimate the corrosivity of steel at proposed culvert sites.

In early studies in California, corrosion rates were found to correlate with the content of certain chemical compounds known to be corrosion agents, the sulfates and chlorides (*13*). The derived relationship was

$$E = 784{,}000/R^{1.15}$$

in which

E = sum of sulfate (SO_4) and chloride (Cl) ions in parts per million (ppm) or milligrams/liter (mg/l), and
R = minimum resistivity in Ω-cm.

This relationship was found to be unreliable when E was less than 100 ppm. Where there is a strong probability that sulfates or chlorides are in the corrosion range, use of the equation can be an economical shortcut to chemical analysis. Some emergencies determine the corrosivity of soil by measuring conductivity in addition to pH, alkalinity and soluble sulfates. Conductivity, the reciprocal of resistivity, is determined using a portable meter and is expressed in millimhos per centimeter (m-mho/cm). When borrow is to be used for pipe backfill, both it and the in-situ soil are tested.

Polarization Curves

Another electrical measurement technique, the use of polarization curves, predicts the corrosion rate of the exterior surface of buried structures. Schwerdtfeger proved its usefulness in extensive studies of buried metals (*14*). Lindberg adopted this method to estimate the corrosion rate of exterior surfaces of aluminum and galvanized steel culverts (*15*). Electrical measurements were made from the highway surface, eliminating the necessity for excavation to the underground pipes.

The method involves applying electrical current and measuring the resulting potential changes. One electrode can be placed over the culvert's centerline on the highway shoulder surface and another also on the surface several feet away from the culvert. Current is applied progressively in small increments and recorded with the resultant change in soil-to-culvert potential. The potential is usually measured with respect to a $Cu/CuSO_4$ reference electrode. The slopes of the potential vs. log(current) curves in the anodic and cathodic directions are called the anodic and cathodic Tafel constants, $\$_a$ and $\$_c$, respectively. The current and potential data in a span of several millivolts on either side of the open circuit, or corrosion potential, follow a linear relationship. The slope of the potential (E) vs. current (I) curve gives the polarization resistance, R_p. The Tafel constants and the polarization resistance are then used to obtain the corrosion current, I_{corr}.

$$I_{corr} = \$_a\$_c /[2.3R_p (\$_a + \$_c)].$$

Faraday's law may be used to calculate the weight loss of metal resulting from this corrosion current in a given time. Therefore, by means of polarization curves, the corrosion rate of different buried metal structures may be compared in a specific environment at a specific time.

Michigan uses the polarization method along with other test parameters but points out that the method estimates total weight loss and does not take into account localized corrosion or pitting, which may lead to perforation and failure (*11*). Depending on moisture, temperature and other soil conditions, measurements should be expected to vary significantly. New York found no correlation between measured metal loss and computed metal loss using the polarization method.

Electrochemical Impedance Method

The high resistivity of soil can create a large resistive potential drop, causing errors in polarizing resistance (R_p) measurements. Use of electrochemical impedance spectroscopy may be considered to overcome this difficulty. In this method, small amplitude alternating potential signals of widely varying frequency may be applied to the pipeline. The resulting impedance signals are then analyzed to obtain a compensated value of R_p, free of ohmic interferences.

Oxidation-Reduction Potential

Oxidation-reduction potential, also commonly known as the "redox" potential, is used as a primary indicator of anaerobic bacterial corrosion. This type of corrosion at the soil-metal interface is most severe in wet, poorly drained soil such as in swamps, marshes and brackish water with pH in the neutral range. There, iron in de-aerated water, but in the presence of sulfate-reducing bacteria (sporovibrio desulfuricans), corrodes at an accelerated rate, often with the odor of hydrogen sulfide gas. These bacteria do not flourish where there is ample dissolved oxygen. Measurement of the redox potential requires an inert metal electrode, such as platinum, and a delicate, not readily portable electrical test apparatus more suitable for the laboratory than the field. Although bacterial corrosion has been observed at culvert sites in many sections of the country, it is not among the more common mechanisms for culvert material deterioration noted in studies by corrosion engineers. A general relationship of the potential for corrosion of underground steel pipe to soil redox potential is given in Table 2. Beaton and Stratful found a relationship between soil types that support anaerobic and aerobic bacteria in limited areas of California (*16*). However, the pH/resistivity correlation was found to be broader and more accurate than soil type in predicting corrosion (*12*).

TABLE 2
REDOX POTENTIAL VERSUS CORROSIVENESS FOR STEEL PIPE (*10*)

Soil Redox Potential (millivolts)	Classification of Corrosiveness
Below 100	Severe
100–200	Moderate
200–400	Slight
Above 400	Noncorrosive

Soil Characteristics

Several investigators have considered soil characteristics, such as the chemical and physical properties, and their effects on the potentials for corrosion and erosion of metals and other materials. In corrosion studies, chemical analyses of soil usually center on determination of water-soluble constituents. Typical constituents are the base-forming elements (sodium, potassium, calcium, and magnesium) and the acid-forming radicals (carbonate, chloride, sulfate and nitrate). Chlorides and other dissolved salts increase the electrical conductivity, promoting the flow of corrosion currents. Sulfate soil and water can corrode metals and harm concrete. States generally restrict the amount of organic material in backfill with Ohio and California examples of states that will not permit any. The permeability of soil to water and soil to oxygen is an important physical property in corrosion.

Studies have been conducted in several states, including Iowa (*17*), Minnesota (*18*) and Nebraska (*19*), for which maps have been prepared to show soil classifications according to the Great Soil Groups (*20*), with each group characterized as to its potential for corrosion. South Dakota has rated the corrosivity of all soil in the state.

Cathodic Protection

Corrosion control of pipelines may also be accomplished by cathodic protection in conjunction with a suitable coating. The current requirement for protection of carbon steel in soil varies in the range of 0.01 – 0.50 mA/m^2. At imperfections or damages in the coating system, cathodic protection applies a protective current to the buried pipe at the soil/pipe interface. Cathodic protection increases the vulnerability of cathodic debondment of the coating from the pipe, a consequence of increased alkalinity in the vicinity of the defect.

A common criterion for cathodic protection in soil is polarization of the structure to be protected to a potential of 0.85 volts vs. a $Cu/CuSO_4$ reference electrode. Degradation of the coating system requires an increase in current to maintain the preferred potentials all along the pipeline. When locations remote to the noted imperfection are of equal or higher potential, current flows to these remote locations, thus setting up the requirement for greater current creating greater local alkalinity in the vicinity of the imperfection. A pH of 12-14 is common, a condition that exacerbates delamination and further degradation of the coating and sets up an ever-increasing requirement for even greater current. It is difficult to cathodically protect large defects in close proximity. A small amount of uniformly distributed cathodic protection is advantageous; more rapid coating failure is likely to follow excessive cathodic protection (*21*). A study undertaken in Louisiana confirms the advantage of cathodic protection of culverts (*22*). Not having experienced soil-side corrosion problems, cathodic protection is not an option for New York. The outside of a steel culvert often requires significantly more current for protection than the inside. Polymeric-coated, galvanized steel culverts generally require the least amount of current for cathodic protection.

Precipitation

Generally, in areas of considerable rainfall, soil and water pHs are acidic, whereas the opposite is true in areas of little rainfall. In areas with abundant rainfall, the likelihood for corrosion is great. However, in areas of little rainfall, such as in the desert, corrosion can also occur because of the highly saline, alkaline soils.

Flow Velocity

Stream or drainage channel flow velocity and slope are important parameters for estimating abrasion rates and the nature and quantity of sediment transport. These, together with corrosion, affect the erosion potential and the nature of protective treatment, should that be required.

CHAPTER THREE

PIPE MATERIALS

Highway drainage pipes are manufactured from four primary material classes: metal, plastic, concrete and clay. For three of these categories, there are subdivisions of materials. Metal pipes may be of steel, ductile iron or aluminum; concrete pipes may be steel-reinforced, earth-reinforced, unreinforced, precast or cast-in-place; and plastic pipes may be of thermosetting resins (e.g., glass-reinforced epoxy or polyurethane) or thermoplastic resins (e.g., polyvinyl chloride (PVC), polyethylene or acrylonitrile-butadiene-styrene (ABS)). The material longest in use is vitrified clay while the newest materials are plastic. Some pipes are built with a combination of materials; for example, plastic (or bituminous) coated pipes lined with metal steel pipes coated with zinc or aluminum; and steel pipes with inverts of paved concrete. Pipe and culvert materials that account for almost all of the total in use are addressed below. Table 3 lists current AASHTO and ASTM material specifications that address aspects relating to the performance of aluminum, clay, concrete, fiberglass, plastic or steel drainage pipes.

TABLE 3

CURRENT SPECIFICATIONS FOR DRAINAGE PIPE

AASHTO	ASTM	AASHTO	ASTM
Aluminum		Plastic	
M 179	C4	M 167	A 761
M196	B 745M	M 252	
M 219	B 746M	M 264	D 2680
Clay		M 278	
M 65	C 14	M 304	
Concrete		M 294	
M 86	C 14		D 635
M 88M			D 643
M 170	C 76M		D 833
M 175	C 444M		D 1784
M 176	C 654		D 1785
M 206	C 506		D 1800
M 207	C 507		D 2122
M 242	C 655		D 2660
M 259	C 789		D 2661
M 273	C 850M		D 2665
M 282	D 3406		D 2751
Fiberglass			D 2774
	D2996		D 2837
	D2997		D 2921
Steel			D 3034
M 36	A 760M		D 4396
M 190			F 405
M 218	A 761		F 412
M 245	A 762		F 628
M 246	A 742		F 679
M 274			F 714
M 289			F 794
	A 849		F 891
	A 885		F 892
	A 929		F 894
	A 930		F 949

CONCRETE PIPE

Materials and Properties

Portland cement concrete is a material composite wherein chemically compatible fine and coarse aggregates of appropriate proportions are bonded together with a lime-based cement paste. Durability of concrete depends on the nature of the exposure and the quality of the concrete. Durable concrete of good quality is properly proportioned with cement, water and aggregates selected to address anticipated service conditions of chemical exposure and abrasive forces. To maintain the integrity of a concrete pipe or culvert, a balance must be struck between the properties of the cement, aggregates, additives, water/cement ratio and curing strategies where service conditions include any combination of the following: aggressive chemical effluent, which acts to corrode concrete and metal reinforcement (where included); aggressive bed loads resulting from hard aggregates transported at high velocities; and cyclic freezing and thawing (in some climates), which may cause spalling or cracking, thereby leaving the concrete open to greater penetration of aggressive chemicals and eroding action of transported aggregates. A high water/cement ratio and/or inadequate consolidation of the plastic mixture may contribute to durability problems.

Because concrete is permeable to moisture, it serves as an electrolyte when in contact with the reinforcing steel. Bare steel, which occurs at locations where concrete cover has spalled off reinforcing bars, is highly anodic to concrete-coated steel. As a result, a potent corrosion cell is likely to form with rapidly accelerating degradation to follow.

Influences of Water and Soil Chemistry

As generally recognized by the state DOTs, the potential for chemical attack of concrete includes sensitivities to low pH and soluble salts (sulfates and chlorides are of particular interest) in both soil and drainage water. Sulfates, mainly those of sodium, calcium, potassium and magnesium, may be found in many areas of the United States, often in the northern Great Plains and the alkali soils of western and southwestern arid regions. Seawater has a high sulfate content.

One type of chemical attack on concrete pipes and culverts embedded in the ground can be initiated by sodium sulfate, magnesium sulfate, calcium sulfate or sodium carbonate salts, in groundwater or waterside, resulting in scaling (expansion and spalling) of the interior (exposed) surface. Evaporation will cause concentration of the salts, thereby intensifying the problem. Hydrated lime and hydrated calcium aluminate, two of the many end products of cement hydration, occur in concrete products at the time of manufacture. When sulfates react with lime, gypsum is formed. When gypsum, in turn, reacts with calcium aluminate, calcium sulfoaluminate is formed. The reaction products in both cases are crystallized salts of greater volume than that of the original lime and calcium aluminate. The result is deterioration and degradation of the concrete surface, exposing increasingly deep layers to sulfate attack.

Effects of Permeability

Deteriorated, unabraded surfaces of the pipe interior will appear similar to those damaged by freeze-and-thaw cycles. Because of the fragility of a degraded invert surface of a pipe so affected, an abrasive bed load will more easily erode the invert at lower velocities of effluent flow. The severity of the degradation increases with increasing cycles of salt crystallization and dissolution; intermittent and/or periodic flows leave such pipes particularly vulnerable and vulnerability increases with increasing permeability. Concrete designed for use in soil where this type of attack is likely, in particular parts of the northern Great Plains and Western states, would benefit from a low water/cement ratio and/or use of a mineral admixture, such as fly ash, calcium nitrite or silica fume to assure low permeability (*23–26*).

Exposure to Salts

General agreement is lacking on the quantitative measures of sulfates in soil, or in water carried by the pipe, that define mild, moderate or severe exposure for concrete pipe. The concentrations are noted as the quantity of soluble sulfates present in the soil, in percent and as the quantity of sulfates in solution in the effluent water in parts per million (ppm). Most of the states with arid areas are particularly sensitive to the potentially deleterious effects of ever-present salts, usually sulfates, chlorides and other salts. The American Concrete Institute offers a conservative position that if the water-soluble sulfates in soil are less than 0.1 percent and the sulfate solution in water is less than 150 ppm, the exposure is considered mild. Exposure is considered moderate when water-soluble sulfates in soil are in concentrations between 0.1 percent and 0.2 percent and the sulfate solution in water is between 150 ppm and 1,500 ppm. Exposure is considered severe when water-soluble sulfates in soil are present in concentrations greater than 0.20 percent and/or the sulfate solution in water is greater than 1,500 ppm (*25*).

Exposure to Acid

No portland cement is resistant to acid attack; Type II and Type V cements are resistant to sulfate attack. The relationship is the less the quantity of tricalcium aluminate (C_3A) in the hydrated cement, the lower the vulnerability to sulfate attack. ASTM C 150 limits Type II cement, moderately sulfate resisting, to a maximum of 8 percent C_3A; Type V cement, identified as sulfate resisting, is limited to 5 percent C_3A (*27*).

Acidic soil is formed by the leaching of alkaline salts in areas of high rainfall or persistent flooding. Acidic soil creates acidic runoff. The alkaline property of hydrated cement paste, rich in calcium hydroxide with pH usually in the neighborhood of 13, makes hardened concrete vulnerable to acid attack.

Quality concrete, with nonreactive aggregates, properly proportioned, placed and cured, is normally not damaged by mild acids such as carbonic acid, common in runoff from natural mountain streams, or humic acid in runoff from marshes. If the acid is aggressive sulfuric acid (a component of acid rain, mine waste or organic waste), sulfate attack in addition to pH is also a factor. Abrasive effects of aggressive bed loads, when present and traveling at high velocities, add to potential distress. Dense concrete of high compressive strength, with hard coarse aggregate and a low water/cement ratio, will result in a pipe more difficult to abrade.

Cyclic Freezing and Thawing

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, if such conditions exist. Air entrainment, when properly selected and proportioned to provide uniformly distributed and nonconnected air voids in hardened concrete, coupled with the use of frost-compatible aggregates, will greatly reduce the consequences of cyclic freezing and thawing.

Corrosion and Abrasion

Abrasion is a consequence of the nature and quantity of the bed load and the velocity of flow. Velocities of flow greater than 4.6 m/s (15 fps), which include bed load, may require an eight sack (42.7 kg) mix and/or increased cover over the reinforcing. Cavitation at pipe joints may be expected with velocities over 12.2 m/s (40 f/s) (*28*).

A synergism exists between corrosion and abrasion in concrete; the combined effect is likely to be more than the sum of separate effects. Wear and erosion often begin with the formation of corrosion products of the concrete in the presence of the offending chemical. These corrosion products are often more brittle, or otherwise less competent, than the parent material from which they were formed. The corrosion products are then carried off by the abrading action of the traveling aggregates thus leaving the surface exposed for subsequent cycles of corrosion and abrasion. The penalty of acid attack and/or sulfate attack on an unprotected concrete invert is that it takes less energy to erode the brittle corrosion products than it would take to erode an uncorroded surface.

When the alkalinity of concrete is in the range $7 < pH < 14$ and in the presence of water, the progressive corrosion of steel reinforcement is inhibited by a protective passive film of iron oxide (Fe_2O). When alkalinity is reduced, as is expected with the presence of chloride ions in deicing salts or marine environments, the protective film breaks down and corrosion of the steel proceeds (*29*). An increasing volume of steel corrosion products create stresses that may spall and/or crack the concrete. This leaves both the concrete and the steel open and more vulnerable to further chemical attack at an accelerated rate.

The process of erosion is often initiated in reinforced concrete drainage pipe by chemical attack and/or abrasion of the concrete invert thus opening the possibility of acid attack on the steel reinforcement. Too wet a concrete mix (too high a water/cement ratio) will result in greater porosity of the hardened concrete, a more rapid diffusion of chloride ions (often in the form of deicing salts) to the steel/concrete interface, easier ingress of oxygen and lower electrical resistivity. In spite of compensating effects, the net effect results in a decrease in the initiation time for corrosion and a decrease in the critical chloride concentration required for corrosion (*30*). Damage to the concrete/steel composite (debonding of the steel and spalling of the concrete) results as a consequence of the larger volume required by the steel corrosion end products. Protective coatings for reinforcing steel, such as epoxy coatings, may be used to eliminate (or minimize) corrosion of the steel. An Ohio study reported that vitrified clay liner plates afforded a very high level of protection for reinforced concrete pipe (RCPs) installed in "extremely acid conditions" (*31*). California requires at least two inches of cover over the reinforcing steel where severe abrasion from high velocity flow is anticipated.

Corrosion of both concrete and its steel reinforcement at their interface often leads to bond failure. Debonded reinforcing bars cannot accept the transfer of stress from the concrete they are intended to reinforce and capture the structurally required, moment-resisting tensile forces that are beyond the low tensile stress capacity of concrete alone.

Useful Service Life

For California, the initiation of debonded reinforcing bars specifically defines the useful service life limit of reinforced concrete pipes and culverts. Florida's definition of useful service life is that period of time until the first crack occurs. Other states define the end of useful service life of reinforced concrete pipes and culverts in less specific ways. For example, in Colorado a committee comprising a project engineer, a hydraulic engineer and a materials engineer determines whether or not a pipe is functionally serving its intended purpose. Missouri defines useful service life as that period of time until replacement of the pipe is required. Mississippi assumes concrete pipe will last the life of the facility. North Carolina defines a design service life as the estimated age to which 80 percent of pipes will reach a limit beyond which true functional failure may be expected (their condition rating 3, or better).

A field survey of drainage pipes in service, including more than 1,600 RCPs, was prepared by the Missouri Highway and Transportation Department. For the particular conditions of service studied, a replacement time (defined as the time to structural failure) for RCP is reported to be significantly greater than 50 years (*32*). Greater than 60 years is the current expected service life for RCP in Missouri, 44 years for corrugated metal pipe (CMP). A national survey conducted by New York reports a wide range of useful service life for RCPs, from 20 to 75 years with an average of 56.5 years (*28, 33, 34*). In southern Indiana where strongly acidic run-off conditions exist, concrete pipe has been judged unsuitable (*35*).

In some Western states (California, Arizona, New Mexico and Texas), cast-in-place/earth-reinforced concrete pipe (CIP/ERCP), up to 3.048 mm (120 in.) in diameter, is employed for major highway drainage facilities. This pipe, cast directly against and formed by the invert bedding and vertical trench walls, is reinforced by the soil envelope interacting with the concrete. Without steel reinforcement, these pipes are not vulnerable to useful service life limitations resulting from steel corrosion and subsequent debonding. CIP/ERCP is not permitted in Arizona if the pH < 5 and in California if the pH < 5.5. The useful service life of CIP/ERCP is often extended by adding thickness to the invert.

Sulfate-Resisting Cements

The useful service life of RCP may be extended by protecting the invert with a layer of coating, lining or paving. The useful service life of RCP may also be extended with the selection of sulfate-resisting Type II and Type V cements. Consistent with their own historical experiences, each state has developed a strategy for the proper selection of cement type to be used. These strategies include attention to anticipated or experienced couplings of salt concentrations, pH and, in some cases, soil resistivity.

Many states restrict the type of cement permitted for concrete pipes subject to sulfate attack. Utah and Wyoming will permit only Type II for the less aggressive conditions, and Type V for the more aggressive conditions. Arizona requires Type V cement if sulfates in the soil exceed 0.2 percent. Utah permits Type II if sulfates in the soil are no greater than 0.5 percent. In Wyoming, Type II is permitted if such sulfates are no greater than 0.20 percent, if dissolved sulfates in the effluent are no greater than 1,000 ppm, if the pH lies in the range $5 < \text{pH} < 12$, and if the soil resistivity is greater than 275 Ω-cm. Type V cement is restricted in Wyoming to conditions wherein, for $5 < \text{pH} < 12$, soil resistivity is above 120 Ω-cm, soluble salts in the soil are no greater than 0.5 percent and the dissolved sulfates in the effluent are no greater than 2,000 ppm.

Colorado permits use of Type I cement only in those locations where soluble salts (sulfates and chlorides) in the soil are no greater than 0.15 percent and where dissolved salts in the water are no greater than 500 ppm. Type II cement may be used where soluble salts are no greater than 0.5 percent and where dissolved salts are no greater than 1,000 ppm. The only restriction on the use of Type V cement is that conditions must satisfy $5 < \text{pH} < 9$. For soil-side or water-side pH < 5, then bituminous coating of concrete pipe is required. Asphaltic coating of the invert only is not permitted.

Nevada places no restrictions on the use of cement type, but requires soil and water resistivity no less than 1,000, 5 <

TABLE 4
GUIDE FOR SULFATE-RESISTANT PIPE AND CONCRETE DRAINAGE STRUCTURES*

Water-Soluble Sulfate (SO^{4-}) in Soil Sample (%)	Sulfate (SO^{4-}) in Water (Parts per million)	Type of Cement	Cement Factor
0–0.2	0–2,000	II	Minimum required by specifications
0.2–0.5	2,000–5,000	V or II	Minimum required by specifications 7 sacks**
0.5–1.5	5,000–15,000	V or II	Minimum required by specifications 7 sacks
Over 1.5	Over 15,000	V	7 sacks

*Recommended measures for cement type and factor based on sulfate content of soil and water (California 7-851.3 D).
**7 - sack cement = 390 kg of cement/m^3 of concrete.

pH < 9.5, and permits dissolved sulfates no greater than 5,000 ppm. If the pH and/or resistivity are outside this range, Type II or Type V cement is required; if the dissolved sulfates are greater than 5,000 ppm, Type V cement is required. Still, other Western states facing high salt concentrations seek to minimize the vulnerability by requiring some kind of asphaltic coating of the pipe. Bituminous coatings may include paving of the invert, which often includes specification of cement type. Arizona credits precast reinforced concrete pipe, and nonreinforced concrete pipe, precast and cast-in-place, with a design service life of 100 years with a soil pH > 5. For pH < 5, cast-in-place pipe is unacceptable and bituminous coating is required for precast pipe, except in a closed storm drain system where bituminous coating is not allowed. For soils with high (undefined) sulfate levels, Arizona requires Type II or Type V cement, to be determined on a case-by-case basis.

California requires specified amounts of Type II or Type V based on the amounts of sulfates in the water and soil (see Table 4), and, in addition, requires invert paving with reinforced concrete, steel plate, channel or rail. With a pH < 6.5 and where severe abrasion from high-velocity flow is not anticipated, a 450-mm (1.8-in.) invert paving cover of the steel is required; with pH < 5.5, additional cover or a protective coat is required.

For conditions of service not addressed by standard manufactured concrete pipes, specially formulated concrete may be used. For example, the Bureau of Reclamation has designed concrete drainage pipe to withstand sulfate concentrations ranging up to 4.61 percent. Important aspects of the specially formulated concrete are increased cement content, reduced water/cement ratio, use of ASTM Type V cement, a lower maximum limit on water absorption, and a lengthy, controlled curing procedure. The Bureau has rated types of cement in order of their effectiveness in producing sulfate-resistant concrete as follows (with the best first): Type V, Type II, Type IV, Type III and Type I. The Bureau also uses approved pozzolans as an additive for high-sulfate locations. The Bureau of Reclamation's guidelines advise the following:

- If soil 0.1< SO_4 < 0.2 percent or water 150 < SO_4 < 1,500 ppm, Type II cement.
- If soil 0.2 < SO_4 < 2.0 percent or water 1,500 < SO_4 < 10,000 ppm, Type V cement.
- If soil SO_4 > 2.0 percent or water SO_4 > 10,000 ppm, Type V cement with sulfate resisting pozzolan *(35)*.

Guidelines from the Federal Lands Highway Division of FHWA *(37)* for a 50-year design service life of RCP preclude its use where the pH < 3 and the resistivity < 300 Ω-cm. A protective coating is required where the pH < 4, or the pipe is exposed to wetting and drying in a salt or brackish water environment. If soil SO_4 > 1.5 percent or water SO_4 > 15,000 ppm, Type V cement with a sulfate resistant pozzolan (or a mix richer in cement) is required. For severe abrasive environments, a seven- or eight-sack mix, or an increase of the cover over the reinforcement steel, is recommended.

Influence of Aggregates

The hardness of aggregates used in concrete, especially that of the coarse aggregates, is an important parameter of abrasion resistance. Concrete aggregates that are harder than bed load aggregates will offer greater resistance to invert erosion. No states include consideration of the aggregate match (concrete aggregates and bedload aggregates) as part of their specifications. However, some states are interested in controlling the bedload causes of invert abrasion. Examples are West Virginia, which requires an upstream catchment device or a paved invert for abrasive bedload, and New Jersey, which prohibits use of RCP for slopes greater than 10 percent.

Many states defend against the expected consequences of invert corrosion-erosion of RCP by requiring a mechanical or chemical barrier, or both. Pennsylvania, for example, requires an epoxy coat, or liner, for all concrete pipe; Ohio requires an epoxy coating of the invert of concrete pipes only under severely acidic conditions. Montana permits uncoated RCP when the pH > 6 and the SO_4 < 0.25 percent. Type V cement is required when 0.25 percent < SO_4 < 1.0 percent; a bituminous coat or a thicker wall (Type C) is required when outside the noted limits. Washington requires a fiber-bonded asphalt liner for drains plus paved inverts for culverts when the pH < 5 or pH > 8.5.

Service Life Regression Studies

To assist in the decision-making processes leading to the most efficient selections of drainage pipes and culverts, forecasting equations have been deduced to predict useful service lives.

Proper execution of life-cycle cost analyses is very sensitive to the measure of such predictions. Florida and Ohio have developed statistical regression equations based on the historical experiences that reflect local conditions in each state. Regression equations are deductive only, and although they are a very powerful means of relating past experiences of interaction of selected variables in selected analytical forms, by nature they are exclusive of theory. Consequently, the usefulness of regression equations for purposes of predictions of useful service life is limited to those situations wherein the same environmental conditions may be expected to be duplicated. A North Carolina DOT study reports that a statistical analysis failed to develop a reliable set of forecasting equations. The forecasting strategy adopted was a set of survival curves for four pipes in three geographical regions of the state (*38*). This same study recommended the development of databases of site-specific information on chemical factors of soil pH, specific resistance of neighborhood soil, alkalinity, hardness and specific conductivity of stream water. The study also recommended databases on physical factors of stream bed slope at the culvert, ratio of sediment to pipe height, size of bed material and the product of streambed slope and size of bed material. A more inclusive data set is recommended for future study for estimating useful service life by regressing the database information to a power curve that relates the loss of rating (of useful service life) to time (t), of the following form:

$$\text{Loss} = At^{b}$$

in which A and b are the regression constants.

Florida DOT (*39*) has developed a regression equation for concrete pipe wherein corrosion only is the environment of concern (to the exclusion of structural performance, velocity of flow and abrasive scouring). Based on the Florida experience and analysis, such service life (SL) may be predicted by

$$SL = 1{,}000\,(1.107\,C^{0.717}D^{1.22}K^{-0.37}\,W^{-0.631}) - 4.22 \times 10^{10}(\text{pH})^{-14.1} - 2.94 \times 10^{3}\,(S) + 4.41$$

where

C = sacks of cement per cubic yard,
D = steel depth in concrete,
K = environmental chloride concentration in ppm,
W = total percent water in the mix, and
S = environmental sulfate content in ppm.

Two other equations, using Ohio data, were developed by Hurd (1985) and Hadipriono (1986) and reviewed by Potter (*28*). A data set of 399 complete observations was obtained by inspections of culverts 42 in. in diameter or larger located throughout the state of Ohio. The data for Hurd's equation were included in a subset restricted to concrete pipes greater than 42 in. with pH < 7. These selected culverts were then reinspected and rerated to assure accuracy and consistency. Hadipriono used Hurd's complete data set. The following regression equations were developed:

Hurd:

$$\text{rate} = [6.50\,(\text{age})^{0.55} \times (\text{rise})^{1.08} \times (\text{slope})^{0.23} \times (\text{pH})^{-3.08}] \times [1\text{-sed/rise})]^{1.47}$$

where

rate = a number from 0 (excellent) to 100 (95 = end of useful life)

Hadipriono:

$$\text{rate} = 5.75 + 0.030\,(\text{age}) - 0.075\,(\text{flow}) - 0.013(\text{sed}) - 4.89\,(\log \text{pH}) + 0.13\,(\text{slope})^{0.5} - 0.0085\,(\text{rise})$$

where

a number from 1 (excellent) to 5 (4.5 = end of useful life)

where

age = age of pipe at time of inspection (years)
rise = pipe vertical diameter (inches)
slope = invert slope (%)
pH = water pH
sed = sediment depth in pipe invert (inches)
flow = a velocity rating number: 1 (rapid), 2 (moderate), 3 (slow), 4 (negligible), 5 (none).

In each of the equations, introducing the terminal condition rating variable "rate" and then solving for the variable "age" (of the pipe in service) is the prescribed manner of establishing the design service life of a proposed concrete pipe culvert.

The general value of the above equations points to a qualitative understanding of the influence of some variables known to influence the design service life of reinforced concrete pipe culverts. One such understanding, a result of the Ohio regression study, is that, based on loss of concrete invert for waterside pH < 7.0, pH is more significant than three other major variables: pipe slope, sediment depth, and age of pipe installation (*40*).

METALLIC-COATED STEEL PIPE AND CULVERTS

In the following discussion, all references to corrugated steel pipe (CSP) apply as well to spiral rib steel pipe (SRSP), unless otherwise noted.

Aspects of Corrosion

As noted in chapter 2, corrosion of steel drainage pipes and culverts may be initiated either from within (water side), from outside (soil side), or both. In Ohio, most of the metal loss associated with corrosion is water-side corrosion (*41*). Soil-side chemical corrosion is most significant in arid or semiarid regions where rainfall is minimal and strongly alkaline soil is likely to be in contact with the metal.

The chemistry of the relationship between a CSP and the water it carries is complex. Calcium carbonate, a chemical constituent of calcareous rocks carried by drainage water, may protect galvanized steel pipe. When calcium carbonate in water exceeds the saturation level,and in the presence of zinc, the excess is deposited as a very thin, insoluble, protective hydrous-oxide coating on the surface of the galvanized steel pipe, isolating the metal from water. If damaged, this protective coat repairs itself rapidly.

The pH value is an important determinant of corrosivity of the transported surface drainage water. Most surface drainage water has a $5.5 < pH < 9$. A relationship exists between the pH, calcium carbonate (also, calcium bicarbonate) and free carbon dioxide in the water. Free carbon dioxide will stabilize the carbonate and bicarbonate ions, but any excess of free carbon dioxide dissolves the protective coat of calcium carbonate, thereby permitting the opportunity for rapid corrosion. Decaying vegetation forms organic acids that react with the bicarbonate ions to produce corrosive acid salts. In an alkaline pH environment, this effect is less damaging. Resistivity of water and soil are generally used as indices of corrosion potential for steel pipe. Most states have found culvert durability correlates with pH and resistivity; other states have been unable to confirm this.

It is common among the states to specify both upper and lower bounds for pH and resistivity for soil side and water side.

Although the ionic chemical reactions and interactions are complex, it may be generalized that sulfate, chloride, nitrate and phosphate ions either disrupt or inhibit scale formation. Climate, rainfall and vegetation determine the ionic content of the drainage water brought to the pipe. Minerals leached from soil as soluble salts produce runoff that is acidic and harmful. In warm, wet climates, the organic decomposition of vegetation generates the harmful presence of carbon dioxide and organic acids.

Protective Coatings, Linings and Pavings

Many coating materials have been developed to protect CSP from aggressive drainage waters and soils. These include metallic coatings such as zinc, aluminum, aluminum-zinc alloy (no longer used); coatings of asphalt, asphalt with asbestos (no longer used), asphalt with aramid fiber (derived from nylon); and polymers such as thermosetting epoxy. A recent product development has SRSP coated on the outside with a thin laminated polymer and lined on the inside with a bonded polyethylene layer.

To help evaluate the potential for success or failure of coatings and linings in use (or future candidates for use) for protection of inverts (and, thereby, extension of useful service life) of steel pipes, a test protocol is being studied by the National Corrugated Steel Pipe Association (*42*). Details on protective coatings, linings and pavings follow in chapter 4.

Reactions of ferrous materials are complex and depend on electropotential, thermodynamic conditions and other factors such as chloride and sulfate content of the electrolyte. Chlorides, in addition to accelerating corrosion by damaging the protective film on anodic areas, also increase the conductivity of the electrolyte.

Limits of pH and Resistivity

A range of soil or water of $6.0 < pH < 9.5$ appears to be generally accepted for uncoated galvanized steel. In some states, environmental conditions particular to regional environments result in differing ranges of acceptability of uncoated galvanized steel, such as $6.5 < pH < 8.5$ in Alabama, $6.0 < pH < 8.5$ in Montana and $5.0 < pH < 8.5$ in eastern Washington. Louisiana does not generally permit uncoated galvanized steel pipe under abrasive conditions. An Indiana study found epoxy and combined polymeric/bituminous coatings suitable for runoff in the highly acidic coal mining regions; only bituminous or only polymeric coatings were found unsuitable (*35*). In the central and western regions of North Carolina, it was found that galvanized CMP without bituminous coating appeared to outlast coated pipes (*37*). The limits in Idaho for galvanized steel pipe are $6 < pH < 9$; for aluminized steel pipe they are $5 < pH < 9$. If aluminized or galvanized steel pipes are bituminous coated on both sides, Idaho expands these limits to $5 < pH < 11$; if they are plastic coated on both sides and if they are not under interstate highways, $4 < pH < 13$ is permitted.

Other states restrict the use of uncoated galvanized steel pipe for particular situations related to service. For example, New Hampshire, New Jersey and North Carolina no longer use uncoated galvanized steel near the ocean. Except for subdrains, the same is true for Maine. Kansas and Vermont do not permit uncoated galvanized steel under primary roadways; the anticipated need for replacement will be disruptive of traffic. Since the mid 1980s, Vermont has had a design policy that requires a polymeric coating on any metal pipe crossing a primary road; asphalt coating is no longer allowed. Many other states set standards based on water and soil pH, chemistry and resistivity. Colorado applies a corrosion index value (CR) of its own design, based on resistivity, pH and sulfate content, to decide the appropriateness of selecting CSP; values range from 0 to 6 (very mild to extreme). Uncoated galvanized steel pipe is permitted only in those locations where the CR is 0. New Mexico requires the $pH > 7.8$ while South Dakota allows unrestricted use. Nebraska does not have pH or resistivity requirements.

With respect to state standards based on water and soil pH, chemistry and resistivity, a great diversity of requirements exists. Requirements of pH and resistivity (R) are generally paired and further coupled with other requirements such as chlorides, sulfates, function, geographical location or service life requirements. In Alberta, Canada, corrosion was found to be much more dependent on soil resistivity than water resistivity (*43*).

States often define acceptable ranges of pH and resistivity. Regional differences are evidenced by different strategies. For example, lesser soil resistivities are required in arid and semi-arid western states where alkaline soils are present. A sampling of such states includes

- Arizona (galvanized steel, $6 < pH < 9$, $R > 2{,}000$ Ω-cm; aluminized steel, $5 < pH < 9$, $R > 1500$ Ω-cm or $7.2 < pH < 9$, $1{,}000 < R < 1{,}500$ Ω-cm);
- Idaho (galvanized steel, $6 < pH < 9$, $R > 1{,}000$ Ω-cm);
- Montana (galvanized steel, $6 < pH < 8.5$, $R > 2{,}000$ Ω-cm);
- Nevada (galvanized steel, $5 < pH < 9.5$, $R > 1$, Ω-cm); and
- Wyoming (galvanized steel, $6 < pH < 9$, $R > 1{,}000$ Ω-cm).

Montana's strategy (currently being reconsidered) permits a pH as low as 5 and an R as low as 800 Ω-cm for galvanized or aluminum Type II coated CSP provided a bituminous coat is added on both sides.

Conversely, greater resistivities are required in the acid soil regions of the heavy and moderate rainfall eastern states. A sampling of such states includes

- Georgia (galvanized steel,$6.0 < pH < 10.5$, $R > 4{,}000$ Ω-cm):
- Mississippi (galvanized steel, $R > 10{,}000$ Ω-cm for a 50-year design service life and $R > 1{,}500$ Ω-cm for a 25-year design service life, both with $5 < pH < 9$); and
- Pennsylvania (galvanized steel, $5.5 < pH < 8.5$, $R > 6{,}000$ Ω-cm).

Other states, including Florida, Illinois, Louisiana, Maine, Mississippi and Washington, invoke the California Test Method (C-643), or some modification thereof, to relate acceptable levels of pH and resistivity with service life requirements. Some states, such as Wyoming, relax requirements if a bituminous coating is applied to both sides of the pipe. Nevada prefers to specify plastic or concrete pipe rather than use bituminous coating of corrugated metal pipe. Iowa is not concerned with soil resistivity and relies on pH only.

Definitions of Service Life

General agreement is lacking among the states responding to this synthesis as to the definition of useful service life of CSP. Years to first perforation is adopted by such representative states as California, Florida, Louisiana, New York, Mississippi, Pennsylvania and Wisconsin. As for the definition of service life, the American Iron and Steel Institute (AISI) states that "the consequences of small perforations in a storm sewer are usually minimal" (*6*). AISI prefers an "average invert life" definition for useful service life, which may be considerably longer than time to the first perforation. The AISI chart, which also includes the same three parameters (years, resistivity and pH) as does the California chart, assumes a bedding that will not be eroded by exfiltrating drainage water. If this is not the case, the AISI prediction of useful service may be overstated. For nonabrasive and low abrasive conditions, the Federal Lands Highway Division of FHWA has modified the California curves to show the expected average service life of metallic-coated steel pipe with a thickness of 1.62 mm (0.064 in. - 16 gauge) for a maintenance-free service life 25 percent longer than the time to first perforation (*37*). Colorado defines useful service life as that period of time until drainage pipes are structurally unfit. Missouri defines useful service life as that period of time until replacement of the pipe, resulting from structural failure or erosion of the roadway bed, is required.

A North Carolina study offers a definition of design service life as the estimated age to which 80 percent of pipes will survive with a defined condition of service. Expectations are different for each of the three regions of the state: west, central and east. The study found that bituminous corrugated steel pipe is expected to have a design life of 20 to 29 years; uncoated galvanized steel, 16 to 32 years; and reinforced concrete pipe, 45 to 59 years (*17*). A field survey of more than 2,200 CSPs in service, prepared by the Missouri Highway and Transportation Department, predicts a replacement time for unrehabilitated zinc-coated CSP of 45 to 50 years (*43*).

The California Test Method (C-643) uses years to perforation of 1.32-mm thick (18-gauge) steel culvert as a design basis for defining the measure of anticipated useful service life. As the wall thickness increases, a multiplier greater than 1 is applied to chart readings. The multiplier may be as large a factor as 3.4 for 4.27 mm (0.05 in. - 8 gauge) steel. The predictions of useful service life that reflect the difference in definition (California's first perforation vs. AISI's average invert life) are not trivial. For example, for a 1.32-mm (0.052-in. - 18-gauge) galvanized CSP, with controlling (either water side or soil side) pH = 6 and resistivity = 1,000 Ω-cm, the California Method chart predicts a useful service life of just under 10 years; the AISI chart predicts a useful service life of just under 20 years.

Influence of Resistivity and pH on Service Life

Predictions of useful service life based solely on pH and resistivity are inconclusive. A Louisiana study revealed that the otherwise conservative California Test Method (C-643) may overstate the expected useful service life where drainage waters are known to be more than usually corrosive (*46*).

An aggressive corrosive condition may occur with soft water (containing very little dissolved alkaline salts), thus preventing development of a protective scale on galvanized steel. Where, by reason of experience with local alkaline salts (usually bicarbonates of calcium and magnesium) which produce precipitates of calcium carbonate, protective insoluble corrosion scale deposits are expected water side, the beneficial effects of the protective deposits could be included to offset a too conservative prediction of the California test. A modified California Method (*47*) defines a parameter of scaling tendency, in ppm, as a function of alkalinity, hardness (of the water) and free carbon dioxide. This is plotted against conductivity, in micro mhos/centimeter (m/Ω-cm), an inverse of resistivity. Predicted years of service life is read from a chart. Proper use of this chart would include recognition that seasonal variations in water chemistry, and the influence of the character of flow of the water being drained (e.g., persistent groundwater flow, nonpersistent surface water flow) must be included as factors. Aluminized Type 2 steel will form an aluminum oxide barrier scale that is not dependent on the presence of hard water.

An Alberta, Canada, study finds poor correlation with the California Test Method (C-643). One reason, of interest to the northern states, proposes that metal culvert corrosion is slowed or stopped by frost action (*43*). Several states have found little or no correlation between pH and culvert durability. As previously noted, New York does not correlate service life with pH, resistivity, chemical content of the soil or drainage waters, or other soil or water properties. A New York study (*48*) concluded that no special durability design is necessary to protect the outside or inside above flow line of galvanized CSP; average rates of metal loss below flow line governs the design. Other states, as previously noted, do not permit use of unlined metal-coated pipes. New York and North Carolina are examples of states that predict service life, in part, by geographic location.

Structural plate pipe arch structures and box culverts are more vulnerable to corrosion at bolted joints because of high levels of local stress existing at these connections. Deicing with road salts will increase chloride levels and, in turn, increase the environmental vulnerability to joint corrosion in such structures and in CSP. In Ohio (*48,49*) and New York, salt-laden groundwater (a result of deicing road salts) in contact with, and seeping through, bolted seams has been found to accelerate the corrosion process. Crown corrosion of steel box culverts was found to be of greater concern than those of aluminum because crown plates as well as bolts were vulnerable. Because of crown corrosion, New York has banned installation of steel box culverts; arch-shaped culverts are preferred. Ohio requires all large structures of steel plate, aluminum plate, and concrete to be sealed on the outside with an impervious coating.

Coatings and Abrasion

Coupled with the potential for corrosion, the nature of the abrasive aggregates bed load determines durability and useful service life of coated CSP. Ohio found water pH and abrasiveness of flow are the only environmental factors that have a significant effect on the deterioration rate of CSP (*39*). Aggregates contained in the bed load generally are much harder than the steel and certainly harder than the soft 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. With continued abrasive action, the scale is easily removed and the surface is exposed to further oxidation. A cyclic process of degradation sets in and continues. A Corps of Engineers' study (*50*) concluded that bituminous coatings provide very little additional life for galvanized steel pipe and are probably not cost effective for water-side protection.

Another Corps of Engineers' study concluded that where galvanized CSP is not expected to attain a desired design life of 50 years, additional nonmetallic and metallic coatings under proper conditions may be successfully used to extend the desired service life (*41*). A summary of findings evaluates bituminous coating; bituminous coating and paving; aramid fiber-bonded coating (a replacement for asbestos-bonded coating); concrete lining; polymer coatings (polyvinyl chloride and ethylene acrylic acid); epoxy coating; and metallic coatings in addition to galvanized (aluminum-zinc, and aluminum-coated Type 2). The report illustrates the complexity of developing general rules that may apply universally to all applications; differences in evaluation of the benefits of specific liners exist in great part as a result of differences in service conditions of different regions.

ALCLAD ALUMINUM PIPE AND ALUMINUM STRUCTURAL PLATE

Corrosion

The corrosion resistance of aluminum pipe (corrugated and spiral rib) is enhanced by a very thin natural coating of aluminum oxide (5×10^{-6} mm) (1.97×10^{-7} in.) that securely adheres to the metal surface. Should a fresh surface be exposed by abrasion or cutting, a new film is quickly created in the presence of air or water. Corrugated aluminum pipes and spiral rib pipes are of clad aluminum material; thicker structural plate materials are not clad. With some exceptions, the protective oxide film that forms is soluble in alkaline solutions and in strong acids and is stable in the middle range of $4 < pH < 9$ (*51*).

An unattractive appearance as a result of shallow pitting of the surface and dirt retention is not necessarily associated with a durability problem. Resistance to pitting is high with soft drainage water. The likelihood of pitting increases with water carrying ions of copper, bicarbonate, chloride, sulfate and oxygen. Colorado and Wyoming limit the use of aluminum pipe to locations where the amounts of soluble salts in soil and water are within the prescribed limits of each state.

A more serious mode of degradation is stress corrosion cracking, which is time dependent and occurs under the combined influence of tensile stress and a corrosive environment. Another form of corrosion is a result of stray electrical currents and galvanic couples. Heavy metal ions (copper and iron are two such common ions) in the backfill material increase the possibility of electrochemical corrosion.

To limit the damage resulting from such corrosion, ALCLAD aluminum pipe, which consists of a metallurgically bonded protective layer of an alloy that is anodic to the aluminum alloy core and corrodes preferentially, is employed (*52,53*). Perforation through the metal thickness is inhibited by the cathodic protection provided by the cladding, whereby corrosion progresses to the core/cladding interface and then spreads laterally. Aluminum-magnesium-manganese alloy 3004 is sand-wiched between aluminum zinc alloy 7072 during the rolling operation, with each outer cladding layer constituting 5 percent of the final sheet thickness.

Abrasion

Although the very thin oxide layer of aluminum is highly resistant to removal and restores itself promptly, the softness of aluminum compared to the much greater hardness of aggregate bed loads usually carried in drainage pipes is predictive of abrasion dominating the durability characteristics of aluminum drainage pipe. The severity of abrasion relates to the cumulative kinetic energy of the bed load, which, in turn, relates to the mass of the "statistical" rock and the square of its average velocity (*54*). Laboratory tests by California show that cladding is sensitive to abrasion; field data also indicate that cladding is more rapidly abraded by bed loads containing shattered angular rocks (*55*). California restricts use of aluminum for culverts where abrasive conditions of flow are expected; Kansas does not. Hawaii requires a thickening of material under abrasive conditions to be determined by the project engineer. Minnesota requires a 10-gauge minimum thickness for difficult-to-replace, large structural plate and pipe arch culverts under major highways when the expected velocities are greater than 1.5 m/s (5 ft/sec). Idaho limits velocities to less than 2.1 m/s (7 ft/sec).

pH and Resistivity

Influence on Service Life

In applications where uncoated aluminum pipe is permitted, most states restrict the pH to a middle range (generally between 4 and 9) and set lower limits for resistivity. These limits may be as low as 500 Ω-cm for Wyoming (the low end of pH equal to 5) and Nevada, but more generally the lower limits are 1,000 Ω-cm as in the case of Idaho and Maine. California, Louisiana and Pennsylvania require a minimum resistivity of 1,500 Ω-cm. Mississippi requires resistivity greater than 10,000 Ω-cm for a 50-year design service life and greater than 1,500 for a 25-year design service life. Arizona sets limits for pH between 4 and 9 and the lower limit for resistivity at 500 Ω-cm, crediting 1.63 mm (0.06 in. - 16 gauge) material with a 50–year life, 62.5 years for 2.01 mm (0.075 in. - 14 gauge), and 87.5 years for 2.77 mm (0.10 in. - 12 gauge). Wyoming, a prairie state, also limits soluble sulfates to 0.125 percent.

Geographical Considerations

The following reports are cited to provide information on the importance of geographic location and the associated environmental features. A Florida study (*56*) of ALCLAD aluminum pipe reported total failure of coatings, with advanced pitting corrosion, in a coastal site where test conditions included the soil becoming saturated with chlorides as a result of tidal effects, $20 < R < 100$ Ω-cm and $6.5 < pH < 7.0$. In another site where $1,350 < R < 8100$ Ω-cm and $5.3 < pH < 9.3$, a similar pipe experienced only moderate oxidation and secondary coat deterioration. In two other sites, where the pHs indicated soil from slightly acid to moderately alkaline, and where the soil resistivities were very high, there was only slight oxidation associated with secondary coat deterioration. A second Florida study (*57*) of aluminum pipe reports that low resistivity, when coupled with high pH, resulted in no significant reduction of corrosion performance; low resistivity, when coupled with low pH, tended to increase the average metal loss. When compared with galvanized steel pipe, a third Florida study (*39*) of the influence of corrosion only ($4.8 < pH < 7.0$ and $14.5 < R < 1,350$) reports details of the superior performance of aluminum clad pipe. A Utah study (*58*) confirms the importance of the chemistry of the soil with respect to the corrosion performance of aluminum pipe. Where soluble salts approach 10 percent, aluminum was shown to perform better than concrete or steel pipe. Colorado permits the use of CAP for a corrosion rating between 1 and 4; that is, no more than moderately corrosive conditions.

In a New York study (*47*) where the chemistry of the soil was identified in only rough qualitative fashion, from least aggressive to most aggressive, metal loss measured from core samples taken along the inverts of the state's uncoated metal culverts led to the conclusion that thickness of aluminum culverts is governed by the culverts' structural requirements and that no special durability considerations are required. A 1981 Washington state study (*59*) reports aluminum alloy culverts have provided highly satisfactory service performance. This same study reports that aluminized steel offers a significantly extended service life over plain galvanized steel culverts. For the aluminum alloy culverts, environmental conditions ranged from free-flowing clean water and granular material to stagnant water with high organic content and bedding in heavy clays. Soil-side and water-side resistivity was greater than 2,000 Ω-cm, $6.1 < pH < 7.7$.

Kansas, which has to deal with high concentrations of agricultural fertilizer nitrates in soil and storm water effluent, does not allow any CMP under highways in the eastern two-thirds of the state. In the western third, aluminum or galvanized steel CMP may be used for any application.

The states responding to this synthesis report are not in agreement as to the benefits of coating aluminum pipe, usually with a bituminous liner. For many states, it is the class of highway to be drained, or the drainage application that sets the conditions for use of aluminum pipe. Kansas requires coating of aluminum pipe for cross road and all primary road drains. Louisiana does not allow uncoated aluminum for any application; Ohio prohibits its use only where abrasive conditions are present. Vermont requires all primary road drains to be coated. On the other hand, Hawaii does not use coated aluminum pipe because of experience with peeling problems after heavy rains. Nevada also does not permit coated aluminum pipe. Arizona requires bituminous coating and adds 20 years to the design service life. If the design service life is greater than 20 years, Idaho equates a bituminous coat with one-gauge thickness and permits soil and water $4 < pH < 9$, more liberal than $5 < pH < 9$ for uncoated aluminum pipe.

To improve performance when under heavy bed loads that may be expected to travel at high velocities, many states often employ paved inverts. Iowa does not permit aluminum pipes greater than 15 in. in diameter under state highway pavements and cross drains no matter what the treatment. Utah does not permit use of paved inverts, but permits use of uncoated, unpaved aluminum pipe in highly reactive and corrosive saline soils.

PLASTIC

Resistance to Corrosion

Plastic pipes are highly resistant to pH and to chemically and electrochemically induced corrosion. In general, states that reported having used plastic resins as alternative materials for drainage pipes noted pipes of these materials are highly resistant to the various corrosive agents, sulfates, chlorides and other aggressive salts found in soil and highway drainage effluents. Where the potential for pH extremes, aggressive salts and other chemical or electrochemical corrosion dominates the anticipated performance of a drainage pipe, plastic pipes offer distinct advantage because, unlike metals, plastics are nonconductors, and therefore, not subject to galvanic corrosion. The Federal Lands Highway Division of FHWA policy requires all permanent drainage pipe installations be designed for a minimum of 50 years maintenance-free service life, temporary installations excepted. With regard to corrosion, the policy states that plastic alternatives may be specified without regard to resistivity and pH of the site (*4*).

Plastic materials used for pipes are classed under thermosetting or thermoplastic resins. Plastic highway drainage pipes belong almost entirely to the thermoplastic group (most commonly, high-density polyethylene (HDPE), PVC, and ABS). Thermoplastic resins are highly resistant to various corrosive agents, sulfates, chlorides and other aggressive salts found in soil and highway drainage effluents. For storm drainage applications, more than 40 states permit use of HDPE and more than 30 states permit use of PVC. Utah permits HDPE for highly reactive and highly corrosive soils. Ohio, California and Pennsylvania have no pH or resistivity restrictions on use of HDPE or PVC pipe.

Oregon permits use of HDPE for storm sewers under state roadway pavements (with a 75-year design service life) and culverts under freeways (with a 50-year design service life), constrained by soil and water characteristics of resistivity > 1,500 Ω-cm and $4.5 < pH < 10$. On a cautionary note, accidental highway spillage may be the source of chemical problems. The unlikely event of high and sustained concentrations of some organic based chemicals, such as crude oils and their derivatives or concentrated acids and bases, may cause swelling and softening of thermoplastics, notably ABS. At stress risers and other high-tensile stress within the pipe wall, stress crack initiation and subsequent propagation may result. ABS pipes are more sensitive to aggressive solvent chemicals, such as gasoline or kerosene, than PVC or HDPE. Thermoplastic pipe is often favored for transporting slurries containing highly abrasive mine tailings.

Resistance to Abrasion

Generally, plastic 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. The FLH design guide, previously noted, permits HDPE and PVC for nonabrasive and low abrasive conditions but requires invert protection for moderate and severe abrasive conditions. Except for plastic pipes, the state of Washington, on the other hand, requires invert protection for pipes subject to significant abrasive conditions. California has restrictions for abrasive conditions for all pipes except HDPE and PVC. Ohio has restrictions for abrasive conditions for only corrugated metal pipe; use of aluminum pipe is restricted to nonabrasive conditions only.

Other Durability Aspects

With the use of fine carbon black, HDPE pipe is often protected against prolonged exposure to sunlight and the potential for ultraviolet (UV) degradation of mechanical properties. Titaniem diozide is a UV light absorber often added to PVC pipe material. It has been claimed, but with contradictory evidence, that a sometimes faded or chalk like surface appearance, because of prolonged UV exposure, is evidence of degradation of the mechanical properties of PVC pipe. For PVC pipe material 1120, a Battelle study showed that with UV exposure, the tensile strength increases and elongation to break and impact resistance, a measure of brittleness, decreases (*60*). Antioxidants are added to protect PVC during the high temperatures that attend the manufacture of pipe (> 400°F). Another study showed that photo reactions degrade the surface and properties that are notch sensitive (such as elongation) but not bulk properties (such as tensile strength) (*61*). It is considered prudent, by some, to protect exposed (to sunlight) ends of installed plastic pipe. Once buried, except for exposed ends, exposure of plastic pipe to sunlight is a nonissue. Outdoor storage practices are managed by the manufacturers and are not subject to industry or other standards.

Plastic resins used in pipe are not of food value to rodents, fungi or microorganisms and are considered resistant to such deterioration. Very thin-walled, corrugated tubing of plastic material may be gnawed by rodents for purposes of creating passage, but this is not a significant problem.

Because plastic is flammable, plastic pipe should be protected from exposure to grass and other fire-prone areas at locations of possible exposure, such as drainage inlets and outlets. PVC pipe will not continue to burn in the absence of a continuing source of heat. Flame-retardant stabilizers are available to protect HDPE pipe in case of contact with open flame. Colorado has experienced two cases of damage to HDPE pipes resulting from weed fires. In California, the uncontrolled 1993

Malibu fires destroyed unprotected HDPE. The Florida DOT concludes that when exposed to grass fires, HDPE is not at significant risk. The Ohio DOT, having used polyethylene pipe as cross drains (with exposed ends) under roadways since 1982, has no recorded incidents of fire and concludes that the overall risk of fire with polyethylene pipe is minimal. Washington has no record of fire related failures and takes the position that the (consideration of) risks associated with the flammability issue are essentially unjustified. Some states require noncombustible exposed ends of plastic pipe. New York reports that HDPE and PVC present no significant risk of damage by fire. This latter stance is consistent with a Battelle study (*60*) wherein it is stated that the flammability of plastic pipe is a nonissue. The National Fire Protection Association (NFPA 704) rates polyethylene with a 1 (slow burning) in a scale from 0 to 4 with higher ratings indicating increasing vulnerability. This same study makes the point that polyethylene piping, in sizes up to and including 457 mm (18 in.) diameter has been used for 30 years in the natural gas industry without reported problems.

Use of Thermoplastic Pipe

Thermoplastic pipes have been used for highway drainage since the early 1970s. In the intervening years, an increasing number of states have adopted thermoplastic pipes for application to highway drainage. More states permit the use of HDPE than of PVC. If that decision is based on the mechanical or chemical properties of the pipe, the reason is not clear. In part, it is likely that historical precedents come into play; PVC pipes were first used more commonly for sanitary sewers before their application in storm sewers and highway drainage facilities. HDPE grew out of application for agricultural drainage before its application for highway drainage purposes.

HDPE- and PVC-specific applications vary from state to state. Where included as alternative choices, they are being used for storm sewers, perforated underdrains, storm drains, slope drains, cross drains and culverts. All states, with the exception of North Dakota, permit use of thermoplastic pipes for highway drainage applications. Three states (Connecticut, New Hampshire and Rhode Island) permit use of thermoplastic pipes for edge drains only. One-half of the responding states, FHWA, FAA, and the Corps of Engineers permit thermoplastic pipes for cross drains.

Thermoplastics are viscoelastic materials; that is, their mechanical properties are time dependent and include strain and creep under a sustained load, or stress and load relaxation under a sustained deflection. The current practice is to prescribe a long-term effective modulus of elasticity that is lower than the short-term modulus. The design procedure for buckling of the pipe wall, incorporated in Section 18 of AASHTO (*62*), follows this pattern.

Because thermoplastics are resistant to the usual corrosive chemicals and abrasive bed loads in highway drainage effluents, the mechanical properties such as the effective modulus of elasticity may dominate service life expectations. This time-dependent modulus, more properly called a modulus of relaxation, is often obtained experimentally by dividing the residual load in a pipe by the constant deflection of the pipe after time has elapsed during the course of an ASTM quality assurance test (*63*). By this method, the longer the test duration, the more the load dissipates, the less the residual load in the pipe and the lower the force required to maintain the constant displacement. Larger pipes take longer to achieve the prescribed test deflection (5 percent of the vertical diameter) at the prescribed rate of loading 12.7 mm/min (0.5 in./min) and therefore, proportionately, more load has been dissipated in large pipes than in small ones. A consistent measure of effective modulus of elasticity, i.e., a material stiffness not influenced by size of pipe and consistent with principles of structural mechanics, and useful in predicting deformations of thermoplastic pipes in service, is corrupted by test time dependency.

Mechanical Properties

Stiffness is defined as the measure of force that is a consequence of an impressed unit of deformation. At any point in time during its service life, including the end point, an effective pipe stiffness may be obtained by introducing the required unit of displacement and measuring the load necessary to cause such displacement; the short-term stiffness is essentially the same at all times. Experience with thermoplastic materials confirms that long-term stiffness, a parameter derived from applying an elastic formula to a viscoelastic event, does not predict deformations of thermoplastic pipe at any period in time. A study conducted by the Corps of Engineers notes that the use of creep modulus in place of elastic modulus results in an increase of factor of safety.

In the 1950s, glass-reinforced thermosetting polyester and epoxy resins were introduced for production of pipes primarily intended for sanitary sewer applications. The pipe was manufactured by laying up, against the outer surface of a rotating mandrel, layers of sand-filled resin and filaments of glass reinforcement. Additional resin coating was applied to the pipe's inner surface to restrict penetration of effluent acid or water into the pipe walls. Many failures occurred, usually after a few years of service, because of hydrogen ion (present in acids and water) penetration and corrosion of the glass at the glass/resin interface. This resulted in debonding of the glass reinforcement from the resin matrix. Once started, wicking along the glass/resin interface resulted in accelerated failure. As a result, this type of glass fiber-reinforced resin pipe was removed from market and production ceased.

Whereas the thermosetting resins used in the manufacture of this type of pipe are highly resistant to attack by chemicals normally found in highway drainage effluent, the glass fiber reinforcement is not. Because corrosive hydrogen ions are available in drainage water and in groundwater, service life projections should be carefully scrutinized. A more recent process for the manufacture of glass-reinforced resin pipe was developed in Europe in the 1960s and is currently marketed, primarily for sanitary sewer applications, in the United States in sizes from 304.8 mm (12 in.) to 2,590.8 mm (102 in.) diameter (1963 data). In this proprietary process, pipes are produced by centrifugal casting of polyester resin, short, randomly oriented glass fibers and sand against the inner surface of a rotating mold. This pipe has been used for under- and above-ground installations, jacking and tunneling, and slip lining of existing pipe as a rehabilitation strategy. Included in the recommendations for couplings is use of standard ductile iron fittings, in the range of 457.2 mm (18 in.) to 1,371.6 mm (54 in.), with further recommendation that corrosion protection of these metal parts be provided.

The standard pipe uses polyester resin and the manufacturer reports good abrasion and corrosion resistance. The vinyl polyester resin has a greater corrosion resistance than the standard polyester resin. Although the pipe itself is generally resistant to corrosion, some gaskets used in the couplers are sensitive to hydrocarbons and many chlorinated and aromatic solvents.

Fiberglass-reinforced thermosetting epoxy and polyester resin highway drainage pipes are not generally included on the lists of acceptable alternatives by state highway departments. Oklahoma permits use of these pipes for chemically contaminated drainage. Worldwide developments in the manufacture and application of fiberglass-reinforced thermosetting resin pipes suggest that more interest in the use of this pipe for highway drainage purposes is likely to occur in the future. A useful design manual is available for the design of fiberglass-reinforced (thermosetting) resin pipes (*64*).

DUCTILE IRON PIPE

In 1948, ductile or nodular iron pipe was used as an alternative to gray cast iron pipe. Ductile iron has chemical properties similar to gray iron and mechanical properties similar to those of steel. Both gray and ductile iron contain carbon, approximately 3.5 percent by weight. In gray iron, the carbon is in the form of flakes; in ductile iron, the carbon is in the form of discrete spheroids or nodules. The flakes in gray iron give rise to planes of weakness, a phenomenon absent in ductile iron.

In the early 1950s, several studies showed that ductile iron pipe had as good as if not better corrosion resistance than the older, more established gray iron pipe. Ductile iron pipe is not generally used by the 50 states for drainage but for sewer and water applications that have high-pressure heads, submerged outfalls and gravity sewers where tight joints are required. As a result of these applications, literature on corrosion of this pipe is geared toward the soil and not the water in the pipeline. Cast iron pipe is specified by pipe diameter, thickness, strength (class), method of jointing, type of interior and exterior linings. This type of pipe has a variety of joint connections. In addition to the standard bell and spigot, there are other connections that are mechanically coupled, such as rubber push-on and ball and socket. Ductile iron pipe uses cast iron fittings; most of the same connections are available for both pipe types.

Ductile iron pipes joined at their ends often include rubber gaskets that serve to electrically isolate one section from another. Electrical discontinuity reduces the likelihood of stray current accumulation and long-line corrosion cells. Therefore, joint bonding is discouraged except in cases where cathodic protection requires electrical continuity (*65*).

Corrosion

Iron pipe, whether cast or ductile, has most of the same characteristics of other metal pipes. Galvanic corrosion often limits correct calculation of the desired service life. Any dissimilar metal nearby or in connection with iron pipe is anodic and likely to start a flow of current away from the iron pipe. Also, electrolytic corrosion or stray direct current from any source will promote corrosion of iron pipe more severely than galvanic corrosion. Common sources of stray direct current are industrial grounding (i.e., welding and heavy equipment); cathodic protection of a nearby pipe line (most oil and gas companies commonly cathodically protect their pipe lines); and current for electric vehicles (i.e., light rail commuter trains). A solution to the stray current problem is insulation. In California, the San Diego Utilities Department uses a polyethylene jacket where the resistivity is below 1,500 Ω-cm, where the pH is lower than 6.5 or where the concentration of sulfates in the soil is greater than 250 ppm.

Another form of corrosion is graphitic corrosion, or graphitization, a result of electrochemical action between the ferritic and graphitic constituents in the cast iron (*66*). Symptoms of graphitic corrosion or graphitization are a dull, black look to the pipe and the lack of a metallic ring when struck by another metallic object. The corrosion products of graphitization adhere to the unattacked substrate and assist in protecting against other forms of corrosion (*67*).

Typical methods for protecting iron pipe are bonded coatings, cathodic protection and polyethylene encasement. Of these methods, the Ductile Iron Pipe Research Association reports that unbonded polyethylene film encasement, which reduces the effectiveness of the electrolyte to support corrosion, is by far the best and most economical for cases of corrosive soils (*68*). The polyethylene is loosely wrapped around the pipe during installation. Eight mils is usually enough thickness and there are guidelines of the area of polyethylene need based on pipe diameter. Groundwater may still find its way through the loose wrap, but since the amount of oxygen is limited, so is the extent of the corrosion.

All corrosion protection methods for ductile iron pipe have disadvantages. Bonded coatings such as coal tar are expensive and may be damaged by handling, during shipping or when installing. With respect to the use of a polyethylene sleeve, usual construction procedures may compromise the integrity of the intended protection.

CLAY PIPE

Vitrified clay pipe is a well-established pipe and has been used for more than 100 years. Although improvements have been made in the manufacture of the pipe, the material properties of fired clay are essentially unchanged. Clay pipe is available in a variety of sizes starting at 3-in. diameter up to 1,067 mm (42 in.) in diameter. Because of its excellent resistance to acid attack, clay pipe is often selected for sanitary sewer applications. More than a dozen states use clay pipe for some type of highway drainage facilities. Maine and North Carolina permit use of clay pipe for culverts.

In the manufacture of clay pipe, clays and shales are mined, shaped and then fired in kilns that reach temperatures as high as 1100°C (2,000°F). The product is a vitrified dense, hard and nearly homogeneous material that is highly stable, very resistant to abrasion (*69*) and capable of resisting the corrosion effects of most acids, including hydrochloric and sulfuric acids. The usual parameters of concern for corrosion (i.e., resistivity, pH, chlorides and sulfides) do not apply to this pipe, but Nevada and Wyoming put limits on clay pipe for resistivity, pH and sulfite concentration. Clay pipe is vulnerable to corrosive attack by high temperatures; these are not common environments for concern in hydrofluoric acid and concentrated caustics at highway drainage. The National Clay Pipe Institute recommends that clay pipe not be used where hydrofluoric or caustics are likely to be present.

The National Clay Pipe Institute claims a useful service life of vitrified clay pipe of 150 years. A Corps of Engineers study recommends the design service life of vitrified clay pipe be limited to 100 years (*28*). Some states, such as Mississippi, assume clay pipe will last the life of the facility.

CHAPTER FOUR

PIPE PROTECTIVE MEASURES

COATINGS, LININGS AND PAVINGS

Coatings, linings and pavings have been discussed, in part, in earlier chapters. In this chapter, specifics of using protective measures are discussed and evaluated in greater detail.

Metallic coatings or claddings such as zinc, aluminum, aluminum-zinc alloy; coatings or linings of asphalt, asphalt with asbestos bonding (no longer marketed), asphalt with aramid-fiber bonding; and polymer coatings or linings such as thermosetting epoxy have been developed to protect metal pipe from potentially damaging corrosive and/or abrasive environmental conditions that are likely to be experienced by a drainage pipe or culvert in service. Pavings of asphalt or concrete, with or without coatings or linings, protect against bed loads likely to cause moderate to severe abrasion.

The noted coatings, claddings and linings are designed, in part, to inhibit the process of electrochemical corrosion that will degrade metal pipes or metal reinforcement within concrete pipes. Electrochemical corrosion, and details pertaining to subsurface metallic pipes, were discussed in chapter 2. Following is a continuing discussion of cathodic protection, a manner of protecting metals from degradation by compromising the efficiency of the electrical circuit.

Nonconducting Barriers

When current flows through an electrical conductor, electrons move from atom to atom along a path confined by the conductor. The driving force, or voltage, a consequence of an electrical potential difference, directionally propels these electrons for purposes of maintaining a dynamic equilibrium within the electrical circuit. In this process, electrons are exchanged, atoms remain unaffected and the metal electrical conductor is not damaged. A metal pipe is such a conductor.

When electrons must leave the metal pipe at one point to complete the circuit of flow and to return at another point after traveling through an electrolyte of moist soil or water, whole atoms or groups of atoms called ions, rather than just electrons, are released to make the journey. The point at which the atoms leave is the point of corrosion and is called the anode; the point where atoms are deposited on the pipe is called the cathode (Figure 1). The anode and cathode of the circuit, called a corrosion cell, may be close together or miles apart. The rate of corrosion is proportional to the number of ions (the electrical current measured in amperes) traveling through the soil electrolyte.

The opportunity to intervene protectively comes directly from the opportunity to interfere with the natural flow of ions from anode to cathode. If the circuit were broken, the corrosion cell would cease to exist. Increasing the resistance to ionic flow by shielding the metal with asphalt, concrete, polymers or other electrical insulating barriers is one manner of protection. Difficulties arise where breaks occur in protective barriers. Among other reasons, breaks may occur because of brittle cracking consequences of thixotropic aging, barrier penetration resulting from pipe handling difficulties, and/or joining difficulties at couplings and fittings. Separation of the barrier and metal pipe often occurs because of bonding problems. At times, bonding failures arise because of the different mechanical properties of the bonding material and the pipe when each is required to respond to similar deformations at the interface where they meet. The opportunity for wicking action at the lead end of a broken bond further exacerbates the difficulty. Whatever the nature of penetration, location of the flow of ions leaving the current conducting pipe becomes concentrated at some point, thereby accelerating metal loss (corrosion) at that point.

Passive Insulating Films

Another type of protective intervention into the corrosion cell is to provide, or develop, an insulating film at the metal surface that is chemically passive when in the environment of the electrolyte; this will inhibit the flow of electrical current. An aluminum oxide film on an aluminum pipe, a consequence of the anodizing process, is such a film. Coating an iron or steel pipe with portland cement concrete or mortar establishes a highly alkaline environment that passively protects iron. The more impermeable the portland cement coat, the more effective the protection.

The chemistry of the electrolyte is very important as is illustrated by the case of stainless steel. When in the presence of chloride ions and water, stainless steel is no longer "stainless." The passive invisible oxide film is compromised and corrosion cells are established.

A more aggressive way of inhibiting the destructive consequences of corrosion cells is to inhibit their efficiencies by reducing potential differences between the attracting cathodes and the feeding anodes. This form of cathodic protection may be accomplished by introducing a more favorable source of ions and substituting sacrificial anodes to satisfy the "appetites" of hungry cathodes. These added anodes may be of similar metal through which direct current is impressed. They may also be of dissimilar metals that are naturally anodic to the metal intended to be protected. This latter method is called galvanic protection. In either case, protection is afforded when the cathode preferentially attracts ions of the substitute anode. Because of the sacrificial nature of this form of cathodic protection, it must be expected that the auxiliary anodes will eventually be consumed and will have to be replaced.

Rather than act as a passive barrier to the flow of current, metal coatings, such as zinc or aluminum on steel pipe, are similarly anodic to the base metal and are similarly sacrificial. Resistivity of the electrolyte and porosity of the coating are two important determinants of service life. Once the sacrificial metal coat is consumed at any location, the bare base metal becomes vulnerable to corrosion. This will take place when the area of exposed metal is large enough to render the protection, from nearby unconsumed coating, ineffective. Increasing the coating thickness increases protection by supplying a greater amount of sacrificial material and by decreasing porosity. Since both zinc and aluminum are softer than steel, abrading bed loads will erode the protection of such coatings. Current needed to protect a pipeline is proportional to the area of exposed metal in contact with the electrolyte. A coating will also enhance the efficiency of cathodic protection using sacrificial anodes.

Galvanizing steel consists of the metallurgical bonding of a thin layer of zinc to steel by a hot-dipping process. Between this zinc layer and the steel, a pitting-resistant intermediate insulating layer of zinc-iron alloy is formed. The protection afforded is proportional to the thickness of the zinc layer. Most pipe specifications require a two-ounce zinc coating, i.e., 610 g/m^2 (2 oz/ft^2), which consists of a zinc deposit averaging not less than 305 g/m^2 (1 oz/ft^2) on each side of the steel sheet. Heavier coatings, such as 915 g/m^2 (3 oz/ft^2), are specified for structural plate pipe but do not appear practical under present manufacturing methods for conventional galvanized pipe. A study conducted at the U.S. Army Engineer Waterways Experiment Station (*41*) revealed that with additional coatings, linings and/or pavings the service life of galvanized steel pipe for surface storm drainage can be extended to 50 years when used under proper conditions. The coatings, linings and/or pavings studied were bituminous coated and paved, polymer coated (ethylene acrylic acid film) and concrete lined.

Aluminum alloy is often used as a protective coat for corrugated steel pipe. The steel is dipped into molten aluminum and a metallurgical bond secures the aluminum to the base metal. A hard intermediate layer of aluminum-iron alloy forms between the soft aluminum layer and the base steel. The exposed surface of the aluminum coat will oxidize and protect against corrosion. This film forms in hard and soft water and resists corrosive attack by sulfates, nitrates, carbon dioxide, oxygen, organic acids and turbulent water. If damaged or removed by abrasive or chemical action, the alloy reforms immediately after these offending influences are gone (*70*). The intermediate layer will add some corrosion protection and better resistance to abrasion than the soft, unalloyed aluminum. The end product, aluminized steel Type II, has a protective coating with the passive attributes of exposed aluminum. It is usual for the aluminum coat to be 305 g/m^2 (1 oz/ft^2) on each side of the steel sheet.

Aluminum coating and zinc coating of galvanized steel perform differently in protecting against corrosion. Zinc coats perform sacrificially (galvanically); aluminum coats serve as a barrier. Soft, high-resistivity water that contains significant free CO_2 and has little natural protective mineral scaling properties, produces a weak carbonic acid that limits the service life of galvanized pipe. The passive oxide film protection of aluminum coating is highly resistant to this aggressive environment (*71*). It is often the case that where states permit use of one coating, they also permit use of the other.

In one study, the U.S. Army Engineer Waterways Experiment Station (*41*) reports that, for storm drainage systems carrying only naturally occurring surface water, with soil and water $5 < pH < 9$, and with minimum soil resistivity no less than 1,500 Ω-cm, aluminum-coated (Type 2) CSP should provide twice the service life of galvanized CSP. These same values of pH and resistivity apply slightly more liberally to the Federal Lands Highways Division of FHWA criteria wherein low abrasive conditions of service are permitted. In a second study by U.S. Army Waterways Experiment Station using a limited data set (14 sites) with "young" (in service for 7 years) culverts, aluminum-coated pipe performed an average of more than six times better than the California method predicts for plain galvanized CSP (*50*).

A manufacturer's study of field installations of culvert pipes in service over 30 years found that aluminized steel Type 2 performed well in the same pH and resistivity ranges noted immediately above, except where abrasion or poor coating quality affected the ratings (*72*). A Florida DOT corrosion-only study reports that aluminized steel performed better than galvanized steel by a factor of 2.9 (*39*). A Washington DOT field study (*59*) of aluminized steel pipe in three different locations included the following conditions: 900 < Field resistivity < μΩ-cm, $4.8 < pH_{soil} < 6.5$, $5.6 < pH_{water} < 7.1$; flat gradients with little or no bed load in two of the locations - neither was specified in the third location. The study reported that aluminized steel culverts, installed between 1953 and 1966, offer an extended (though unspecified) service life over plain galvanized culverts A $5 < pH < 8.5$ and soil resistivity > 100 Ω-cm was recommended for aluminized steel culverts. A New York study showed that Aluminized Type 2 coated CSP gives greater resistance to abrasion than galvanized coating (*73*).

Galvalume is a coating alloy composed by weight of aluminum (55 percent), zinc (36.4 percent), silicon (1.6 percent), and other minerals (7 percent). The steel is coated by a hot-dipped process. During the cooling process, an aluminum-rich (up to 80 percent) dendritic area forms first, followed by zinc-rich (up to 95 percent) areas that form between the aluminum dendrites (*74*). Corrosion will begin in the zinc-rich areas and conclude with depletion of the zinc. Corrosion of the aluminum-rich areas follows with the formation of a protective coating with the passive attributes of exposed aluminum. An Indiana study found that when $4.0 < pH < 5.0$, galvalume-coated pipe performed better than aluminum-coated pipe but not as well as galvanized pipe. Recommendations resulting from this study include galva-lume-coated pipe should not be used in areas where $pH < 5.5$, and aluminum-coated pipe should not be used where $pH < 5.0$.

The Indiana study (*74*) also found that aramid fiber-bonded bituminous-coated pipe is more durable than the formerly used asbestos fiber-bonded metallic-coated pipe in highly acidic conditions. As a consequence, Indiana now includes aramid fiber-bonded pipe in its specifications.

An Oklahoma evaluation study (*75*) of polymer-coated and asphalt-paved corrugated galvanized steel culverts found that after 16 years of acid effluent and soil embedment, and exposure to abrasive bed loads, such coatings and pavings were required for the culverts to reach their 50-year design service life. Polymer coating on the inside acted as a protective layer and reduced degradation resulting from abrasive bed loads; on the outside, the coating protected against attack from acid soil conditions.

On Federal Lands Highway projects, the following values are assigned as additional design service life (to that obtained from FLH's chart of the Modified California Method (*76*)) for the specified nonmetallic coatings on steel pipe (*4,77*):

1. Bituminous coated (AASHTO M 190) additional 10 years to water side and 25 years to soil side.
2. Bituminous coated and paved invert (AASHTO M 190) additional 25 years to water side.
3. Concrete lined (ASTM A 849) additional 25 years. Because of the cracking potential of concrete, it is required that this liner be used with an asphalt coat if corrosion protection is needed.
4. Polymer coated (Ethylene Acrylic Acid Film) (AASHTO M 245) additional 30 years with a minimum of 0.25-mm (0.01-in.) thickness.
5. Because of limited data, aramid-bonded and epoxy-coated steel pipes with nonmetallic coatings are not credited by FLH with additional design service life.
6. As previously noted, for low abrasive conditions, with 5 < pH < 9 and resistivity > 1,500 Ω-cm, aluminum-coated Type 2 steel pipe may be assumed to have a design service life up to twice that of galvanized steel pipe (each as determined by FLH's Modified California Method).
7. For moderately and severely abrasive conditions, FLH permits steel pipe only if the selected metal thickness will be predictive of a 50-year life. In these cases, no increase in design service life beyond 50 years is permitted. For moderately abrasive conditions, should the required thickness be less than 4.27 mm (0.17 in., 8 gauge), an increase of one standard thickness or the addition of invert protection is required. Both are required for severely abrasive conditions.

Where the cost of drainage pipe replacement is high, such as in long lines under city streets and pipes crossing primary highways under high fills and/or where traffic is not easily diverted, design for "permanence," with acceptable levels of maintenance, should be considered. In a privately sponsored California study (*78*) of spiral rib pipe, the above criteria were considered. Table 5 lists the recommended levels of soil-side protection deemed appropriate for galvanized steel in soils ranging from normally benign to extremely corrosive, assuming the pipeline or culvert is electrically isolated from foreign metallic structures. Such isolation is an important first protective step. The recommendations noted as optional are biased toward higher first cost and lower maintenance costs. Only soil with 5 < pH < 9 is considered. The above compares with

TABLE 5

GALVANIZED STEEL-PIPE RESISTIVITY AND PROTECTIVE TREATMENTS

Category	Resistivity (ohm-cm)	Protective Treatment
Normally benign	R > 10,000	Bare galvanized steel
Optional-coating		
Mildly corrosive	10,000 > R > 5,000	Coating Opional–anodes
Moderately corrosive	5,000 > R > 1,000	Coating plus anodes
Extremely corrosive	1,000 > R	Special design

TABLE 6

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

TABLE 7

RESITIVITIES OF SOIL AND WATER

	Classification	Resistivity (ohm-cm)
Water	Surface water	R > 5,000
	Brackish water	R = 2,000
	Seawater	R = 25
Soil	Rock	R > 50,000
	Sand	50,000 > R > 30,000
	Gravel	30,000 > R > 10,000
	Loam	10,000 > R > 2,000
	Clay	2,000 > R > 750

information on the correspondence of soil corrosiveness (of unspecified pH) and soil resistivity provided by the National Corrugated Steel Pipe Association (NCSPA) (*79*) as noted in Table 6.

In Table 7, typical resistivity values of water and soil judged appropriate by the NCSPA are listed.

The following paragraphs offer a sampling of the strategies of some regionally representative states.

For either zinc or aluminum coating, Idaho has the same pH requirements but permits resistivities as low as R > 1,000. Georgia permits both types of coating for side drains (not permitted for cross drains) provided 6 < pH < 10 and R > 4,000 Ω-cm for galvanized CSP, and 5 < pH < 9 and R = 1,500 for aluminized CSP. Iowa does not permit either type of coating for cross drains under pavements for state highways or for any drainage application in highly acidic soils. Louisiana does not permit zinc-coated CSP without additional coating, and does not allow aluminum-coated CSP at all. Although not disallowed, and except for subdrains, Massachusetts does not use either metallic coating near the ocean unless protected with an additional coating.

Minnesota requires that large CSP structural plate and pipe arch culverts, with either metallic coating, and draining important highways at velocities greater than 1.5 m/s (5 ft/sec), have a minimum metal thickness of 3.5 mm (0.13 in., 10 gauge). For storm sewers 304.8 mm (12 in.) and greater, zinc-coated pipe is not permitted. Aluminum-coated steel pipe is not preferred, and although Minnesota's specification permits its use with a bituminous paved invert, it is not used. Missouri permits use of each coating for cross drains only when the roadway above the pipe is paved with concrete. Neither zinc nor aluminum-coated CSP is permitted for storm sewers under pavements; beyond pavements they are permitted. Mississippi does not allow zinc-coated steel pipe in marshy areas where standing water is a common occurrence. Where abrasive conditions are expected, Ohio generally does not permit use of aluminum-coated steel pipe without invert paving.

Oregon permits both coatings for culverts, storm sewers and under drains, but requires additional asphalt coating if the resistivity < 1,500 Ω-cm, the pH < 4.5, or both. With soil resistivity > 1,500 Ω-cm and pH > 4.5, Oregon will add 10 years to the expected design service life of an asphalt-coated pipe; for more severe conditions, an increase in gauge thickness plus an asphalt coat is required and no credit is taken for the expected design service life. For hostile abrasive conditions, such as high velocities and/or heavy bed loads, Oregon requires the addition of a paved invert, again without any credit taken for extension of service life.

Pennsylvania allows either metallic coating if the water and soil are 5.5 < pH < 8.5 and the soil is R > 6,000 Ω-cm. With a 2.77-mm (0.10-in.) polycoat, for zinc-coated CSP, the permissible pH and resistivity may drop to 4 < pH < 5.5 and 2,000 < R < 6000 Ω-cm; with a 3.5-mm (0.13-in.) polycoat, pH < 4 and R < 2,000 Ω-cm respectively. South Dakota limits use of CSP with metallic coatings to less than moderately corrosive soils. Such pipes are prohibited for cross drains under major state highways for moderately corrosive and severely corrosive soils. Washington prohibits use of either coating in certain corrosive regions. Wisconsin permits use of both for cross drains if the average daily traffic is less than 7,000 vehicles, but does not permit the use of zinc-coated pipe in corrosive conditions.

CHAPTER FIVE

INSPECTION, MAINTENANCE AND RESTORATION

One constraint in the selection of a drainage system is the desired service life specified by the agency of jurisdiction. As with all engineering designs, the risk of failure—in this case, the risk of the useful service life plus maintenance not meeting the longevity requirements of the desired service life—must be anticipated in advance. Success in achieving the desired service life is most often realized with frequent and periodic inspections by well-trained personnel. Too often inspection and maintenance schedules for pipelines and culverts are either poorly defined or deferred. Well-defined and efficiently executed maintenance is key to achieving the anticipated longevity of a drainage system but is often compromised. California's Legislative Analyst reports a continually widening gap between infrastructure maintenance needs and maintenance spending (*80*).

The FHWA defines a bridge as follows: "... a structure ... over a depression or an obstruction, such as ... highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 6096 mm (20 ft.) between abutments, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening." Accordingly, large culverts of the size noted are classified as bridges and must be inspected frequently and their condition rated as required in the 1988 FHWA guidelines (*81, 82*).

INSPECTION STRATEGIES

Inspection strategies vary widely. In California, culverts spanning more than 6.1 m (20 ft) are under the jurisdiction of bridge maintenance and repair. Culverts spanning less than 6.1 m (20 ft) are generally inspected less frequently than larger culverts. Hostile environments, such as will occur at locations of acid mine drainage, industrial and sanitary wastewater, swamp and brackish waters, seawater and possible stray direct currents from utilities, rail lines and cathodic protection systems, require more frequent inspection. Maine, New York and Mississippi are examples of states that have developed methods for evaluating pipe and culvert performance based on visual inspection findings. Although numerical measures of performance are recorded, the ratings are essentially qualitative. Utah goes a step further in that inspection also includes core samples of the culvert wall and soil samples. Maryland assigns ratings on the amount of bituminous coating loss.

With new culverts, FHWA (*83*) recommends inspections once a year for 2 years. For culverts with a history of significant problems, inspections are recommended annually, or every six months if required. For all other small culverts, inspections should be conducted periodically as determined by agency budget. FHWA rates the condition of in-service culverts on a scale from 0 (partial or complete failure) to 9 (near original condition). The Bureau of Reclamation has found it advantageous to inspect major pipelines at two-year intervals (*84*). The American Iron and Steel Institute (AISI) (*6*) recommends inspection on an annual or semiannual basis, but always following major storms.

In addition to observations made at and near the convenient exposed ends of pipelines and culverts, internal inspections should be made where safety, pipe size and flow conditions permit. Silt deposits, loosened coatings, scale and rust should be removed to permit examination of the particularly corrosion-abrasion susceptible invert. In some cases, temporary damming and diversion of flow upstream from the culvert may be required for inspection. Coring, nondestructive ultra-sound testing (as in some circumstances is practiced by New York), or excavation to expose the soil-pipe interface may be required. Such procedures may be necessary in highly acid, alkaline, sulfate or chloride soil.

REPAIR, REHABILITATION AND REPLACEMENT

For culverts of all sizes and pipelines, should damage or other degradation occur that is more serious than what might be managed by regularly scheduled maintenance, on-site repairs or more costly rehabilitation or replacement must be considered. Rehabilitation or replacement is justified when it is unsafe, or uneconomical, to maintain elements of the drainage system in service. Decisions related to the timing of intervention must be based on both the likelihood of continuing degradation (or failure) and consequences of such. Life-cycle economic analyses may be used to improve the efficiency of initial selection of pipelines of alternative materials in site-specific applications. The evaluation should include the likelihood of faulty installation. One example of such are those conditions that give rise to leaky joints, the consequences of which may lead to infiltration and problems of loss of soil support and accelerating structural failure. Not all joint closures are equally effective; not all problems of infiltration lead to the same consequences.

Analytical strategies for the timing of pipeline replacement in the natural gas industry may serve as a starting point for establishing a timing for replacement or repair of deteriorating storm drain installations. Timing of replacement incorporates the fact that problems of any installed pipe increase exponentially with time. One approach for replacement timing is to compare predicted maintenance costs with depreciated value and replace the segment of interest when these curves cross.

Another approach is to compare the prevalent interest rate (cost of capital) with the ratio of expected repair cost to the replacement cost, and replace pipes when the ratio is predicted to exceed the interest rate (*85*).

With the ever-increasing age of highway drainage infrastructures, restoration of pipelines and culverts becomes a more frequent necessity. In the process of restoring a failing or failed culvert or pipeline to service, the choice between repair, rehabilitation and replacement includes consideration not only of cost, but also consideration as to whether the culvert or pipeline need be taken out of service for an extended period while improvements are made.

Repairs of drainage infrastructures include patching, crack sealing, joint repair, seam repair (on structural plate), invert coating and invert paving.

TRENCHLESS PIPELINE REHABILITATION

Trenchless methods of rehabilitation include sliplining, flexible tube lining and portland cement mortar lining. Since rehabilitation is likely to take place in a confined breathing area, mortars that include polymers or other potentially hostile cements are usually rejected unless an appropriate ventilation system is put in place. In cases where plastic linings have to be welded, materials that can be thermally lapped or butt welded (e.g., HDPE) are less likely to require ventilation; materials that must be chemically welded with solvents (e.g., PVC) are more likely to require ventilation.

Use of preformed linings of plastic, such as sliplining with rigid pipe or flexible tube linings that are expanded to approximate the shape of the void after insertion, is often, but not always, followed with grouting of the annular space between the liner and the existing pipe. An opportunity may exist for having the useful service life of the drainage system extended for a significant period of time. The cost of such a strategy must be balanced by the value of minimum disruption of highway service during a period of rehabilitation. Where a reduced cross-sectional area cannot be tolerated, high-powered hydraulic pipe-bursting machines can expand the opening and permit insertion of like-size or larger pipes. A Minnesota study (*86*) found that culvert relining can be inexpensive and minimally disruptive when a reduction of cross-section is permitted. Reliners with smooth exteriors are preferred; grout debonding was not found to be a serious problem.

Where the existing pipe is expected to maintain its structural integrity, the lining will be free of external soil and highway live loads. Should the lined existing pipe leak and permit development of hydrostatic head, either by drainage waters or by groundwater, the liner may be subject to buckling. If such a possibility of hydrostatic head on the liner exists, grouting of the annular space between the outside of the liner and the inside of the existing pipe should be considered. Anticipated hydrostatic and/or design grouting pressures should not exceed the design buckling strength of the liner; this may dictate the stiffness of the liner. If alignment of the liner is critical to its performance, grouting procedures must include a defense against liner flotation.

Where the existing pipe is not expected to maintain its structural integrity, the lining must be designed to respond to external soil and highway live loads. In this case, a structural grout introduced into the annular space between existing pipe and its liner is an option as it would add structural integrity and distribute load concentrations that arise as a consequence of the geometry of the severely damaged pipe. To achieve this same end, it may also be necessary to grout large voids in the surrounding soil, if such are known to exist.

Many strategies exist for introducing a plastic lining into a pipeline. Many proprietary systems exist and the principles of material selection, techniques of installation and service performance vary widely. A particularly useful study, sponsored by the U.S. Army Corps of Engineers, presents a state-of-the-art review of competing advantages and disadvantages of the large array of choices available (*87*).

One class of plastic liner is generically known as cured-in-place plastic pipe (CIPP). Thermosetting unsaturated polyester resins (the usual choice for gravity drainage systems), epoxy resins, or vinyl ester resins are used to soak a fabric tube. The composite is introduced by pulling or driving it forward using air or water pressure to invert the tube into the pipeline to be rehabilitated. It is then expanded by water or air pressure against the wall of the pipe followed by thermal curing using hot water or steam.

A second, but older, class of liner is that of inserting a pipe of smaller diameter into the pipeline to be rehabilitated. Known as sliplining, the liner pipe is pulled (with a winch) or pushed (pipe jacking) into the existing annulus of the host pipe. This host pipe must not exhibit a deformed geometry sufficient to inhibit the insertion and installation of the liner pipe. The space between liner and host pipe is often filled with grout. Depending on the condition of the host pipe and the selection of the liner pipe, reduction of hydraulic capacity as a result of lesser cross-sectional area may be compensated by the improved flow characteristics of the liner pipe. Liner pipe may be inserted as a continuous tube wherein segmented lengths are heat welded (in the case of HDPE), or otherwise joined at the point of insertion. Other plastic pipes especially prepared for slip lining include PVC, polypropylene (PP) and thermosetting glass-reinforced plastic (GRP). Variations include helical windings and preformed panels with interlocking edges.

A third class of plastic liner used to rehabilitate degraded pipes is that of a preformed thermoplastic liner (HDPE or PVC) of reduced cross-sectional area inserted (often in folded form) into the host pipe and subsequently expanded to provide intimate contact with the inner surface of the host pipe.

Where the host pipe is damaged to the extent that the geometry of cross section has been degraded to a point where it is inappropriate to install liners as noted above, hydraulic pipe-bursting machines may be used to radially expand broken and/or other significantly deformed pipe to a diameter that may be larger than the originally installed host pipe. This then permits the insertion of a replacement pipe following immediately behind the pipe-bursting machine. Care must be taken to inhibit the damage to nearby utilities and other underground construction, and to limit the damage to connecting laterals. An alternative, where soil conditions are sufficiently stable, is to employ micro-tunneling machines to remove old, nonreclaimable pipe and replace it with new pipe sections immediately behind the machine and its advancing shield.

Replacement of damaged pipelines include the options of cut and cover, jacking and micro-tunneling. The latter two replacement options may not require diversion of traffic. Cut and cover is the most popular method of replacement in Oregon, Washington, Nevada, Idaho, Utah and Arizona (*82*). Trenchless pipeline rehabilitation strategies of jacking, slip lining, flexible tube lining and micro-tunneling are generally favored in the order stated.

CHAPTER SIX

PIPE SELECTION: LIFE-CYCLE COST ANALYSES

An efficient pipe is one that satisfies the previously discussed constraints of the desired service life of the drainage system, the material and structural performances of its component parts and associated costs. The years of assigned design service life, influenced by preferences that come directly out of experience with various products serving under various conditions, results in each state adopting a strategy in response to its own needs. These strategies may vary widely. Arizona (*88*) has a particularly well-defined way of addressing and presenting the menu of choices that are associated with the desired service life. Parameters include the performance of pipe materials of steel, aluminum, concrete and polyethylene under various conditions and environments of service.

Expectation of a useful service life drives the adoption of a design (desired) service life. A report of a survey conducted jointly by the American Association of State Highway and Transportation Officials (AASHTO), the Associated General Contractors (AGC) and the American Road and Transportation Builders Association (ARTBA) charts the percent of respondents predicting years of expected useful service lives for pipelines and culverts of all materials. Categories of use include cross drains, side drains, storm drains, under drains and sanitary sewers (*89*).

Life-cycle economic analyses are used for cost comparisons of design alternatives. Their use enhances the opportunities for efficient use of construction and maintenance funds for a proposed project. The life-cycle cost of an alternative system, or part of a system, anticipates all the costs that are likely to occur over the defined period of time of the desired service life. The desired (design) service life is often set by policy based on experience and includes both direct and indirect costs of anticipated disruption of services associated with each of the alternatives.

Indirect costs may include facility user costs of detours, accidents and damage to vulnerable areas during the period of replacement or major repair. The setting of the desired service life requires anticipation and inclusion of the likelihood of future increases in the hydraulic capacity requirements of the drainage facility, changes in the aggressiveness of effluent and other environmental factors. Systems designed to drain rural areas at present may be required to drain urban areas, or urban areas of changed character, in the future. Life-cycle costs of drainage pipes and culverts of competing materials and systems are very sensitive to the selection of the desired service life of the facility and its component parts. In Florida, traffic volume, a key variable for the design service life of highway drainage facilities based on function (storm, median, cross, side, etc.), is charted for 18 types of pipe (*90*).

Once the desired service life is set, the economic analyses should include estimates of the pipe material's survival; initial cost of the installed facility; the discount rate (interest rates which include expectations of inflation); inspection and maintenance costs; timely repair, rehabilitation or replacement costs, and the number of such required events; salvage credits (if appropriate); and residual value at the end of the design service life. Present worth studies (*91*) for comparison of alternatives include all of the above. The period of analysis need not be, but most often is, the desired service life. Alternative periods of analysis include the expected survival time of the pipe alternative that will need the earliest rehabilitation or replacement; the alternative that will have the longest expectation of survival; the period of time for which increased capacity is expected to be needed; or any other period that is consistent with the physical or economic constraints of the owner of the facility.

A great deal of uncertainty attends the employment of all economic studies that must include best estimates of future conditions. The qualities of the assumptions of the parameters used in the studies govern life-cycle cost analyses. Objectivity in estimating the longevity of a drainage system, and its many parts, is of primary importance. Often it is difficult to maintain in face of anecdotal experiences and claims made by manufacturers of pipes of different materials. Too liberal or too conservative an estimate of the expected survival life of any of the alternatives may skew the outcome of a life-cycle analysis and lead to a less efficient selection. The assignment of expected survival lives for pipes of different materials with different protective treatments should be heavily influenced by experiences with such pipes in local environments similar to the drainage facility of interest.

CHAPTER SEVEN

CONCLUSIONS

Nineteen years have passed since the publication of *NCHRP Synthesis of Highway Practice 50: Durability of Drainage Pipe.* During this period, greater efficiencies in the use of pipe and culvert materials, and the introduction of new materials, have taken place. Other materials have been deleted from the menu of pipe material choices available to design engineers. Materials on the contemporary menu may be more or less favored today than at the time of the earlier study's conclusion.

The parameters most frequently related to chemical and electrochemical corrosion are soil-side and water-side pH, soil-side and water-side electrical resistivity, chemical composition (including the concentration and distribution of oxygen) of soil surrounding the pipe, and chemical and mineral composition of soil in the drainage area feeding the pipe. In those locations where acid rain is expected, the implications for unprotected metal and concrete pipes are significant. Specially formulated sulfate-resisting concrete, including the use of sulfate-resisting cements, provides some advantage.

Pipes that are a composite of two or more materials are receiving increasing attention. Coatings and claddings of metal pipes provide a margin of defense against chemical and electrochemical attack. To the extent these coatings and claddings are able to maintain their integrity free of damage, serious flaws and/or abrasive degradation resulting from high velocities of aggressive bed loads, these modes of defense are viable.

An important and notable change in material usage has been in the increasing use of thermoplastic materials with high-density polyethylene (HDPE) and polyvinyl chloride (PVC) experiencing the greatest gain in usage. The resistance of plastic to chemical corrosion, electrochemical corrosion and abrasion has stimulated its acceptance for increasingly large diameters of gravity-flow drainage pipes.

In general, linings for flexible metal pipes continue to encounter problems associated with loss of bond between liner and pipe. With improved materials and techniques for establishing proper bond between liner and pipe, difficulties associated with mechanical and chemical incompatibilities may be resolved. To the extent that the stiffness of the liner matches that of the pipe, the deformation of each will be compatible with the deformation of the other. Liner instability and separation from the parent metal pipe will be less likely. The opportunity for crevice corrosion will be minimized. Studies focused on improving the surety of bond between a liner and a metal pipe may therefore be of interest. A recent study establishes a protocol for testing, screening and qualifying coatings and invert treatments for corrugated steel pipe *(93).* Surety of performance requires maintaining integrity of the materials of the composite pipe.

Important improvements have occurred in the ability to predict the structural performance of the soil/structure composite. For flexible metal and plastic pipes, the ability to properly anticipate strain and deformation response is an important condition precedent to an ability to predict useful service life. For rigid pipes, the recently enhanced ability to analyze (with finite element strategies) for stress-strain response associated with given loading and embedment conditions contributes to decisions that are related to longevity of service. The likelihood of stress corrosion becomes more predictable, albeit in qualitative fashion. Capabilities of pipe and culvert analyses far exceed capabilities of predicting loads introduced into the analyses. Focus on strategies for predicting loads because of active and passive surcharge may be of interest for future investigative studies.

Predicting the quality and longevity of defenses, introduced to address the irreversible problems of chemical corrosion, electrochemical corrosion and abrasion, is a necessary but insufficient condition for efficient estimation of useful service life. Changes in volume, velocity and character of drainage effluent including bed load must be anticipated over the design service life of the facility. This is a difficult task to execute, however. Databases of empirical experiences of pipes in service are developed for particular regions and particular conditions of service. In some cases, database information has been reduced to regression equations, applicable only to the peculiar conditions of the pipes included in the databases of interest.

Decisions as to the size and type of pipe to employ may be arguably improved with studies that include life-cycle analyses. Input includes service needs, and anticipated changes and predictions (often 50 or more years into the future) of the patterns of expected inflation, interest rates and other major construction costs. Whether or not a state makes these early decisions based on the formalities of life-cycle analyses, the commitment to active programs of inspection and maintenance and fidelity to the timely execution of such programs is essential to the realization of the predicted outcomes. Trade-offs between repair, rehabilitation and replacement are often the focus.

REFERENCES

1. Stratton, F. W., J. A. Frantzen and J. A. Meggers, *Cause of Deterioration of Corrugated Metal Pipe Installed After 1974,* Kansas Department of Transportation, Topeka, Kansas (1990).
2. Brasunas, A. deS., et. al. editor, "NACE Basic Corrosion Course," *National Association of Corrosion Engineers,* Houston, 2nd printing (April 1971).
3. Uhlig, H.H., *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering,* 2nd ed., Wiley, New York City (June 1971).
4. *Design Guidance on Alternative Pipe Selection,* Federal Lands Highway Project Development, electronically published www.bts.gov/NTL/frames/smart facilities @ BTS. Gov.htm (1996).
5. Garber, J.D. and J.H. Lin, *Accelerated Corrosion Test For Metal Drainage Pipes,* Louisiana Transportation Research Center, Baton Rouge (June 1987).
6. *Modern Sewer Design Fifth Ed.*, American Iron and Steel Institue, Washington, D.C. (1995).
7. *Handbook of Street Drainage and Highway Construction Products,* Fifth edition, American Iron and Steel Institute (1994).
8. Lowe, T.A. and A.H. Koepf, "Corrosion Performance of Aluminum Culvert," in *Highway Research Record 56,* Highway Research Board, National Research Council, Washinton D.C. (1964) pp. 98–115.
9. Peterson, D.E., *Evaluation of Aluminum Alloy Pipe for Use in Utah's Highways,* Utah State Highway Department, Salt Lake City, Utah (June 1973).
10. Romanoff, M., *Underground Corrosion,* Circular 579, National Bureau of Standards, U.S. Government Printing Office, Washington, D.C. (April 1957).
11. Ellis, J.G., *Corrosion Performance of Aluminum Culverts,* Res. Rep. R-976, New York State DOT (November 1975).
12. Beaton, J.L. and R.F. Stratful, "Field Test for Estimating Service Life of Metal Pipe Culvert," *Proceedings of the Highway Research Board,* Vol. 41, Highway Research Board, National Research Council, Washington, D.C. (1962) pp. 225–272.
13. Stratful, R.F., "Field Method of Detecting Corrosive Soil Conditions," *Proceedings of the 15th Annual Street and Highway Conference,* ITTE and University Extension, University of California Los Angeles (January 1963).
14. Schwerdtfeger, W.J., "Soil Resistivity as Related to Underground Corrosion and Cathodic Protection," in *Highway Research Record 110,* Highway Research Board, National Research Council, Washington, D.C. (1966) pp. 20–21.
15. Lindberg, R.I., "Method of Estimating Highway Culverts by Means of Polarization Curves," in *Highway Research Record 204,* Highway Research Board, National Research Council, Washington, D.C. (1967) pp. 1–10.
16. Beaton, J. L. and R. F. Stratful, "Corrosion of Corrugated Metal Culvert in California," in *Highway Research Bulletin 223,* Highway Research Board, National Research Council, Washington, D.C. (1959) pp. 1–13.
17. Malcom, M.J, *Durability Design Method for Galvanized Steel Pipe in Iowa,* Corrugated Metal Pipe Assocation of Iowa and Nebraska (1968).
18. Kill, D.L., *Serviceability of Corrugated Metal Culverts,* Investigation No. 116, Minnesota Department of Highways, St. Paul, Minnesota (1966–67).
19. Bearg, E.A. et al., *Durability Design Method for Galvanized Steel Pipe in Nebraska,* ARMCO Steel Corporation (1966–67).
20. Marbut, *Soils of The U.S., Atlas of American Agriculture, Part III,* U.S. Government Printing Office, Washington, D.C. (1935).
21. Leeds, J.M., "Parameters That Determine the Need for External Pipeline Refurbishment," *Pipeline Risk Assessment, Rehabilition and Repair Conference,* Houston, Texas (1991).
22. Garber, J.D., J.H. Lin and L.G. Smith, *Feasibility of Applying Cathodic Protection to Underground Culverts,* Report No. FHWA/LA-94/289, University of Southwestern Louisiana, Lafayette (1995).
23. Lea, F.M., *The Chemistry of Cement and Concrete,* First American Edition, Chemical Publishing Company, New York (1971).
24. Mehta, P.K., "Discussion of Cambating Sulfate Attack in Corps Engineers Concrete Construction," *ACI Journal,* Vol.73, No. 4 (April 1976) pp. 237–238.
25. ACI Manual of Concrete Practice, Part I, *American Concrete International,* "Chapter 2: Aggressive Chemical Exposure," American Concrete Institute (January 1996).
26. Haynes, H.R. O'Neill and P.A. Mehta, "Concrete Deterioration from Physical Attack by Salts," *Concrete International,* American Concrete Institute, Farmington Mills, Michigan (January 1996).
27. Mather, B., *Field and Laboratory Studies of Sulfate Resistant Concrete,* Performance of Concrete-Resistance of Concrete to Sulfate and Other Environmental Conditions, Thorvaldson Symposium, University of Toronto Press, Toronto, Canada (1968) pp. 66–76.
28. Potter, J.C., *Life-Cycle Cost for Drainage Structures,* Department of the Army, Waterways Experiment Station, Corps of Engineers, Vicksburg, Mississippi (1988).
29. Borgard, B. et al., *Mechanism of Corrsion of Steel in Concrete,* ATMP STP 1065, American Society for Testing Materials, Philadelphia (1990) pp. 174–188.
30. Hansson C.M. and B. Sorensen, *The Threshold Concentration of Chloride in Concrete for the Initiation of Reinforcement Corrsion,* ASTM STP 1065, American Society for Testing Materials, Philadelphia (1990) pp. 3–16.

31. Hurd, J.O., "Field Performance of Protective Linings for Concrete and Corrugated Steel Pipes," in *Transportation Research Record 1001*, Transportation Research Board, National Research Council, Washington, D.C. (1984).
32. *Life Expectancy Determination of Zinc-Coated Corrugated Steel and Reinforced Concrete Pipe Used in Missouri,* MR 91-1, Missouri Highway and Transportation Department, Division of Materials and Research, Jefferson City, Missouri (1990).
33. Renfrew, W.W. and R.M. Pyskadio, *National Survey of State Culvert Use and Policies,* Special Report 68, New York State Department of Tranportation, Albany (May 1980).
34. Ring, G.W., "Culvert Durability: Where Are We?" in *Transportation Research Record 1001*, Transportation Research Board, National Research Council, Washington, D.C. (1984).
35. Sudol, J.J., *Pipe Coating Study,* Indiana Department of Highways, Indianapolis, Indiana (1982).
36. Bureau of Reclamation, *Concrete Manual, 8th Ed.*, U.S. Government Printing Office, Washington, D.C. (1975).
37. *Design Guidance on Alternative Pipe Selection,* Federal Lands Highway Project Development and Design Manual, Federal Highway Administration, Washington, D.C. (1996).
38. Malcolm, H.R., *Forecasting Service Life of Culverts in North Carolina,* Center for Transportation Engineering Studies, North Carolina State University, Raleigh (1993).
39. Cerlanek W.D. and R.G. Powers, *Drainage Culvert Service Life Performance and Estimation,* Report No. 93–4a, State of Florida, Department of Transportation, State Materials Office, Corrosion Research Laboratory, Tallahasee, Florida (1993).
40. Hurd, J.O., "Field Performance of Concrete and Corrugated Steel Pipe Culvert and Bituminous Protection of Corrugated Steel Pipe Culverts," in *Transportation Research Record 1001*,Transportation Research Board, National Research Council, Washington, D.C. (1984).
41. Potter, J.C., L. Lewandowsky and D.W. White Jr., *Durability of Special Coatings for Corrugated Steep Pipe,* FHWA-91-FLP-006, U.S. Army Waterways Experiment Station, Geotechnical Laboratory, Vicksburg, Missouri (1991).
42. Ocean City Research Corporation, *Evaluation Methodology for Corrugated Steel Pipe Coating/Invert Treatments,* National Corrugated Steel Pipe Association, Washington, D.C. (March 1996).
43. Jonas, S. et al., *Corrugated Metal Pipe Study—Final Report,* Alberta Agriculture Irrigation Branch, Alberta, Canada (March 1988).
44. *Life Expectancy Determination of Zinc-Coated Corrugated Steel and Reinforced Concrete Pipe Used in Missouri,* MR91-1, Missouri Highway and Transportation Department, Division of Materials and Research, Jefferson City, Missouri (1990).
45. Temple, W.H., S.L. Cumbaa and B.J. Gueho, *Evaluation of Drainage Pipe by Field Experimentation and Supplementary Laboratory Experimentation,* FHWA/LA-85/174, Louisiana Department of Transportation, Baton Rouge (1985).
46. Bednar, L., "Plain Galvanized Steel Drainage Durability Estimation with a Modified California Chart," in *Transportation Research Record 1231*, Transportation Research Board, National Research Council, Washington, D.C. (1989) pp. 70–79.
47. Bellair P.J. and J.P. Ewing, *Metal-Loss Rates of Uncoated Steel and Aluminum Culvert in New York,* New York State Department of Transportation, State Campus, Albany (1984).
48. Degler, D.H., D.C. Cowherd and J.O. Hurd, "An Analysis of Visual Inspection Data of 900 Pipe-Arch Structures," in *Transportation Research Record 1191*, Transportation Research Board, National Research Council, Washington, D.C. (1988).
49. Hurd J.O. and S. Sargand, "Field Performance of Corrugated Metal Box Culverts," in *Transportation Research Record 1191*, Transportation Research Board, National Research Council, Washington, D.C. (1988).
50. Potter, J.C., "Aluminum-Coated Corrugated Steel Pipe Field Performance," *Journal of Transportation Engineeing ASCE*, Vol. 116, No. 2 (March/April 1990).
51. American Society for Metals, *Corrosion Resistance of Aluminum and Aluminum Alloys,* Metal Handbook, Desk Edition, Materials Park, Ohio.
52. Lowe T.A. and A.H. Koepf, "Corrosion Evaluation of Aluminum Culvert," in *Highway Research Record 56*, Highway Research Board, National Research Council, Washington, D.C. (1964) pp. 98–115.
53. Lowe, T.A. et al.,"Corrosion Evaluation of Aluminum Culvert Based on Field Performance," in *Highway Research Record 262*, Highway Research Board, National Research Council, Washington, D.C. (1969) pp. 56–68.
54. *Progress on Durability Study of Corrugated Aluminum Drainage Pipe,* Sponsored by the Aluminum Association, Committee A2C06, Report to Transportation Research Board, National Research Council, Washington, D.C. (January 1987).
55. Nordlin E.F. and R.F. Stratful, "A Preliminary Study of Aluminum as a Culvert Material," in *Highway Research Record 95*, Highway Research Board, National Research Council, Washington, D.C. (1965) pp. 1–70.
56. Kessler, R.J., R.G. Powers and R.M. Langley, *Two Years Evaluation of Corrugated Metal Pipe Alternate Materials,* Florida Department of Transportation, Materials Office, Corrosion Research Laboratory, Gainesville (1989).
57. Sagues, A.A., *Corrosion Measurement of Aluminum Alloys and Reinforced Concrete for Determination of Culvert Service Life,* University of South Florida, Tampa (1989).
58. Jenkins, S.V., J.L. Leatham and S.E. Goodwin, *Pipe Culvert Durability,* Utah State Department of Transportation, Salt Lake City (1989).
59. Gietz R.H., *Metal Culvert Performance,* Washington State Department of Transportation, Material Office, Tumwater (1981).

60. Cassidy, M., *Review Specifications and Performance Requirements for Plastic Pipe Systems,* Battelle, Columbus, Ohio (1994).
61. Puterman M., "Natural and Accelerated Weathering of PVC and Polyethylene Wastewater Pipes," *Materials and Construction,* Vol. 22, No. 129 (1989) pp. 170–175.
62. AASHTO, American Association of State Highway and Transportation Officials, *Bridge Design Specifications,* Section 18, paragraph 18.4.3.1.1., Washington, D.C.
63. *Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading,* ASTM D2412, American Society for Testing and Materials, Philadelphia (1993).
64. American Waterworks Association, *Fiberglass Pipe Design Manual M-45, Manual of Water Supply Practices,* Denver, Colorado (1996).
65. Stroud, T.F., *Control Measures for Ductile Iron Pipe, Corrosion/89,* National Association of Corrosion Engineers, Houston, Texas (1989).
66. Romanoff, M., "Performance of Ductile Iron in Soils," *Journal of the American Water Works Association,* Vol. 60, No. 6 (June 1968) pp. 645–655.
67. Sears, E.C., "Comparison of the Soil Corrosion Resistance of Ductile Iron Pipe and Gray Cast Iron Pipe," *Materials Protection,* Vol 7, No. 10 (1968) pp. 33–36.
68. Stroud, T.F., "Polyethylene Encasement versus Cathodic Protection," *Ductile Iron Pipe News* (Spring/Summer 1968).
69. Bortz, S.A., "Durability of Clay Pipe," *Proceedings of the International Conference on Advances in Underground Pipelines Engineering,* American Society of Civil Engineering, New York (1985).
70. Morris G.E. and L. Bednar, "Comprehensive Evalutaion of Aluminized Type 2 Pipe Field Performance,"in *Transportation Research Record 1001,* Transportation Research Board, National Research Council, Washington, D.C. (1984).
71. Bednar, L., *Aluminized Steel T2 Pipe,* Insustrial Report, Armco, Inc. (December 1991).
72. Bednar, L., *Resistivity and pH Limits for the Use of Aluminized Steel Type 2 Drainage Pipe,* Armco Research and Technology (1989).
73. Pyskaldo, R.M., *Experimental Culvert Test Plates,* Engineering Research and Development Bureau, New York Department of Transportation, Albany (1988).
74. Jiang Y. and R.S. McDaniel, *Evaluation of Galvalume and Aramid Fiber Bonded Bituminous Coated Pipes,* Indiana Department of Transportation, Indianapolis (1990).
75. Koscelny J.A., *Polymer Coated and Paved Culverts in Southeastern Oklahoma,* Oklahoma Department of Transportation, Oklahoma City (1992).
76. California Test 643, Method for Estimating the Service Life of Steel Culverts, State of California DOT, Division of New Technology and Material Research, Sacramento (1993).
77. *Durability of Special Coatings for Corrugated Steel Pipe,* FHWA-FLP-91-006, Federal Highway Administration, Washington, D.C. (1991).
78. *Design of Spiral Rib Pipe System for Control of External Corrsion,* Farwest Corrosion Control Company, Gardena, California (1984).
79. *Sewer Manual for Corrugated Steel Pipe,* National Corrugated Steel Pipe Association, Washington, D.C. (1949).
80. Statement Attributed to California Legislative Analyst Elizabeth G. Hill, *Sacramento Bee,* Forum 3, Sacramento, California (December 3, 1975).
81. Federal Highway Administration, *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges,* FHWA-PD-96-001, U.S. Department of Transportation, Washington, D.C. (1995).
82. Aryani, C. and J. Al-Kazily, *Culvert Restoration Techniques,* FHWA/CA/93-14, California State University, Sacramento (1993).
83. Federal Highway Administration, *Culvert Inspection Manual,* FHWA-IP-86-2, U.S. Department of Transportation, Washington, D.C. (1986).
84. Bellport, B.P., *Combating Sulfate Attack on Concrete on Bureau of Reclamation Projects,* U.S. Bureau of Reclamation, paper presented at symposium, Toronto, Canada (1967).
85. "Pipeline Risk Assessment, Rehabilitation, and Repair," in *When to Renew a Pipeline,* Gulf Publishing Company and Scientific Surveys Ltd., Houston, Texas (1991).
86. Johnson, D. and J. Zollars, *Culvert Renewal,* Minnesota Department of Transportation, Office of Materials and Research, St. Paul (1992).
87. Najafi M., *Trenchless Pipeline Rehabilition,* Missouri Western State College, St. Joseph (1994).
88. *Pipe Selection Guidelines and Procedures,* Arizona Department of Transportation, Phoenix (February 1, 1996).
89. *Cross-Reference for Drainage Pipe Specifications for Waterways, Airports, Railroads, Transit and Highways,* AASHTO-AGC-ARTBA Joint Committee, Subcommittee on New Highway Materials, Task Force 22 Report, Washington, D.C.
90. *Table 6-1, Culvert Material Application and Design Services Life (DSL) Drainage Manual, Vol. I—Standards,* Florida Department of Transportation, Tallahassee (1993).
91. *Economic Studies for Military Construction Design—Applications,* TM 5-802-1, Department of the Army, Headquarters, Alexandria, Virginia (December 1986).
92. *Evaluation Methodology for Corrugated Steel Pipe Coating/Invert Treatments,* Prepared for National Corrugated Steel Pipe Association, Ocean City Research Corporation, Washington, D.C. (March 1966).

APPENDIX A

Survey Questionnaire

The following request for information was addressed to the states:

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

PROJECT 20-5, TOPIC 25-21

SERVICE LIFE OF DRAINAGE PIPE

INFORMATION REQUEST

The following information and documents are necessary in order to produce an accurate and useful synthesis on the selection, use, and durability experience of drainage pipe products in each state transportation agency. If the documentation is in limited supply and you would like the copies returned, please note on each document.

1. Materials specifications for all drainage products included in the book of Standard Specifications. Additionally, any special provision specifications in current use and those that are being used for experimental products.
2. Statistical data relative to the actual use of the various drainage pipe products. We recognize that some products are often specified but seldom used, usually on products where alternates are allowed.
3. Documents that present the state's policy on product or material selection and the policy on environmental condition limitations on the use of these products and materials.
4. Documents that explain the state's policy on allowing alternate materials or alternate material bidding on a specific project.
5. The method of product selection, based on life-cycle-cost involving the principles of engineering economics if your agency has developed such a method in professional journals.
6. Copies of research reports dealing with pipe durability not already published. Please include both laboratory studies and condition surveys conducted in the field.
7. Copies of research study plans which are in progress, or are planned to be in the near future.
8. Structural fill tables showing maximum and minimum overfills allowable. We do not intend to deal with the structural aspects of pipe in this Synthesis, but there is often information contained in these tables that impacts on product selection and durability.

In your response to the above request for general information, it would be useful, and very much appreciated, if you would place special focus on the following:

1. The factors that influence material durability where the potential for corrosion and/or other chemical and mechanical degradation heavily influences performance.

These are to include:

a. Experience related to pH of drainage effluent.

b. Experience related to pH of soil.

c. Relation of bed load to abrasion.

d. Relation of velocity to abrasion.

e. Influence of sulfate, chloride, and other salt reactions.

f. Influence of soil resistivity on galvanic corrosion.

g. Experience, if any, with protective linings and protective coatings.

h. Experience, if any, with ultraviolet degradation.

i. Experience, if any, with flammability.

Note: The experience reported should be based on your agency's practice and should not be based on opinion which is not supported by your agency's practice.

2. Appropriate sections of each states' specifications and/or standards relating to other aspects of service life of drainage structures. These include, but are not limited to:

   a. A definition of service life. Please discern any difference between perceived service life and design service life which may be present in your agency's practice.

   b. Manner of calculating and assigning values to life-cycle costs.

   c. Criteria for the selection of one drainage product over another.

3. Other information known to each state that is reported in other Transportation Research Board reports, that has appeared in industry reports, periodicals, or is yet to be published.

****

Thank You for Your Assistance! Your cooperation in providing this information is very much appreciated.

Please send responses by June 10, 1994 to:

L.H. Gabriel, Ph.D., P.E.
Professor Emeritus of Civil Engineering
4841 Tono Way
Sacramento, California 95841–4338

Telephone: (916) 482–6560

****

APPENDIX B

Acknowledgments

The material used in this synthesis was derived from many sources including state departments of transportation, federal agencies, manufacturers of pipes and culverts of all materials, reports of professional organizations, and reports of research organizations associated with universities and industry. References cited in the report are intended to lay a trail to enable the reader to retrieve more complete information on that which has been addressed in the text.

This synthesis of state of art and practice began with a solicitation to each state addressing practice in that state. Either by correspondence, follow-up phone calls, or both, all states were consulted during the course of the study. Although not necessarily referenced by name in the text, the practice of each of the states, associated with the subject matter noted below, is recognized for important contributions to the substance of this report.

DESIGN SERVICE LIFE
(years assigned based on function)

Arizona, Arkansas, California, Colorado, Florida, Hawaii, Indiana, Kansas, Louisiana, Maine, Minnesota, Mississippi, Montana, Nevada, North Dakota, New York, Ohio, Oklahoma, Oregon, Pennsylvania, South Dakota, Utah, and Washington.

DESIGN SERVICE LIFE
(requirements for pipes and culverts of all materials)

Arizona, California, Colorado, Florida, Indiana, Kansas, Louisiana, Minnesota, Mississippi, Montana, New Hampshire, New York, Ohio, Oregon, Pennsylvania, Washington, and Wisconsin.

FACTORS OF CORROSION AND ABRASION
(all materials)

Alabama, Arizona, Arkansas, California, Colorado, Florida, Georgia, Hawaii, Idaho, Illinois, Kansas, Louisiana, Maryland, Minnesota, Nevada, New Hampshire, New York, Ohio, Pennsylvania, South Dakota, Utah, Washington, and Wisconsin.

CULVERT AND PIPELINE PROTECTION
(all materials)

Alabama, Arizona, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Idaho, Illinois, Iowa, Kansas, Minnesota, Mississippi, Montana, New Hampshire, New Jersey, New Mexico, New York, North Carolina, Ohio, Pennsylvania, and West Virginia.

PIPE OR CULVERT BY FUNCTION
(type, size, material)

Alabama, Arizona, Arkansas, California, Colorado, Connecticut, Florida, Georgia, Hawaii, Idaho, Illinois, Indiana, Iowa, Kansas, Kentucky, Louisiana, Maine, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New Mexico, New York, North Carolina, North Dakota, Ohio, Oklahoma, Oregon, Pennsylvania, Rhode Island, South Carolina, South Dakota, Texas, Utah, Vermont, Virginia, Washington, West Virginia, Wisconsin, and Wyoming.

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, a private, nonprofit institution that provides independent advice on scientific and technical issues under a congressional charter. The Research Council is the principal operating arm of the National Academy of Sciences and the National Academy of Engineering.

The mission of the Transportation Research Board is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research findings. The Board's varied activities annually draw on approximately 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encouraging education and research, and recognizes the superior achievements of engineers. Dr. William A.Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences, by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

ADDRESS CORRECTION REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
WASHINGTON, D.C.
PERMIT NO. 8970

000021-05
Robert M Smith
Research & Asst Matls Engr
Idaho DOT
P O Box 7129
Boise ID 83707-1129