# Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe

ISBN
978-0-309-13163-6

186 pages
6 x 9
PAPERBACK (2009)

Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe; National Research Council

# Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe

Committee on the Review of the Bureau of Reclamation's
Corrosion Prevention Standards for Ductile Iron Pipe

National Materials Advisory Board

Division on Engineering and Physical Sciences

NATIONAL RESEARCH COUNCIL
*OF THE NATIONAL ACADEMIES*

THE NATIONAL ACADEMIES PRESS
Washington, D.C.
**www.nap.edu**

**THE NATIONAL ACADEMIES PRESS 500 Fifth Street, N.W. Washington, DC 20001**

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract No. 08CS811405 between the National Academy of Sciences and the Bureau of Reclamation. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number-13: 978-0-309-13163-6
International Standard Book Number-10: 0-309-13163-4

This report is available in limited quantities from

National Materials Advisory Board
500 Fifth Street, N.W.
Washington, DC 20001
nmab@nas.edu
http://www.nationalacademies.edu/nmab

Additional copies of this report are available from the National Academies Press, 500 Fifth Street, N.W., Lockbox 285, Washington, DC 20055; (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area); Internet: http://www.nap.edu.



Printed in the United States of America

**COMMITTEE ON THE REVIEW OF THE BUREAU OF RECLAMATION'S CORROSION PREVENTION STANDARDS FOR DUCTILE IRON PIPE**

DAVID W. JOHNSON, JR., Stevens Institute of Technology, *Chair*
RONALD BIANCHETTI, Blackstone Group, Ltd.
RICHARD J. FIELDS, KT Consulting
CAROL A. HANDWERKER, Purdue University
JOHN O'BRIEN, Water and Wastewater Division, Genesee County, Michigan
MATTHEW O'KEEFE, Missouri University of Science and Technology
JOHN R. PLATTSMIER, HDR Engineering
ALBERTO A. SAGÜÉS, University of South Florida
WILLIAM S. SPICKELMIRE, RUSTNOT Corrosion Control Services, Inc.
DAVID TREJO, Texas A&M University

*Staff*

EMILY ANN MEYER, Program Officer
TERI G. THOROWGOOD, Administrative Coordinator

# Preface

Water is a resource that is often not fully appreciated until its supply becomes diminished or interrupted. In the western United States, where water is not always readily available, it is often transported large distances in pipelines that may serve large populations. If these transmission pipelines fail, the interruption of the water supply can have severe economic and public health impacts. In some cases a catastrophic failure can even lead to the potential loss of life, which became undeniably clear just as the committee was completing a final stage in the preparation of this report: On the morning of December 23, 2008, a 66-inch water main broke in Montgomery County, Maryland, and 150,000 gallons of water per minute gushed from the 44-year-old ruptured pipe, leaving cars with their occupants trapped in the torrent. Some of these individuals had to be rescued by helicopter, and there was concern that some cars might have been swept away. Beyond the immediate problem of rescuing people caught in the floodwaters, other problems quickly developed: the need for people to deal with no water, contaminated water, and destruction of the local landscape. Although the Bureau of Reclamation in the U.S. Department of the Interior does not have oversight of water in the Washington, D.C., area and although the pipe involved in the break was of a material different from that studied in this report, early indications are that the failure may have been caused by corrosion, which underscores the importance of corrosion control and the extent of damage that corrosion can create—well beyond an interruption in service.

It is in the western United States where the Bureau of Reclamation has some jurisdiction over the water supply. Recognizing the potential consequences of a disruption in that supply, the bureau publishes technical memorandums directed toward minimizing, if not preventing, malfunctions on its projects. One such technical memorandum, TM 8140-CC-2004-1,[1] "Corrosion Considerations for Buried Metallic Water Pipe," and Table 2, entitled "Corrosion Prevention Criteria and Minimum Requirements," in that document, specify corrosion control measures for buried underground water pipe. One aspect of these specifications—that concerning corrosion control for ductile iron pipe (DIP) in highly corrosive soils—is the subject of this report. The report was prepared by the Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe, which was established by the National Research Council (NRC) in response to the request for the review from the Bureau of Reclamation. The charge to the committee is discussed in detail in Chapter 1 of the report.

The committee was asked to address the appropriateness of Table 2 in TM 8140-CC-2004-1. On its surface this appears to be a very straightforward question of materials science, metallurgy, and electrochemistry. The reality was that the question was much more controversial than one might have expected, with stakeholders both obvious (the Ductile Iron Pipe Research Association) and less obvious (the steel pipe industry as a primary competitor to DIP, and the coatings industry because the ready availability of its product is impacted in part by the DIP industry's unwillingness to use that product) stepping forward to provide their opinions and competing analyses of the available data.

In addition to the highly charged nature of the study, the time frame within which the committee did its work was unusually condensed. The committee's first meeting was on July 28-30, 2008, in Washington, D.C.; its second and final meeting was held on September 24-28, 2008, in Woods Hole, Massachusetts; its charge was to provide a final report to the sponsor by the end of 2008, so it was necessary to supplement the meetings with numerous conference calls and other methods of virtual meeting. This tight deadline was at the sponsor's request, and for this reason, the committee had to operate within the time frame given.

The committee believes that, considering the time allowed, this report provides the best possible response to the charge given. It must be recognized that the limited and diverse data available on pipeline corrosion rates and failure rates do not support a rigorous statistical analysis. Therefore, the committee could not always differentiate between a corrosion mitigation system that provided a desired level of reliability and one that would not. In such cases, the committee used its collective professional acumen to make the best recommendation possible based on the evidence available.

I thank the committee members for their dedicated efforts in carrying out the

[1] Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe," Washington, D.C., July 2004.

study and preparing this report, giving freely of their time despite the demanding schedule. The committee was fortunate to have represented among its members a broad spectrum of skills and areas of expertise relating to metal pipeline corrosion and corrosion control, including experience in pipeline design, installation, and corrosion control as well as metallurgy and corrosion research. In spite of their diverse backgrounds and, at times, differing opinions regarding the validity of data or their proper interpretation,[2] the committee members successfully shared their expertise and experience in carrying out their charge and were able to arrive at positions of reasoned consensus for all major conclusions and recommendations. For all of this, I offer my deepest gratitude.

This committee was supported in its work by a highly competent and dedicated NRC staff. Program officer Emily Ann Meyer capably coordinated this study and the work of the committee from the study's inception to the publication of this report. Because of the controversial nature of the study subject, responsibility for contacting pipeline users for information fell almost exclusively to NRC staff, and Ms. Meyer used her legal skills, innate ability, and experience to assemble an unbiased set of data, again under demanding time constraints. Her exceptional skills in quickly constructing and modifying drafts of a complex report using information supplied by the various committee members were critical to the successful completion of this report. The committee also expresses its gratitude to Gary Fischman, director of the National Materials Advisory Board, for his efforts on behalf of the committee and staff. He was unfailingly available for consultation, and both his presence and his voice in meetings imparted a steadying influence. The committee also recognizes the capable support of NRC staff members Teri Thorowgood and Laura Toth, who efficiently organized the affairs of the committee, thus ensuring its smooth functioning. The committee thanks Dennis Chamot, deputy executive officer of the Division on Engineering and Physical Sciences, for his able assistance on questions of process both routine and unique. William Colglazier, National Research Council executive officer, and James Hinchman, National Academies' counsel, deserve acknowledgment and thanks for assisting in an unusually complex committee composition and balance process. Finally, the committee acknowledges Shelly Wolfe in the National Academies' Office of News and Public Information for her capable handling of the frequent public inquiries regarding this project.

David W. Johnson, Jr., *Chair*
Committee on the Review of the Bureau of
Reclamation's Corrosion Prevention
Standards for Ductile Iron Pipe

[2] One such differing opinion on the interpretation of the data appears in Appendix B.

# Acknowledgment of Reviewers

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

Graham E.C. Bell, Schiff Associates,
Gerald R. Frankel, Ohio State University,
Robert P. Frankenthal, Bell Laboratories (retired),
Katherine G. Frase, IBM (NAE),
Paolo Gardoni, Texas A&M University,
Balvant Rajani, National Research Council of Canada,
Shari Rosenbloom, Exponent Corporation, and
Michael Szeliga, Russell Corrosion Consultants.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Elsa Garmire, Dartmouth College. Appointed

by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

# Contents

# Summary

## BACKGROUND OF THE STUDY

Cast iron is a material that was used for years to fabricate pipe for applications such as water transmission and distribution. About 50 years ago ductile iron pipe (DIP) was introduced as a more economical and better-performing product. DIP is similar to cast iron pipe (CIP) in that it contains several percent carbon distributed as graphite in an iron matrix. However, by the addition of small amounts of magnesium and the controlled annealing of DIP, the graphite becomes distributed as spherical nodules in DIP, whereas it is distributed in the form of flakes in traditional CIP. This microstructure in DIP results in mechanical properties that are superior to those of traditional cast iron.

As with iron or steel pipes, DIP is subject to corrosion, the rate of which depends on the environment in which the pipe is placed. Corrosion mitigation protocols that depend on the corrosivity of the soil are employed to slow the corrosion process to an acceptable rate for the application. A popular, economical, and often effective corrosion mitigation method for DIP in buried applications is the use of polyethylene encasement (PE), consisting of a sheet of polyethylene wrapped around the pipe or a tube of polyethylene sheeting slipped over the pipe at the time of installation. Another protective method is to use bonded dielectric coatings consisting of various polymers applied as coatings on prepared surfaces or to wrap tapes with adhesives on the same prepared surfaces. Bonded dielectric coatings are commonly used on steel pipes but are less commonly used on DIP. Cathodic protection (CP) can also be used to protect metal pipes, including DIP. CP electrochemically protects the metal structure either by imposing a direct current (dc) electrical potential to the pipeline or by connecting the pipeline to a sacrificial anode made of a more electrochemically active metal.

The decision to use corrosion mitigation systems and the choice of the system to use for buried DIP depend on the corrosivity of the soils in which the pipeline is buried. Many methods of assessing the corrosivity of soils have been developed. All use the resistivity of the soil either as the defining parameter or as one parameter in conjunction with others, such as the presence or concentration of specific chemical species that foster corrosion. Soils with low resistivity are more corrosive than soils with high resistivity.

The Bureau of Reclamation (commonly called Reclamation or BOR) of the U.S. Department of the Interior has from its inception fostered in the western United States water transmission projects designed to provide water for agricultural and municipal uses in areas otherwise deficient in local water supplies. In doing so, Reclamation has specified the types of materials appropriate for particular applications and the type of corrosion mitigation systems appropriate for each pipeline material depending on the corrosivity of the soils. As technology has been developed further and as experience has been gathered, Reclamation has changed the specifications for corrosion mitigation systems from time to time, most recently in 2004.

The Bureau of Reclamation has chosen a relatively simple means of classifying the corrosivity of soils for pipelines installed under its control. For any section of pipeline to be designed, the in situ soil resistivity is measured at multiple positions along the length of the pipeline. A computer program develops a layered model of true resistivities and forms an ordered probability plot developed from these resistivities; the resistivity at the 10th percentile of probability is selected. In other words, 10 percent of the true resistivities derived from the in situ resistivity measurements have lower resistivity values than this characteristic resistivity, and 90 percent have higher resistivity values. If this characteristic resistivity is greater than or equal to 3,000 ohm-cm, the soil is considered to be in the least-corrosive category. If it is between 2,000 and 3,000 ohm-cm, the soils are considered to be of moderate corrosivity. If the characteristic resistivity is less than or equal to 2,000 ohm-cm, the soils are considered to be highly corrosive.

When Reclamation issued modified corrosion protection requirements in its technical memorandum, TM 8140-CC-2004-1,[1] polyethylene encasement (PE) was specified as the corrosion mitigation method for DIP in soils of low corrosivity. For DIP used in moderately corrosive soils, PE and CP were specified. For highly corrosive soils, Reclamation specified that bonded dielectric coatings and CP were needed for adequate corrosion protection of DIP. It is this latter specification that

[1] Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe," Washington, D.C., July 2004.

has been and continues to be contested by some as an overly stringent requirement that necessitates the modification of the pipe from its as-manufactured state and thereby adds unnecessary cost to a pipeline system. In particular, the Ductile Iron Pipe Research Association (DIPRA), representing North American manufacturers of DIP, has conducted research both at test sites and in controlled installations; DIPRA interprets this research as showing that PE with CP provides adequate protection to DIP even in highly corrosive soils.

In the past, bonded dielectric coatings on DIP were available, and a limited amount of such pipe was installed and is in use. However, the current specification of bonded dielectric coatings for DIP is difficult to meet, because in recent years the U.S. manufacturers of DIP have discouraged the application of bonded dielectric coatings on their product and will not supply DIP with such coatings, citing the difficulty of preparing the surface for coating application and the expense of applying such coatings to a relatively rough surface.

Considering the research data available and the lack of DIP with bonded dielectric coatings, DIPRA and supporters of its position have vigorously petitioned the Bureau of Reclamation and the U.S. Department of the Interior to reconsider the decision to specify bonded dielectric coatings for DIP used in highly corrosive soils and to allow PE as at least part of the corrosion mitigation system. DIPRA also believes that Reclamation's specification for this form of corrosion protection in highly corrosive soils has an impact on the use of DIP not only for applications specified by Reclamation but also for much broader applications, because the Reclamation specifications are used by many others designing pipeline systems.

By contrast, the Bureau of Reclamation and those supporting its standards contend that the specifications are needed to ensure the reliability of Reclamation's pipeline systems, particularly since most of these systems are large-diameter, non-redundant water transmission systems in which a failure affects large numbers of users and therefore has major economic and public health consequences. Nevertheless, recognizing the persistent criticism of its specifications, the Bureau of Reclamation has requested that the National Research Council (NRC) form a study committee to make recommendations concerning corrosion protection for DIP in highly corrosive soils. In response to Reclamation's request, the NRC established the Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe. This committee of experts was convened to study corrosion protection of DIP in highly corrosive soils. Specifically, the charge to the committee was that it provide advice to Reclamation concerning the following:

- Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils?
- Will polyethylene encasement and cathodic protection reliably provide a minimum service life of 50 years?

- If the committee answers either of the above questions in the negative, the committee will provide recommendations for alternative standards that would provide a service life of 50 years.

The committee met twice, in July 2008 and September 2008, and conferred many times in teleconference. To meet the charge, the committee heard the findings of experts, studied available data, and sought information from users concerning their experiences with the reliability of pipeline systems. The committee reviewed and discussed the information and data that were presented to it and sought out by the committee in order to come to the findings, conclusions, and recommendations outlined in this report. The information and data were sorted on the basis of their relevance to and reliability in predicting the first failures to occur in a pipeline system. Specifically, the first failures are expected to be represented by corrosion behavior at the tails of the distribution, where the corrosion is fastest, and not by average behavior. The more relevant and reliable data (i.e., those that included the full distributions as opposed to those that included only averages) were therefore used as the primary basis for the findings, conclusions, and recommendations presented here.

## FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

At the committee's first meeting, it sought clarification from the Bureau of Reclamation regarding some of the language in the charge to the committee. Written clarification provided after the meeting was as follows:

> **Project Scope Question A:** *Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils?*
> **Reclamation Clarification:** This question is intended to seek the committee's technical assessment of the ability of this corrosion mitigation system to protect DIP from corrosion in highly corrosive soils. This question is not intended to solicit a response on how effective this system is, only if the committee does or does not believe the system is a technically sound approach to corrosion mitigation in highly corrosive soils.
> **Project Scope Question B:** *Will polyethylene encasement and cathodic protection reliably provide a minimum service life of 50 years?*
> **Reclamation Clarification:** This question is intended to seek the committee's technical assessment of the ability of DIP, installed in severely corrosive soils with CP and PE, to delay or reduce corrosion induced failures to a level that would allow the pipeline to provide reliable service for the minimum 50-year service life, which Reclamation requires. The question of what Reclamation considers *reliable service* is discussed below in our responses to some additional questions posed by the committee.[2]

[2] Michael Gabaldon, Bureau of Reclamation, letter to Emily Ann Meyer, National Research Council, re: National Academies Review of the Bureau of Reclamation's Corrosion Prevention Standards

Regarding the first question, on whether PE with CP works on DIP in highly corrosive soils, **the committee finds that if manufactured and installed correctly, polyethylene encasement with cathodic protection provides *a betterment* to bare and as-manufactured ductile iron pipe without cathodic protection in highly corrosive soils.**

Regarding the second question, on whether PE and CP reliably provide a minimum service life of 50 years, the committee asked Reclamation for a definition of what level of reliability it seeks for the 50-year service life. The response was that, ideally Reclamation would prefer that its pipeline systems be designed in such a way that no failures would take a system out of service during a service life of 50 years. However, it is recognized that no engineering system can be designed to ensure absolutely that no failures will occur, and Reclamation advised the committee that the level of reliability experienced by the extensive natural gas pipeline systems in the United States is a reasonable benchmark to strive for in its water pipeline systems. Reclamation calculated a benchmark failure rate from natural gas pipeline data from the Office of Pipeline Safety in the U.S. Department of Transportation. The committee also studied the data sets available from the Office of Pipeline Safety and calculated rates of failure for these pipelines.

The committee then studied the available research data on the corrosion rates of DIP protected by PE and by PE with CP. It went on to find and evaluate known failures on water pipelines using these corrosion mitigation systems. The available data on known failures of DIP with PE and CP in highly corrosive soils are sparse, since relatively little DIP—perhaps in the hundreds of miles—has been installed in highly corrosive soils with this corrosion mitigation system in place. Although DIP with CP and PE should work in theory and has been successful in many instances, the practical application of these technologies has not always been successful. Moreover, in order to provide a full analysis of the potential reliability of this system, it was necessary for the committee to focus on the failures rather than on the successes.

**The committee finds that the limited data available and the scientific understanding of corrosion mechanisms show that ductile iron pipe with polyethylene encasement and cathodic protection is not likely to provide a reliable 50-year service life in highly corrosive soils (<2,000 ohm-cm).**

In part, this finding reflects the high standard set by the highly engineered and maintained gas pipeline systems and in part it reflects a meager but marginally significant set of data demonstrating probabilities of failure higher than the benchmark rate.

In view of that finding, it was necessary for the committee to address the

for Ductile Iron Pipe—A Response to the Committee's Request for Clarification on Project Scope, August 21, 2008.

request by the Bureau of Reclamation concerning recommendations for alternative standards that would provide a service life of 50 years. To carry out that task, the committee studied available and conceptual means of providing adequate corrosion mitigation that would meet Reclamation's benchmark. In doing so, it devoted considerable effort to analyzing the reliability experience for DIP with bonded dielectric coatings and CP in highly corrosive soils, since that system is the current stated specification of Reclamation.

**After considerable study and deliberation, the committee finds that using the performance of bonded dielectric coatings on steel pipe with cathodic protection as a benchmark for reliability, and based on available information, it is unable to identify *any* corrosion control method for DIP that would provide reliable 50-year service in highly corrosive soils.**[3]

The committee considered other corrosion mitigation methods such as anti-MIC (microbiologically influenced corrosion) PE, microperforated PE, zinc coatings with epoxy top coat, controlled low strength material backfill, and the building in of a corrosion allowance. **The committee finds that these other corrosion mitigation methods show promise, but the evidence is too limited to make any recommendations for their use at this time.** This finding does not mean that any of these corrosion mitigation systems *will not* meet the required benchmark, but rather that the data are insufficient to draw a conclusion in either the affirmative or the negative.

The majority of the data were on bonded dielectric coatings with CP on DIP, and although the committee is aware of no failures for systems in place, the length of time during which these systems have been in place is generally less than 50 years, and the number of miles of such pipeline again is in the hundreds. **Therefore, while the use of bonded dielectric coatings with cathodic protection (CP) on ductile iron pipe (DIP) appears to be more effective than the use of polyethylene encasement with CP on DIP, the committee finds that it has insufficient evidence to assure that bonded dielectric coating with cathodic protection will meet the expected level of reliability.**

The committee recognizes that the case for using bonded dielectric coatings with CP appears to be supported in part by analogy with such coatings on steel pipe. Steel pipe, DIP, and cast iron pipe are generally acknowledged to corrode at roughly the same rate. Bonded dielectric coatings with CP are used on the steel pipe analyzed to set the benchmark standard for gas pipelines. Therefore, simple logic would suggest that bonded dielectric coatings on DIP should provide the same level

[3]Committee member Alberto A. Sagüés, while agreeing with the committee's conclusions and recommendations, disagreed with the interpretation of the data. His dissenting statement appears in Appendix B.

of protection of DIP against external corrosion. However, some of the committee members thought that there could be no assurance that bonded coatings on DIP would function analogously with those on steel pipe.

A primary concern is that the cast surface of DIP is rougher than that of steel, reflecting the texture on the mold surfaces for DIP. As a result, the surface preparation of DIP is quite different from that of steel. Additionally, the nature of pipe section connections for DIP involves a bell on one end of the pipe, imparting significant diameter fluctuations along the pipeline not seen in the welded steel pipe used for natural gas pipelines. This diameter variability poses different challenges for a complete bonded dielectric coating on DIP because the spiral wrapping specified for tape is reportedly difficult to achieve on conically shaped objects, bends, and other irregular shapes.[4]

There is also a drawback to CP when it is used with coatings. Whether they are PE or bonded dielectric, coatings provide their own level of corrosion protection and limit the current needed for adequate corrosion protection compared to that needed for bare pipe protected only with CP; both are advantageous characteristics. However, if the coatings are damaged as a result of tears, breaks, or other defects in the dielectric layer, reactants for corrosion can enter the area between the pipe and the coating. CP will protect the pipe in the vicinity of the damage, but the needed current does not protect at distances from the damage where corrosion may eventually appear, a phenomenon known as current shielding. This is particularly acute with PE as there is no intended bonding between the pipe and the PE.

**Despite these shortcomings in surface preparation and in ensuring adequate cathodic protection (CP), the committee finds that bonded dielectric coatings with CP may provide superior protection to ductile iron pipe when compared to the protection provided by polyethylene encasement with CP.**

The committee recommends several areas in which additional studies could clarify these findings and provide data to improve the reliability of water-carrying pipe systems.

- **The committee recommends that to improve the reliability of existing pipelines, modern testing systems such as intelligent in-line inspection ("smart pigging") should be studied and introduced in order to monitor more closely the corrosion of pipes and permit the repair of pipe systems prior to failure.**

The adoption of such pipeline monitoring systems that send a remotely con-

[4] L. Gregg Horn, *Product Advisory: Tape Coat* (Birmingham, Ala.: Ductile Iron Pipe Research Association, 1990).

trolled measuring device down the pipe to collect data such as pipeline wall thickness is not common in the water industry, but if adopted they could enhance the reliability of these pipelines, particularly where failure would have large negative impacts. The method of random digging to diagnose the corrosion behavior of pipelines is inadequate to predict the state of corrosion for the total pipeline and thus to examine fastest corrosion rates at the tail of the distribution. Studies should be initiated to evaluate some of the promising corrosion control systems considered in this study for water pipelines in order to determine whether the adoption of any of these systems would meet the desired level of pipeline reliability. There is evidence that better monitoring has led to enhanced reliability on the gas pipeline system. It is expected that a similar asset management program for critical water pipelines would enhance the reliability of these systems as well.

- **The committee recommends that data on pipeline reliability be assembled for all types of pipe specified by the Bureau of Reclamation in Table 2, entitled "Corrosion Protection Criteria and Minimum Requirements," in Technical Memorandum 8140-CC-2004-1 along with the specified corrosion protection applied in the various soil types.**

The Bureau of Reclamation and the committee had to rely on an expansive, but not entirely analogous, data set from the U.S. Department of Transportation on gas pipelines to set a benchmark for achievable pipeline reliability. The committee evaluated these data in many ways, but it believed that more data should have been available on the reliability of water pipelines of the type that Reclamation specifies. While the challenge to Reclamation's specifications concerned only DIP in highly corrosive soils, there are other categories of pipes (steel, pretensioned concrete, and reinforced concrete) and corrosion mitigation methods (including mortar/coal tar epoxy, mortar, concrete, and concrete/coal tar/epoxy; the methods vary depending on the pipe material) that are not challenged, and implicit is the assumption that these pipe types and corrosion mitigation methods meet Reclamation's expectations for reliability. Therefore, had such reliability data been available on this large body of installed pipelines, a better-justified reliability benchmark reflecting Reclamation's expectations could have been calculated. Such information would also allow the Bureau of Reclamation to gain a better understanding of what level of reliability it will accept and at what cost.

The committee believes that the questions on adequate corrosion protection for DIP in highly corrosive soils and the appropriateness of Reclamation's specifications can be answered with greater certainty only after more data are generated. Greater experience is needed with the use of DIP in highly corrosive soils protected both by PE with CP and by bonded dielectric coatings with CP. Only with such experience and the data on reliability from that experience can recommendations with more robust statistics be forthcoming. Unfortunately, the prospects for more data other than those from existing pipelines in the United States are not encouraging. While some users appear reluctant to use DIP with PE and CP in highly corrosive soils, others may find it difficult to obtain DIP with bonded dielectric coatings owing to its unavailability from U.S. manufacturers.

# 1

# Introduction

This report addresses the corrosion performance issues associated with ductile iron pipe (DIP) with polyethylene encasement (PE) and cathodic protection (CP). This chapter discusses the history of the standard that the committee is reviewing and the request for this report.

## THE BUREAU OF RECLAMATION'S TECHNICAL MEMORANDUM 8140-CC-2004-1: HISTORY AND DEVELOPMENT

The Bureau of Reclamation (Reclamation) of the U.S. Department of the Interior concisely summarized the history and evolution of its positions on the use of DIP in its projects in the Background section of Technical Memorandum (TM) 8140-CC-2004-1, which is entitled "Corrosion Considerations for Buried Metallic Water Pipe." Excerpts from that section follow:

> Reclamation first considered using [DIP] on projects in the mid 1960's. At that time, Reclamation's position from a corrosion standpoint was that ductile iron pipe would be treated the same as steel pipe, except that steel pipe could be coated with either cement mortar or a bonded dielectric coating (depending on soil conditions), while [DIP] could only be coated with a bonded dielectric coating.
>
> In the 1970s, Reclamation added PE . . . as an alternative corrosion mitigation method for [DIP].
>
> In the mid-1980s, a table was developed which outlined corrosion protection criteria for various types of metallic pipe. . . .

> In the early 1990s, Reclamation revised the table for both steel and [DIP]. For steel pipe, a coating option for mortar encased with coal tar epoxy was added. For [DIP], a footnote was added limiting the use of PE . . . on [DIP] to diameters of 24 inches or smaller and weights of 150 pounds per foot or lighter. This limitation was based on concerns that damage may occur to the PE . . . during the handling and installation of larger diameter and heavier pipe. The limitation was not based on the inability for larger pipes to be adequately protected by intact PE. . . . In 2003, Reclamation revised the footnote by adding the following: "NOTE: Given recent pipe industry experience with [DIP], Reclamation plans to reexamine this provision."
>
> Reclamation's use of [DIP] is somewhat limited. Approximately 30 miles of [DIP] have been installed on Reclamation-designed projects. The ductile iron pipelines on Reclamation designed projects were installed beginning in the late 1970s and are 24 inches in diameter or less.
>
> Additionally, over 300 miles of [DIP] have been installed on non-Reclamation projects where Reclamation has had oversight responsibilities (projects not designed by Reclamation). Ductile iron pipelines installed with Reclamation oversight typically have been installed with PE . . . and CP. To date, Reclamation is unaware of any failure of [DIP] on a Reclamation designed project or on a project for which Reclamation has had an oversight responsibility.[1]

Reclamation indicated to the National Research Council's (NRC's) Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe that since that statement in 2004, there have been corrosion leaks on Reclamation projects—one failure of DIP with PE and CP on the Southwest Pipeline in North Dakota in October 2004 and two leaks on the Fountain Valley Project in Colorado in 2007.[2]

Reclamation's guidelines are updated occasionally to reflect the most current and applicable corrosion design parameters, and—according to Reclamation's presentation[3] to the committee—in 2003 Congress prompted Reclamation to conduct an evaluation of the corrosion mitigation alternatives in Reclamation's April 23, 2003, table entitled "Corrosion Prevention Criteria and Requirements" and to recommend a more definitive standard. The evaluation conducted by Reclamation in response to the congressional directive analyzed the corrosion protection measures for buried metallic pipes currently used by Reclamation, with special focus on steel and DIP. Upon completion of this evaluation, Reclamation concluded that some changes were warranted, and it incorporated these changes into its 2004 Technical Memorandum. Reclamation concluded that—

---

[1] Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe," Washington, D.C., July 2004.

[2] Bureau of Reclamation Technical Service Center Staff, U.S. Department of the Interior, "Corrosion Considerations for Buried Ductile Iron Pipe," presentation to the committee, Washington, D.C., July 28, 2008.

[3] Bureau of Reclamation Technical Service Center, presentation to the committee, July 28, 2008.

- PE was acceptable on ductile iron pipe in all but the most corrosive environments.
- In highly corrosive soils, a more robust system was needed.
- Bonded coatings were available and, when used with CP, would provide that extra protection.[4]

The Bureau of Reclamation's "Corrosion Prevention Criteria and Minimum Requirements" of July 2004, excerpted from Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe," is reprinted as Figure 1-1 for reference. The row of primary interest to the committee is circled.

## CURRENT IMPLEMENTATION

Reclamation has good experience with both steel and DIP performance when the pipes are properly designed, manufactured, and installed. Consequently, Reclamation commonly specifies multiple pipe options, including steel and ductile iron, for its projects. When Reclamation designs or reviews corrosion protection plans for pipelines, many factors are considered, including the current guidelines in the "Corrosion Prevention Criteria and Minimum Requirements" table (see Figure 1-1). This table has been the center of considerable controversy primarily because it specifies bonded dielectric coatings for DIP in soils with resistivity equal to or less than 2,000 ohm-cm. Reclamation believes that this degree of protection is prudent for the pipelines that it designs, considering Reclamation's needs for reliability. However, the U.S. ductile iron pipe industry together with the Ductile Iron Pipe Research Association (DIPRA) as well as some users and corrosion consultants have argued that, under these soil conditions, PE (with specified corrosion monitoring and CP) provides adequate and economically acceptable protection. That controversy led Reclamation to sponsor this study.

Following is a brief synopsis of the minimum corrosion requirements from TM 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe."

The current corrosion prevention strategy and required corrosion control methods of Reclamation are based in part on a 10 percent probability of encountering soils with a given resistivity. Soils with soil resistivity values below certain levels require more stringent corrosion protection methods; higher resistivity soils require less stringent levels of corrosion control.

Metallic pipe in the bureau's TM 8140-CC-2004-1 is defined as steel, ductile iron, or any concrete pipe containing ferrous elements. Coatings vary from bonded dielectric coatings for steel and ductile iron, to PE for ductile iron, to mortar or concrete coatings with or without a coal tar epoxy top coat for steel and concrete

[4] Bureau of Reclamation Technical Service Center, presentation to the committee, July 28, 2008.

Corrosion Prevention Criteria and Minimum Requirements[1]

| Pipe Alternative | Soil Resistivity—10% Probability Value (ohm-cm) | Minimum External Protection (Primary / Supplemental) | Corrosion Monitoring | Cathodic Protection[2] |
|---|---|---|---|---|
| Ductile Iron | ≤2,000 ohm-cm | Bonded dielectric[3] | YES | YES |
| | >2,000 ohm-cm <3,000 ohm-cm | Polyethylene encasement | YES | YES |
| | ≥3,000 ohm-cm | Polyethylene encasement | YES | NO |
| Pretensioned Concrete | <3,000 ohm-cm | Mortar / coal-tar epoxy | YES | YES |
| | ≥3,000 ohm-cm | Mortar | YES | NO |
| Reinforced Concrete | <3,000 ohm-cm | Concrete / coal-tar epoxy | YES | YES |
| | ≥3,000 ohm-cm | Concrete | YES[4] | NO |
| Steel | ≤2,000 ohm-cm | Bonded dielectric[3] | YES | YES |
| | >2,000 ohm-cm <3,000 ohm-cm | Mortar / coal-tar epoxy | YES | YES |
| | ≥3,000 ohm-cm | Mortar | YES | NO |

[1]This table [presents what] should be considered to be the minimum corrosion prevention requirements for a pipeline corrosion design. Additional soil conditions and risk assessment factors should be considered on a case-by-case basis for each specific project.
[2]OMR&E [operation, maintenance, replacement, and energy] costs for cathodic protection for each pipe type should be evaluated.
[3]Bonded directly to the metal to be protected.
[4]Corrosion monitoring is required for concrete pipe with steel joint rings, but not for concrete pipe with concrete joints.

FIGURE 1-1 The Bureau of Reclamation's Table 2, "Corrosion Prevention Criteria and Minimum Requirements," July 2004. SOURCE: Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe," Washington, D.C., July 2004.

pipe types. Cathodic protection consists of either galvanic anode or impressed-current-type CP systems.

The current corrosion criteria and requirements summarized in the TM's Table 2 (see Figure 1-1) list the minimum corrosion control methods required based on soil resistivity values. While more stringent corrosion control methods can be selected if desired by the designer or owner, this table provides the minimum level of corrosion control required for the four different types of pipe materials.

As previously stated, the overall corrosion protection methods required are based in part on a 10 percent probability of encountering soils with a given resistivity. The soil resistivity values for the minimum corrosion protection measures required were revised in the July 2004 requirements to include the following:

- For both steel and ductile iron, a bonded dielectric coating, corrosion monitoring, and CP are required for soil resistivities below 2,000 ohm-cm. The minimum corrosion control requirement for soil resistivities between 2,000 and 3,000 ohm-cm is an unbonded coating (PE for DIP and cement mortar with coal tar epoxy for steel pipe) with both corrosion monitoring (test stations and joint bonding) and CP. For soil resistivities above 3,000 ohm-cm, the minimum corrosion control requirement is PE with corrosion monitoring for DIP and mortar coating and corrosion monitoring for steel pipe.
- Although corrosion monitoring is not a protection measure, it is required for all pipe materials regardless of soil conditions. CP is required for both steel and DIP regardless of coating type for all soils in conditions with resistivities below 3,000 ohm-cm. This includes both bonded dielectric coating and loose-bonded coated (polyethylene encased) DIP.

In addition to Reclamation's minimum corrosion requirements as shown in Figure 1-1, the Technical Memorandum also recommends that the following items be considered during the corrosion evaluation and selection of the minimal corrosion control protection required for each project and pipe type:

- Reclamation points out that in evaluating soil corrosion factors, the use of soil resistivity values alone (see Reclamation Table 2 in Figure 1-1) does not address the need for the evaluation of other soil corrosion factors such as the presence of pH, sulfates, chlorides, and stray current interference. For soils above 2,000 ohm-cm, Reclamation recommends that since bonded dielectric coatings are not required in these conditions, additional soil tests be performed to ensure that there are not any other conditions that could cause severe corrosion cells to develop.
- In soil conditions with soil resistivities below 2,000 ohm-cm, Reclamation

points out that additional soil testing may not be necessary, since the more stringent corrosion control measures are already required.

- Reclamation recommends that each pipe route be evaluated to determine if soil conditions change dramatically. Where route conditions vary greatly, the potential for corrosion may be greater, and the required corrosion prevention methods should be adjusted accordingly.
- Where PE is utilized, the use of sand or rounded 0.25-inch (0.625-mm) diameter or smaller backfill should be considered in order to minimize damage to the PE.
- Reclamation recommends that a life-cycle cost analysis be considered for the different pipe, coatings, and corrosion control options being evaluated.
- Reclamation recommends that a CP life-cycle analysis comparison be included in the evaluation of the different initial pipe materials costs. The Technical Memorandum recommends that an adjustment for operation, maintenance, replacement, and energy costs be made for different CP systems where different pipe coating types are allowed. This evaluation should include the differing costs for the CP systems needed because of the higher amount of CP current required for corrosion control options with different coating types and efficiencies.
- More conservative corrosion control measures may be adopted in the presence of additional soil conditions and risk assessment factors on a case-by-case basis for specific projects. Reclamation recommends a risk assessment analysis to evaluate the pipe use, ease of access, pressure requirements, and other pertinent design information to be considered. It recommends that the risk assessment be used in determining the level of corrosion protection required, regardless of soil resistivity.

In its presentation to the committee,[5] Reclamation identified the following six technical concerns with the use of PE in highly corrosive soils:

1. Holidays and damage (e.g., tears, punctures, or other types of damage that penetrate the PE) can and do occur in PE;
2. Corrosion can occur away from the holidays or damage under intact PE as long as water and an oxidizer are available to support the electrochemical process;
3. Holidays or damage allow water, dissolved oxygen, and other chemical species from the surrounding soil environment to get between the PE and the pipe wall to facilitate this corrosion;

[5] Bureau of Reclamation Technical Service Center Staff, presentation to the committee, July 28, 2008.

4. While CP can mitigate corrosion at the holidays or damage, most in the industry agree that it will not provide a benefit far from the holiday due to the shielding effects of the encasement;
5. In mildly or moderately corrosive soils, Reclamation believes that corrosion away from the holidays or damage is likely to progress at a slow enough rate to allow the pipe to reach its (50-year) service life; and
6. In highly corrosive soils, the accelerated rate of this corrosion is more likely to produce pipe failures before the pipe reaches its service life.

In its presentation, Reclamation concluded that most corrosion engineers believe that a bonded dielectric coating with CP provides more robust protection, as supported by the National Association of Corrosion Engineers (NACE) Standard SP0169.[6] Reclamation's presentation concluded with the statement that since 2004, the bureau has believed that corrosion under intact PE occurs but that it is relatively slow to develop and difficult to detect. Reclamation believes that as time passes and this corrosion progresses, a significant problem will emerge, preventing DIP with PE from reaching the service life desired by the bureau.

In the presentation by Reclamation it was further stated that the bureau has continued to review and evaluate all available data and reports and still believes that its 2004 Technical Memorandum 8140-CC-2004-1 reflects a reasonable and balanced approach to corrosion control for DIP. However, it understood that others have different viewpoints and believed that the National Research Council could provide the independent review of the issue that the Secretary of the Interior was seeking.

## RECLAMATION'S REQUEST

The Bureau of Reclamation has sponsored this study by the National Research Council with the following charge:

> Issue a report containing [the NRC committee's] findings and conclusions regarding the appropriateness of the corrosion prevention requirements. In particular the report will address the following questions:
> —Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils?
> —Will polyethylene encasement and cathodic protection reliably provide a minimum service life of 50 years?

The charge went on to say:

[6] NACE Standard SP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems. NACE International, Cleveland, Oh., 2007.

—If the committee answers either of the above questions in the negative, the committee will provide recommendations for alternative standards that would provide a service life of 50 years.

At its first meeting, the committee established by the NRC to conduct this study sought clarification from Reclamation on the meaning of the word "work" in the question, *Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils?* and on the definition of "reliably" in the question, *Will polyethylene encasement and cathodic protection reliably provide a minimum service life of 50 years?*

Reclamation considered the definitional questions and gave the committee oral feedback during its first meeting on July 28, 2008. During that discussion, Reclamation stated that its view that for PE with CP to "work" on DIP installed in highly corrosive soils, it should deliver the project benefits for the design lifetime of 50 years without failure due to external corrosion. For the PE and CP to "reliably" provide a minimum service life of 50 years, Reclamation prescribed a system that would have no failures due to external corrosion that would cause the system to be out of service during the 50-year service life. This initial feedback was clarified later in writing.[7]

Reclamation stressed that its standard generally applies to large transmission systems in which a failure has severe consequences, such as the interruption of municipal water to an entire community or city.

The committee sympathized with Reclamation's need to ensure the reliability of its pipeline systems, but it emphasized that no engineering system can ever be guaranteed to have no failures. Rather, most engineered systems have a small, but nonzero, probability of failure. To ensure that there can never be a loss of service would probably necessitate redundant systems, and this is done in some water supply systems in the United States, although it is generally considered cost-prohibitive in systems as lengthy as those under Reclamation's oversight.

Therefore, Reclamation was asked if it could quantify the upper limit on acceptable failure rates, perhaps as the number of failures per mile per year to meet its definition of reliable service life for 50 years. Reclamation responded that it would provide more information later in that regard, but it agreed that if the information was insufficient to define an upper limit on the probability of a failure, then the committee could assess existing data and make its best estimate of what would be reasonable assurance of reliable service for 50 years.

Reclamation provided written responses to these and associated questions in

[7] Michael Gabaldon, Bureau of Reclamation, letter to Emily Ann Meyer, National Research Council, re: National Academies Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe—A Response to the Committee's Request for Clarification on Project Scope, August 21, 2008.

its letter of August 21, 2008. For the primary queries, the questions and answers were as follows:

> **Project Scope Question A:** *Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils?*
> **Reclamation Clarification:** This question is intended to seek the committee's technical assessment of the ability of this corrosion mitigation system to protect DIP from corrosion in highly corrosive soils. This question is not intended to solicit a response on how effective this system is, only if the committee does or does not believe the system is a technically sound approach to corrosion mitigation in highly corrosive soils.
> **Project Scope Question B:** *Will polyethylene encasement and cathodic protection reliably provide a minimum service life of 50 years?*
> **Reclamation Clarification:** This question is intended to seek the committee's technical assessment of the ability of DIP, installed in severely corrosive soils with CP and PE, to delay or reduce corrosion induced failures to a level that would allow the pipeline to provide reliable service for the minimum 50-year service life, which Reclamation requires. The question of what Reclamation considers *reliable service* is discussed below.[8]

In that following discussion, Reclamation reiterated, "Our target performance level is zero external corrosion induced leaks/ruptures/failures which would require the pipeline to be taken out of service during the minimum service life (i.e., 50 years)."[9] The bureau's response went on to justify the concept of zero leaks based on experience that pipelines have failure records with a "bathtub" shaped curve, where there may be a relatively high failure rate early in the life of a pipeline due to improper installation or other human errors, followed by a period of very low (or in many cases, zero) failures, again followed by a period of increasing failures due to factors such as external corrosion. The committee accepts that data can be obtained for pipeline projects that support this "bathtub" curve shape, and that the technical reasoning behind each of the stages is sound. The committee also accepts that in many cases the period of low failure rates may include many years of zero failures. However, the committee continues to maintain that no pipeline can be engineered to provide a probability of failure that is exactly zero for any specified period of time. That probability can be vanishingly small leading to extensive data showing no failures, but the probability can never be exactly zero.

Therefore, the committee sought data from Reclamation that might put an upper bound on the acceptable probability of failure. In particular, the committee asked if Reclamation would accept a failure rate for DIP installed in severely corrosive soils with PE and CP similar to the failure rate that it would get from steel pipe with a bonded dielectric coating and CP installed in highly corrosive soils. Reclamation's response was as follows:

---

[8] Gabaldon, letter to Meyer, August 21, 2008.
[9] Gabaldon, letter to Meyer, August 21, 2008.

> We have concluded that the level of performance provided by steel pipe, installed in severely corrosive soils with cathodic protection and bonded dielectric coating, is a *reasonable benchmark* [emphasis added] against which to measure the performance of ductile iron pipe installed in severely corrosive soils with polyethylene encasement and cathodic protection.[10]

The committee considered that since there were various data available on the performance of steel pipe with CP and bonded dielectric coating, this provided a starting point for defining an acceptable level of reliability expected by Reclamation for DIP with PE and CP in highly corrosive soils. Reclamation also sought data on such pipeline failure and found that the largest data set available on steel pipe, installed in severely corrosive soils with CP and bonded dielectric coating, was available through the Office of Pipeline Safety (OPS) in the U.S. Department of Transportation's (DOT's) Pipeline and Hazardous Materials Safety Administration (PHMSA). Reclamation correctly noted that these data are "related to steel pipelines carrying materials other than water, but the causes and rates of external corrosion and protection against such corrosion are the same regardless of the product being carried." Reclamation went on to state: "We have, therefore, concluded that this database is the best source of quantitative data on this issue to date."[11] The committee concurs in this conclusion.

Reclamation reviewed the data from the OPS with the following comment:

> We focused our review of this data on those pipelines that most closely matched the Committee's interest (i.e., coated steel pipe installed with cathodic protection) and, like most of Reclamation's projects, were transmission lines versus smaller distribution lines. We also limited our review to significant incidents[12] that were caused by external corrosion.
>
> Focusing on this subset of data within DOT's database, we were able to compute an average annual failure rate for these pipelines of 0.0000444 failures per mile per year (based on about 93,000 miles of installed steel pipe). Using the results of this analysis, a 450-mile long steel pipeline installed with coating and cathodic protection could be expected to experience one failure due to external corrosion during the first 50 years of service.[13]

Concerning this data set, Reclamation also noted the following:

> The DOT data is extremely helpful in quantifying the performance this corrosion mitigation system has achieved on steel pipe in real world conditions, and the average age of the

[10] Gabaldon, letter to Meyer, August 21, 2008.

[11] Gabaldon, letter to Meyer, August 21, 2008.

[12] A "significant incident," as defined by the Department of Transportation for these pipelines, involved one or more of the following: (1) a fatality or injury requiring in-patient hospitalization; (2) $50,000 or more in total costs; (3) highly volatile liquid releases of five barrels or more or other liquid releases of 50 barrels or more; or (4) liquid releases resulting in an unintentional fire or explosion.

[13] Gabaldon, letter to Meyer, August 21, 2008.

> pipe in the data set (49.5 years) happens to be close to Reclamation's 50-year minimum service life. However, the DOT database does not include information on the soil conditions in which the pipelines are installed, so we are unable to further screen the data to include only pipe installed in severely corrosive soils. We are not able to quantify the impact this issue has on the calculated performance data noted above, but some adjustment to the computed failure rate may be warranted to compensate for this uncertainty in soil conditions across the data set.[14]

Reclamation provided the committee with a simple analysis to determine the annual failure rate per mile of steel pipe with dielectric coating and CP. However, this rate of 0.000044 failures per mile per year included failures that occurred after 50 years and only included pipelines with failures. A failure that occurs after 50 years would be considered as meeting Reclamation's requirements. The committee reviewed these data sets and chose to include a few weld seam failures not considered by Reclamation. Also, pipelines with no failures should be included in the total mileage of the pipe. Thus, the committee reanalyzed the data, excluding the failures after 50 years, which resulted in a failure threshold value of 0.000012 failures per mile per year. The committee believes that such a failure rate is another benchmark, and uses it for the purpose of comparing it to rates of failure as gleaned from other data sets with fewer data points. The OPS data set applies to natural gas transmission pipelines. The oil and gas industry has established asset management programs in the past two decades whereby pipelines are routinely inspected with advanced techniques and repaired before a failure occurs. The data on repairs were unavailable to the committee to account for this effect. Therefore, this OPS data set may not reflect all failures that might have occurred were these water transmission pipelines.

To address this last issue, the committee obtained an earlier data set from OPS. It was made up of gas transmission pipeline failures from a time when inspection procedures were more similar to those currently employed on water transmission lines. These data were analyzed in a fashion similar to the analysis described above, resulting in an alternative benchmark of 0.000041 failures per mile per year.

## MEETINGS

In order to address its charge, the committee held two meetings. The first, on July 28-30, 2008, at the Keck Center of the National Academies in Washington, D.C., included open presentations and closed deliberation time. On the first day, the committee heard from officials of the Bureau of Reclamation and used some of this time to ask for clarification on the committee's statement of task, in addition to learning more about Reclamation's function and reasons for requesting this study.

[14] Gabaldon, letter to Meyer, August 21, 2008.

Additionally, the committee heard the perspective of DIPRA, which has been one of the critics of Reclamation's standard for pipelines in soils with resistivities less than 2,000 ohm-cm. On the second day, the committee heard from Graham E.C. Bell, with Schiff Associates; Michael Szeliga, with Russell Corrosion Consultants; and Mike Woodcock, with the Washington Suburban Sanitary Commission,[15] who provided greater perspective from the point of view of individuals who encounter these issues on a regular basis.

The committee's second meeting was held on September 28-30, 2008, at the J. Erik Jonsson Center of the National Academies in Woods Hole, Massachusetts, and was closed in its entirety to allow the committee to come to consensus on the report's findings, conclusions, and recommendations, and to continue to draft the report.

In addition to these two face-to-face meetings, the committee met regularly via teleconference to discuss progress in information gathering and data analysis and to identify and request additional data for its analysis.

## STRUCTURE OF THE REPORT

Following this introductory chapter, the report provides technical background information on corrosion, corrosion control, and ductile iron pipe in Chapter 2. It then presents in Chapter 3 some cases that illustrate the issues contributing to corrosion-related failures of DIP, and discusses in Chapter 4 the data compilation and analysis used by the committee to formulate its conclusions and recommendations. Chapter 5 discusses other methods of corrosion control, and Chapter 6 presents the committee's findings, conclusions, and recommendations.

It is important to note that the charge to the committee is a technical one. Thus, while much criticism over the appropriateness of bonded dielectric coatings on DIP centers on the relative expense of this corrosion control method as compared to that of PE with CP, the committee was not tasked to, nor did it, conduct an economic analysis. Rather, the committee regards cost as a question that must be considered by the Bureau of Reclamation and pipeline owners on the basis of the relative utility of each method and individual project needs.

[15] Mr. Woodcock was speaking based on his own expertise, not as a representative of Washington Suburban Sanitary Commission.

# 2

# Ductile Iron and Corrosion

## DUCTILE IRON PIPE

Ductile iron pipe (DIP) is a ferrous-based alloy fabricated into seamless pipe using a centrifugal casting process in which the mold is rotated while the molten metal (1399°C) is poured into it from bell to spigot.

For water and sewage distribution applications, the specifications for DIP are based on mechanical properties rather than on chemical composition. Typically, the grade of DIP for these applications is 60-42-10, indicating a minimum required tensile strength of 60,000 pounds per square inch (psi) (414 megapascal [MPa]), a minimum required yield strength of 42,000 psi (289 MPa), and a minimum required elongation of 10 percent. While the nominal composition in mass fraction for unalloyed ductile iron is 3.1 to 3.9 percent carbon, 2.1 to 2.8 percent silicon, and less than 1 percent of other elements (chromium, nickel, molybdenum, and others) with the balance iron, it is the shape and distribution of the nodular carbon within the iron matrix that imparts the desired mechanical properties. Heat treatments and chemical additives (e.g., magnesium) are used to transform the as-cast microstructure into a softer material with uniformly distributed graphite nodules, which give the ductile iron the desired combination of strength, ductility, and resistance to fracture for use in water transmission pipelines. The annealing heat treatment also produces an adherent, silicon-rich oxide layer of ~5 mils (0.125 millimeters [mm]) on the surface of the pipe that is subsequently coated with ~1 mil (0.025 mm) of asphaltic coating, which prevents atmospheric corrosion and maintains the aesthetic appearance of the pipe prior to burial. For water-bearing applications, the pipe is also internally lined with cement mortar.

Ductile iron contains approximately 3.5 percent graphite by weight. The final microstructure of ductile iron consists of a uniform distribution of graphite nodules within a ferritic iron matrix. When corrosion occurs, the carbon present remains an integral part of the corrosion by-products that adhere firmly to the noncorroded metal substrate. These graphitic by-products are not as strong as the original iron matrix but do have some mechanical strength and can provide a barrier against further corrosion. Left undisturbed, the residual carbon can slow or even stop the corrosion process in many soil environments. The spherical graphite structure of DIP promotes more uniform corrosion over the surface of the metal as opposed to more localized attacks.[1] The electrical discontinuity (isolation) of the individual ductile iron pipeline sections (without cathodic protection [CP]) is considered important by some for avoiding the creation of corrosion cells over extended distances, as well as for preventing stray current accumulations. Others recommend that joints be bonded to allow corrosion monitoring and interference mitigation. Of course, such electrical isolation is neither possible nor desirable when CP is used for the protection of the pipeline as it is for the subject of this study.

With respect to DIP metallurgy for transmission applications, DIP manufacturers have stated that alloying elements, such as nickel, improve the corrosion resistance but may degrade the mechanical properties of DIP.[2] However, alloying additions also significantly increase the cost of the pipe. Based on experience and according to the available literature, changes in the chemical composition and microstructure to improve the corrosion resistance of DIP within the guidelines of the performance specifications from the American National Standards Institute (ANSI) and the American Water Works Association (AWWA) have not been explored and are not considered an engineering alternative at this time.

After the casting and annealing process, DIP has an exterior surface that looks “peened.” The peened surface has an irregular profile of approximately 5 to 15 mils (0.127 to 0.381 mm), depending on the manufacturer and casting process. The standard length of DIP in the United States is between 18 and 20 feet. A minimum yield strength of 42,000 psi (290 MPa) is required for DIP. The casting allowance is between 0.05 and 0.09 inch depending on pipe size, and the service allowance is 0.08 inch regardless of pipe size.

---

[1] Troy Stroud and James Voget, “Corrosion Control Measures for Ductile Iron Pipe,” 46th Annual Appalachian Underground Corrosion Short Course (Morgantown, W.Va.: West Virginia University, 2001).

[2] Gene Oliver, “Memo on Ductile Iron Pipe Metallurgy for the NAS Committee,” September 8, 2008.

Currently, U.S. manufacturers cast pipe in standard pressure classes of 150, 200, 250, 300, and 350 psi, with a minimum thickness of 0.25 inch. The wall thickness required for a section of pipe is determined on the basis of hoop stress induced in the pipe wall by the internal pressure that the pipe is to carry, or on the basis of external loads, and owners and engineers can specify wall thickness different from the standard thickness. Table 2-1, which is derived from application of the conventional formula and has been presented in various forms in AWWA publications, shows the wall thicknesses of pipe manufactured in the United States today.

Of relevance to this study is the fact that, over time, as manufacturing processes have improved and control of metallurgy has become more consistent, DIP manufacturers have been able to produce pipe with increasingly thinner walls. For example, a 30-inch pipe manufactured before 1992 for the lowest thickness

TABLE 2-1 Wall Thickness of Ductile Iron Pipe, by Pressure Class

| Nominal Pipe Size (in.) | Outside Diameter (in.) | Pressure Class 150 | 200 | 250 | 300 | 350 |
|---|---|---|---|---|---|---|
| | | Nominal Wall Thickness (in.) | | | | |
| 3 | 3.96 | — | — | — | — | 0.25* |
| 4 | 4.80 | — | — | — | — | 0.25* |
| 6 | 6.90 | — | — | — | — | 0.25* |
| 8 | 9.05 | — | — | — | — | 0.25* |
| 10 | 11.10 | — | — | — | — | 0.26 |
| 12 | 13.20 | — | — | — | — | 0.28 |
| 14 | 15.30 | — | — | 0.28 | 0.30 | 0.31 |
| 16 | 17.40 | — | — | 0.30 | 0.32 | 0.34 |
| 18 | 19.50 | — | — | 0.31 | 0.34 | 0.36 |
| 20 | 21.60 | — | — | 0.33 | 0.36 | 0.38 |
| 24 | 25.80 | — | 0.33 | 0.37 | 0.40 | 0.43 |
| 30 | 32.00 | 0.34 | 0.38 | 0.42 | 0.45 | 0.49 |
| 36 | 38.30 | 0.38 | 0.42 | 0.47 | 0.51 | 0.56 |
| 42 | 44.50 | 0.41 | 0.47 | 0.52 | 0.57 | 0.63 |
| 48 | 50.80 | 0.46 | 0.52 | 0.58 | 0.64 | 0.70 |
| 54 | 57.56 | 0.51 | 0.58 | 0.65 | 0.72 | 0.79 |
| 60 | 61.61 | 0.54 | 0.61 | 0.68 | 0.76 | 0.83 |
| 64 | 65.67 | 0.56 | 0.64 | 0.72 | 0.80 | 0.87 |

NOTE: An asterisk in the last column refers to the minimum casting thickness for that size pipe. The pipe wall thickness is in excess of the requirements for a 350 pressure class rating. The dash indicates that pipe is not manufactured in that class. SOURCE: Adapted from standard pressure classes as given in AWWA C150 and C151. (American Water Works Association, ANSI/AWWA Standard C150/A21.50-02 (2002): "American National Standard for Thickness Design of Ductile-Iron Pipe." American Water Works Association, ANSI/AWWA C151/A21.51-09 (2002): "Ductile-Iron Pipe, Centrifugally Cast, for Water.")

class[3] (Class 50) would be 0.390 inch thick; if manufactured after 1992 for the lowest pressure class thickness (150 pressure class), the pipe would be 0.340 inch thick—a reduction in thickness of 13 percent. This demonstrable reduction in the pipe thickness will decrease the time required for corrosion to penetrate the entire thickness of the pipe.

## CORROSION MECHANISMS

External corrosion of DIP can occur in soils through a number of mechanisms, described in the following subsections.[4]

### Uniform Corrosion

*Uniform corrosion* is defined as "corrosion that proceeds at about the same rate over a metal surface."[5] It occurs when there are no anomalies on the surface or in the soil. This mechanism is not generally considered as serious as other mechanisms because corrosion rates are predictable and the pipe wall thickness can be specified for adequate strength even in the presence of corrosion.

It is should be noted that monitoring (discussed later in this report) can be used to evaluate the service condition of materials undergoing uniform corrosion, as this form of corrosion generally happens at a somewhat steady pace. Failures can be avoided through preventive maintenance based on what is learned through monitoring and inspection.

### Pitting Corrosion

*Pitting corrosion*, which is one of the more frequently seen forms of corrosion on DIP, is initially confined to a point or small area that takes the form of cavities.[6] These pits can penetrate deep in the metal and, in DIP, can cause failure due to perforation. Pits are usually initially small in diameter and isolated, and occur in areas that are more anodic with respect to the rest of the metal surface. Soils with relatively high concentrations of chloride, nitrate, or sulfate can cause pitting. Once a pit is initiated,

---

[3]Pipes manufactured prior to 1992 were manufactured to a "thickness" class rather than to the "pressure class" in use currently.

[4]L. Veleva, "Soils," in *Corrosion Tests and Standards*, R. Baboian, ed. (West Conshohocken, Pa.: ASTM International, 2005); P. Roberge, *Corrosion Basics, 2nd ed.* (Houston, Tex.: NACE International, 2006); S. Corcoran, "Effects of Metallurgical Variables on Dealloying Corrosion," in *Corrosion: Fundamentals, Testing and Protection, ASM Handbook, Vol. 13A* (Materials Park, Ohio: ASM International, 2003).

[5]American Society of Testing and Materials (ASTM), ASTM Standard G 15-08, *ASTM Book of Standards, Vol. 03.02* (West Conshohocken, Pa.: ASTM International, 2008), p. 57.

[6]ASTM Standard G 15-08.

an active corrosion cell is established in which rapid dissolution of metal in the pit produces an excess of positive metal ions that hydrolyze to form hydrogen ions and cause the environment in the pit to become more acidic. Once initiated, these pits can become autocatalytic, continuing even if the initial source of corrosion is removed.

Pitting can also be associated with local inhomogeneities on the metal surface, mechanical or chemical defects in films or coatings, galvanic effects, or biological activity. Pit propagation rates are not generally linear and, all other things being equal, unless autocatalytic, tend to decrease as the pit gets deeper.

Unlike some other forms of corrosion, pitting is not easily detected during corrosion monitoring or inspection. Thus, due to the difficulties in detection and the unique nature of the corrosion mechanism, pitting corrosion can be particularly damaging, leading to failure of the pipe with little or no warning.

### Crevice Corrosion

*Crevice corrosion*, a particular form of pitting, is the localized corrosion of a metal surface at or adjacent to an area that is shielded from full exposure to the environment.[7] Crevice corrosion is initiated at unbonded or disbonded coatings, gaskets, bell and spigot joints, surface deposits, and other crevice geometries. Oxidation occurs within the crevice, while reduction reactions (decreases in oxidation state) occur on the metal surface external to the crevice.

### Galvanic Corrosion

Buried metal systems that contain dissimilar metals are susceptible to *galvanic corrosion*, which is the accelerated corrosion of a metal that occurs when it is in electrical contact with a more noble metal in the soil.[8] The potential difference between dissimilar metals in electrical and electrolytic contact causes electron flow between them. Attack of the more noble metal is usually decreased and corrosion of the less noble (more active) metal is usually increased. For example, buried ductile iron can corrode at an accelerated rate when coupled to bare copper bonding straps or copper services. The extent of this corrosion depends not only on the magnitude of the potential difference of the metals, but also on their polarizability (i.e., the amount of current required to change the potential of the metals). This factor is dependent on the nature of the metal surfaces, the soil environment (i.e., conductive soil can contribute to galvanic corrosion, as it will determine the influence of the ohmic potential drop), their configuration (i.e., the distance between the dissimilar metals), and the area ratio of the different materials' surface area.

One example of galvanic corrosion of DIP in soils is the result of the corrosion

[7] ASTM Standard G 15-08.
[8] ASTM Standard G 15-08.

layer formed on iron pipe that has been buried for a relatively long time. This older pipe section is typically cathodic to a newer pipe, even when the composition of the older and newer pipe is identical. Therefore, when a section of DIP is replaced, the newer iron in contact with the older, passivated iron surface can locally corrode galvanically in the soil environment.[9]

Another example of galvanic corrosion is the effect of surface oxide films formed on DIP during fabrication. The oxide layer, or "scale," provides some corrosion protection to the metal if it remains adherent. However, this scale is brittle and vulnerable to impact; small pieces may crack and fall off the DIP surface. Areas covered with the oxide scale are cathodic to areas of bare metal, so galvanic corrosion of the bare metal can occur in the soil environment. This effect can be particularly damaging as the relative surface area ratios—that is, large cathode to small anode—are favorable to aggressive galvanic attack.

### Graphitic Corrosion

*Graphitic corrosion* is a form of selective leaching (the removal of one element from a metal or alloy by corrosion) unique to iron structures containing graphite.[10] The graphite is cathodic to the iron in the pipe, and therefore the iron corrodes galvanically leaving a graphite network. The nature of this graphite network is different in various cast irons. In ductile iron, the graphite precipitates as discrete spheroids and thus results in embedded nodules of graphite in a continuous iron corrosion matrix.

Graphitic corrosion occurs over time, often in water with varying chloride levels, to yield a structure that is weaker and more brittle than the original structure. Although little dimensional change occurs, the strength and other metallic properties—such as hardness and electrical and thermal properties—of buried pipe can be significantly altered. However, it has been shown that graphitized pipe can have enough mechanical strength to withstand minimum pressure requirements in service.[11] These pipes may ultimately fail under mechanical stresses such as water hammer[12] and frost heave.[13]

---

[9] Roberge, *Corrosion Basics*; Veleva, "Soils," in *Corrosion Tests and Standards*.

[10] Corcoran, "Effects of Metallurgical Variables on Dealloying Corrosion," in *Corrosion: Fundamentals, Testing and Protection*.

[11] T. Spence, "Corrosion of Cast Irons," in *Corrosion: Materials, ASM Handbook, Vol. 13B* (Materials Park, Ohio: ASM International, 2005).

[12] *Water hammer* consists of pressure variations caused by sudden changes in flow rates from closing of valves too quickly, pumps starting or stopping too quickly, or a sudden drop or increase in water flow, and so on.

[13] *Frost heave* consists of pressure from the soil on the pipe wall caused by the increased volume of a soil when it freezes. Other physical soil pressures can include the swelling of clays, frost going out of the ground, and excavation or physical activity near the pipe.

Graphitized iron pipe sounds dull when struck with a metal object, is soft (like a pencil), and can be gouged with a knife or screwdriver. To evaluate the damage fully, the graphite layer must be removed by abrasive blasting or tested by nondestructive evaluation methods (e.g., ultrasound or remote eddy field current). Recent papers summarizing an assessment of pipe material by both the city of Ottawa[14] and the city of Calgary[15] confirm that the pipe needs to be abrasively blasted (to remove surface debris) in order to identify the actual metal loss. This is so because the smooth surface appearance of graphitized cast iron, and in some cases ductile iron, may lead a casual observer to believe that the pipe has no corrosion damage and is still structurally sound.

### Microbiological Activity

Microbes can play an important role in the corrosion of metals owing to the chemical activities associated with their metabolism, growth, and reproduction.[16] This phenomenon is referred to as *microbiologically influenced corrosion* (MIC). Generally, microbes influence corrosion by changing the chemistry of the electrolyte at the metal surface, forming a biofilm. In buried soil environments, because of local chemistry, moisture, and surface characteristics, the moist soil itself is able to localize organisms near the metal surface and change the chemistry of the pore water in the soil.[17] Biological influences on this chemistry can be divided into four general categories: (1) production of organic or inorganic acids as metabolic by-products, (2) production of sulfides under anaerobic conditions, (3) introduction of new redox reactions, and (4) production of oxygen or chemical concentration cells. In soils, the most important of these categories is the production of sulfides by sulfate reducing bacteria (SRB).[18]

SRB are anaerobic and live in poorly drained, wet soils with little or no oxygen that contain sulfate ions, organic compounds, and minerals. Conditions for MIC due to SRB can vary but are typically in the range of a pH of 6 to 8 and temperatures from 20°C to 30°C. As temperatures increase, SRB metabolism also increases. During metabolism of the bacteria, oxygen is extracted from the sulfate ions, and

[14] L.B. Carroll, P. Eng, and J. Luffman, "Pipe Material and Soil Examination Techniques Used in the City of Ottawa Drinking Water System Maintenance and Planning Program," presented at the NACE International Northern Area Eastern Conference, Ottawa, Ontario, October 2003.

[15] G. Kozhushner, R. Brander, and B. Ng, "Use of Pipe Recovery Data and the Hydroscope® NDT Inspection Tool for Condition Assessment of Buried Water Mains," presented at the 2001 American Water Works Association Infrastructure Conference, Denver, Colo.

[16] Veleva, "Soils," in *Corrosion Tests and Standards.*

[17] S. Dexter, "Microbiological Effects," in *Corrosion Tests and Standards*, R. Baboian, ed. (West Conshohocken, Pa.: ASTM International, 2005).

[18] Veleva, "Soils," in *Corrosion Tests and Standards.*

this reaction converts the soluble sulfates to sulfides and promotes corrosion of the metal surface. MIC of metals by SRB is a well-recognized problem in DIP; the corrosion rate of DIP due to MIC can be over an order of magnitude greater than that in comparable sterile soils.[19]

### Stray Current

*Stray currents*—or interference in buried structures—are currents flowing through earth from a source not related to the structure. Sources of these currents include direct current (dc) equipment and systems such as electric railway and streetcar systems, grounded dc power supplies, electric welders, CP systems, electroplating plants, and electric transmission systems.[20] When these stray currents are discharged from the structure, such as a metal pipe, electrolytic corrosion may occur.

This type of corrosion could result from the interaction between an electric railway and a buried iron pipe. Current can enter the pipe from the railway positive feeder and travel to a location of discharge in close proximity to a negative return. Severe corrosion of the pipe can occur at this location.

## SOIL CORROSIVITY

Because of the complex content and characteristics of soils, a wide range of factors are important in soil corrosivity.[21] These include the following:

- Moisture content,
- Resistivity,
- Permeability,
- Chloride ion content,
- Sulfide ion content,
- Sulfate ion content,
- Presence of corrosion-activating bacteria,
- Oxygen content,
- pH, and
- Total hardness of soil moisture.

[19] Veleva, "Soils," in *Corrosion Tests and Standards.*

[20] Veleva, "Soils," in *Corrosion Tests and Standards.*

[21] J. Bushman and T. Mehalick, "Statistical Analysis of Soil Characteristics to Predict Mean Time to Corrosion Failure of Underground Metallic Structures," in *Effects of Soil Characteristics on Corrosion*, V. Chaker and D. Palmer, eds. (West Conshohocken, Pa.: ATM International, 1989).

### Soil Moisture

Soil corrosivity is strongly dependent on the amount of water retained by a soil and is a result of equilibrium between capillary and gravitational forces. The impact of moisture changes over time can also influence corrosion. For example, a sandy soil in a dry area may not be very corrosive. However, if there is infrequent moisture (from rain) and the soil contains chlorides, there can be highly aggressive, albeit transient, conditions of high corrosivity. During drying, these chlorides can become concentrated on the surface, making the local conditions even more aggressive. If pitting is initiated, this wet/dry process can lead to very intense corrosion, especially if the pits are small and become self-sustaining.

### Relative Acidity/Alkalinity, pH

Most soils range from pH 4 to 8, and in this range soils are considered to be less corrosive.[22] When lower than 4 and higher than 8.5, the pH can be a considerable factor in corrosivity. While natural environmental processes (e.g., mineral leaching, decomposition of plants, acid rain and snow, and some types of microbiological activity) can produce acidity in soils,[23] soils with pH levels in the extremes above this range are rarely found unless other contamination has occurred. A neutral pH is the most favorable for SRB that would contribute to MIC, as described earlier in this chapter.

### Resistivity

Electrical resistivity is an indication of the ability of an environment to carry corrosion current. A soil's resistivity is a function of moisture and the concentration of current-carrying soluble ions and is typically measured in ohm-cm, either in situ or by sampling from the actual environment. Soil resistivities can range from less than 1,000 ohm-cm in soils with high water and ion contents to more than 100,000 ohm-cm in dry sand or gravel.[24]

---

[22] Veleva, "Soils," in *Corrosion Tests and Standards.*

[23] Veleva, "Soils," in *Corrosion Tests and Standards.*

[24] D. Palmer, "Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping," in *Effects of Soil Characteristics on Corrosion*, V. Chaker and D. Palmer, eds. (West Conshohocken, Pa.: ASTM International, 1989); V. Chaker, "Corrosion Testing in Soils—Past, Present and Future," in *Corrosion Testing and Evaluation*, R. Baboian and S. Dean, eds. (West Conshohocken, Pa.: ASTM International, 1990); D. Palmer, "Field Soil Corrosivity Testing," in *Corrosion Testing and Evaluation*, R. Baboian and S. Dean, eds. (West Conshohocken, Pa.: ASTM International, 1990); E. Escalante, ed., *Underground Corrosion* (West Conshohocken, Pa.: ASTM International, 1981).

Models have been created that link soil resistivity to corrosion rate, and rating scales are commonly used for this purpose. However, other variables can influence soil corrosivity; the relationship between resistivity and corrosivity is more fully explored in the section that follows.

## DEFINITION OF HIGHLY CORROSIVE SOILS

Part of the charge to the committee is to answer the following question: Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils? In the committee's review of the charge and the literature, it became clear that the pipeline community does not have a common definition for "highly corrosive soils." The Bureau of Reclamation, in Table 2, "Corrosion Prevention Criteria and Minimum Requirements," of its Technical Memorandum 8140-CC-2004-1, defines "highly corrosive soils" as any soil with a soil resistivity of 2,000 ohm-cm or less (see Figure 1-1 in this report).[25] In their analysis of corrosion rates on iron piping used for water distribution, Kozhushner and colleagues report that soil resistivity is the most important factor, along with the type of pipe and wall thickness and the presence of copper services and conclude that soil resistivity below 2,000 ohm-cm is most corrosive to iron pipe.[26]

Alternatively, DIP manufacturers, through the Ductile Iron Pipe Research Association (DIPRA), have developed a 10-point system to evaluate other environmental conditions in addition to soil resistivity that contribute to ductile iron corrosion. This 10-point system uses soil resistivity, pH, redox potential, sulfides, and moisture to assess the corrosivity of a soil. This soil assessment method, although not a part of the ANSI/AWWA C105/A21.5-05 Standard, "Polyethylene Encasement for Ductile-Iron Pipe Systems," is included with that standard as Appendix A.[27] Under this soil corrosivity scale, a total of 10 points or more indicates that the soil is corrosive to as-manufactured DIP, and additional corrosion protection measures are recommended. When the effects of all other factors are eliminated, soil would have a resistivity of 1,500 ohm-cm or less to be considered corrosive to DIP.

Some utilities and corrosion consultants have developed their own methods for soil classification based on an expansion of the 10-point system. Some have developed a 25-point system[28] that assesses soil corrosivity as a function of the

[25] Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe," Washington, D.C., July 2004.

[26] G. Kozhushner, R. Brander, and B. Ng, "Use of Pipe Recovery Data and the Hydroscope® NDT Inspection Tool for Condition Assessment of Buried Water Mains."

[27] American Water Works Association, ANSI/AWWA Standard C105/A21.5-05 (2005): "Polyethylene Encasement for Ductile-Iron Pipe Systems, Denver, Colo."

[28] W. Spickelmire, "Corrosion Considerations for Ductile Iron Pipe—A Consultant's Perspective," *Materials Performance* 41(7):16 (2002).

pipeline type so as to assign a risk factor and allow designers to determine what level of corrosion control measures is appropriate. Another method is the proprietary Design Decision Model (DDM™) employed by Corrpro and DIPRA. This model expanded the 10-point soil evaluation system with the inclusion of field and laboratory data. The DDM™ risk model considers both the likelihood and the consequence of pipe failure due to external corrosion.[29]

The Bureau of Reclamation uses a 10-percentile probability to sense resistivity. This means that if resistivity measurements are performed for 100 separate soil samples, the 10th-lowest measured value is the soil resistivity used as the design criterion, which results in a conservative approach to determining corrosion control requirements for pipeline projects. Reclamation justifies this approach by stating:

> While all these factors are important in development of pipeline corrosion strategy, these tests can be cost intensive for long pipe alignments and very much subject to judgment or interpretation as to which point values should be assigned.[30]

It was noted by Reclamation during the committee's first meeting[31] and in Technical Memorandum 8140-CC-2004-1 that the designers of pipeline projects have the liberty to consider other factors but that the soil resistivity criteria in Table 2 of the Technical Memorandum (see Figure 1-1 in this report) are the absolute minimum.

However, it should be noted that, according to Reclamation's procedures, the designer is allowed to identify and treat areas differently as the circumstances dictate. For instance, if a pipeline is 20 miles long and 1 mile of soil is identified as highly corrosive and 19 miles are identified as moderately corrosive, the 1-mile section may be isolated and treated differently from the remaining 19 miles.

## METHODS OF CORROSION PROTECTION FOR DUCTILE IRON PIPE

Corrosion of buried and submerged metallic substrates is a naturally occurring phenomenon. As previously discussed, common causes of corrosion on buried DIP include low-resistivity soil, soil chemistry, anaerobic bacteria, the presence of dissimilar metals, and stray currents.

---

[29] D.H. Kroon, D. Lindemuth, S. Sampson, and T. Vincenzo, "Corrosion Protection of Ductile Iron Pipe," Corrosion 2004 Conference, Paper No. 46, Houston, Tex., 2004.

[30] Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, July 2004.

[31] Bureau of Reclamation Technical Service Center Staff, U.S. Department of the Interior, "Corrosion Considerations for Buried Ductile Iron Pipe," presentation to the committee, Washington, D.C., July 28, 2008.

There is no consensus on what corrosion protection methods would best protect DIP in specific environmental conditions. When corrosion protection for DIP is required or recommended, the following methods are commonly used either individually or in combination:

- Polyethylene encasement,
- Cathodic protection,
- Bonded dielectric coatings.

### Currently Available Corrosion Protection Methods

This subsection reviews corrosion control methods used for DIP. It identifies which are available in the United States and which are available only outside the United States. As noted in Chapter 1, "Introduction," this report does not discuss economic aspects of these corrosion control methods.

*Polyethylene Encasement*

The Ductile Iron Pipe Research Association and Corrpro have reported that the majority of soils found in North America are not considered corrosive to ductile iron.[32] Where the soils are considered aggressive, DIPRA recommends the addition of polyethylene encasement (PE) for corrosion protection. PE was introduced in 1958 and has evolved into two main products: linear, low-density polyethylene film (8 mils thick) and high-density, cross-laminated polyethylene film (4 mils thick). Both types of film are available in tube or sheet form.

AWWA adopted the first standard for PE, ANSI/AWWA Standard C105, in 1972, and other standards for PE are available in the United States, Japan, Great Britain, and Australia.[33] According to the ANSI/AWWA standard, PE is to be fitted to the pipe contour in a snug, but not tight, encasement with limited space between

[32] David H. Kroon, Dale Lindemuth, Sheri Sampson, and Terry Vincenzo, *Advanced Corrosion Protection Solutions for Ductile Iron Pipe* (Medina, Ohio: Corrpro Companies, Inc., 2004).

[33] American Water Works Association Standard ANSI/AWWA C105 (2005) "Polyethylene Encasement for Ductile-Iron Pipe Systems"; International Standards Organization Standard ISO 8180 (August 15, 2006): "Ductile Iron Pipelines—Polyethylene Sleeving for Site Application," 2nd ed.; ASTM International Standard ASTM A 674-05 (2005): "Standard Practice for Polyethylene Encasement for Ductile Iron Pipe for Water or Other Liquids"; British Standard BS 6076 (1996): "Specification for Polymeric Film for Use as a Protective Sleeving for Buried Iron Pipes and Fittings (for Site and Factory Application)"; Japan Ductile Iron Pipe Association Standard JDPA Z 2005-1989, "Polyethylene Sleeve for Ductile Iron Pipes and Fittings"; Australian Standard AS 3680 (1989): "Polyethylene Sleeving for Ductile Iron Pipelines."

the pipe and the encasement.[34] In 1993, the standard was revised to allow the use of either an 8-mil low-density polyethylene film or a 4-mil high-density cross-laminated polyethylene film. A recommendation added that in wet conditions the PE should be taped every 2 feet around the pipe.

In 2000, ANSI/AWWA Standard C105 was again revised to replace low-density polyethylene with linear, low-density encasement material, and the soil resistivity ranges were modified, resulting in more conservative evaluation procedure values. A paragraph was also added to the standard acknowledging that other corrosion control methods may be required in "uniquely severe" environments.

ANSI/AWWA Standard C105 does not recommend any particular method of PE installation; however, the tube form is favored for most installations because it speeds field installation while minimizing accidental contamination by means of foreign material that becomes lodged under the PE.[35] The shape of the tube also helps limit entry of oxygen under the film at unsealed edges when compared to the flat-sheet type of PE. The flat-sheet type is reportedly more useful for the encasement of irregularly shaped appurtenances such as valves and tees.

On the basis of testing that it conducted, DIPRA recommends either 4-mil or 8-mil material and states that the newer 4-mil, high-density, cross-laminated film and the 8-mil, linear low-density film are more resistant to damage than is the older 8-mil, low-density PE.[36] Like ANSI/AWWA Standard C105, DIPRA does not recommend either a preferred specific film thickness or installation method.

Polyethylene, like any other material, can degrade over time, although the degradation is usually minimal. The Bureau of Reclamation conducted a 7-year test on underground polyethylene sheeting that was being used as canal liner material; this test indicated that the polyethylene film demonstrated limited loss of tensile strength and elongation.[37] Reclamation also conducted accelerated testing (estimated to be 5 to 10 times faster than field burial conditions) which indicated that polyethylene is highly resistant to bacteriological deterioration. Similarly, a DIPRA brochure on polyethylene encasement states that polyethylene encasement "doesn't deteriorate underground."[38]

---

[34] ANSI/AWWA Standard C105/A21-5-05 "Polyethylene Encasement for Ductile-Iron Pipe Systems," AWWA, Denver, Colo.

[35] Cast Iron Pipe Research Association, "Protection of Cast Iron Pipe by Encasement in Polyethylene Tube," Chicago, Ill. (1967).

[36] DIPRA, "Polyethylene Encasement Effective, Economical Protection for Ductile Iron Pipe in Corrosive Environments," DIPRA Brochure POLYTECH/5-07/5M, January 1992, rev., May 2007.

[37] U.S. Department of the Interior, Bureau of Reclamation, *Laboratory and Field Investigation of Plastic Films*, Rept. No. ChE-82 (Washington, D.C., September 1968); Harry Smith, "Corrosion Prevention with Loose Polyethylene Encasement," *Water and Sewage Works*, May 1972.

[38] DIPRA, "Polyethylene Encasement Effective."

At a location where some of the oldest polyethylene-encased pipe is buried (LaFourche Parish, Louisiana), DIPRA in 2008 indicated that the polyethylene encasement "is not suffering from significant deterioration, while in service."[39] DIPRA did acknowledge that the PE material can change during burial, but believed that the material would be flexible enough to provide adequate protection to the pipe.

The purpose of the PE is to develop a physical barrier between the pipe and its surrounding environment. It is therefore important during installation that (1) no soil becomes trapped between the pipe and polyethylene; (2) the polyethylene is snug, but not tight, to allow it to bridge irregularities without stretching; (3) overlaps and ends are secured with adhesive tape or plastic tie straps; (4) any damaged areas that occur during installation are repaired prior to final backfilling; and (5) service lines of dissimilar metals are wrapped with polyethylene or a suitable dielectric tape for a minimum of 3 feet clear distances.[40] PE is reported to possess good dielectric insulating characteristics, which protect the pipe from low-level stray direct current.[41]

In theory, intact PE is a passive corrosion protection system that may prevent direct contact with the soil and limit the access of oxygen to the pipe surface; PE is also said to minimize the electrolyte available to support corrosion.[42] Typically the weight of the backfill around the pipe and the small space between the PE and the pipe are assumed to reduce any significant exchange of groundwater from the backfill to the area between the pipe and the PE. Initially there may be groundwater trapped under the wrap that can exhibit the same characteristics as the surrounding soil. If that water is corrosive and has a high oxygen content, the initial corrosion rate can be relatively high. This initial corrosion cell activity should decrease over time as the oxygen is depleted. However, in very corrosive soils, with high or fluctuating groundwater, the replenishment of oxygen and electrolytes may support the corrosion process and allow it to continue.

Some case studies have suggested that PE might not provide enough protection in continuously saturated soils, although it might be used in conjunction with a CP system.[43] Others maintain that pinholes do not significantly diminish the ability of the PE to provide protection and that unlike bonded dielectric coatings, PE can

---

[39] DIPRA, "Polyethylene Encasement Effective"; Cast Iron Pipe Research Association, "Protection of Cast Iron Pipe by Encasement in Polyethylene Tube."

[40] ANSI/AWWA C105/A21.99, "Polyethylene Encasement for Ductile Iron Pipe Systems."

[41] DIPRA, "Polyethylene Encasement Effective."

[42] DIPRA," Polyethylene Encasement Effective."

[43] Ian Lisk, "The Use of Coatings and Polyethylene for Corrosion Protection," *Water Online*, January 14, 1997, available at: http://www.wateronline.com/article.mvc/The-Use-of-Coatings-and-Polyethylene-for-Corr-0001, Accessed December 28, 2008.

protect the pipe without the formation of concentration cells at holidays (tears or defects in loose or bonded coating).[44]

Although PE is a standard form of corrosion control for DIP in less corrosive environments, there is an ongoing debate about the benefits of PE in more corrosive soils.[45] Advantages of PE reported by DIPRA include low cost, ease of installation, no needed maintenance or monitoring, and ease in repairing damage to the PE prior to burial.[46] DIPRA states that "the number of documented failures of polyethylene encased pipelines—the vast majority of which are the result of improper installation—is insignificant compared to the miles of Cast and Ductile Iron pipe that are afforded excellent protection with this method of corrosion prevention."[47]

Based on 20 years of experience and field research, Smith[48] reported that there had been no failure of DIP with PE. Historical data from DIPRA indicate minimum corrosive attack of DIP with PE installed in the United States,[49] but DIPRA does not recommend PE as the sole protection method in areas where high-density stray currents may be present.[50]

In contrast to the results reported by DIPRA, other reports describe failures of DIP with PE. A 1975 study conducted by Hawn and Davis for the city of Calgary, Alberta, concluded that PE was not protective of pipes, and fittings could be severely corroded.[51] Experience and problems with PE have been documented in other Canadian cities, many of which have aggressive soils.[52] In a paper presented

---

[44] DIPRA, "Polyethylene Encasement Effective."

[45] C.W. Crabtree, M.R. Breslin, J.A. Terrazan et al., "Assessing Polyethylene Encased Ductile Iron Pipeline," Advances and Experiences with Trenchless Pipeline Projects, Pipelines Conference 2007; Roy Brander, "Water Pipe Materials in Calgary, 1970-2000," in *AWWA 2001 Infrastructure Conference Proceedings* (Denver, Colo., 2001); Kevin Garrity, "Corrosion Control Design Considerations for a New Well Water Line," Corrosion Conference Paper 408, New Orleans (1989); B. Rajani and Y. Kleiner, "Protecting Ductile Iron Water Mains: What Protection Method Works Best for What Soil Condition," *Journal of the American Water Works Association* 95(11):110-125 (2003); Michael Szeliga, "An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe," paper presented at ASCE Pipelines Conference, Atlanta, Ga., 2008.

[46] Stroud and Voget, "Corrosion Control Measures for Ductile Iron Pipe."

[47] Troy Stroud, "Polyethylene Encasement Versus Cathodic Protection: A View on Corrosion Protection," *Ductile Iron Pipe News* (Spring/Summer 1998).

[48] W.H. Smith, "Corrosion Prevention with Loose Polyethylene Encasement," *Water and Sewage Works* (May 1997).

[49] Stroud and Voget, "Corrosion Control Measures for Ductile Iron Pipe."

[50] DIPRA, "Polyethylene Encasement Effective."

[51] D.E. Hawn and J.R. Davis, *Special Corrosion Investigation*, Report for the City of Calgary, Water Transmission and Distribution System (Edmonton, Alberta: Caproco Corrosion Prevention Ltd., 1975).

[52] Caproco Corrosion Prevention Ltd., *Underground Corrosion of Water Pipes in Canadian Cities, Case: The City of Calgary*, CANMET Contract Report No. OSQ81-00096 (Edmonton, Alberta, May

at the 2001 AWWA Infrastructure Conference, the city of Calgary compared its experience with bare DIP and DIP with PE, noting: "From the two studies, we can say roughly that [PE] offered us about a 30% average reduction in corrosion rate and consequently in corrosion break rate, where no (uninsulated) copper services are involved."[53]

Through field evaluations,[54] others have identified cases where DIP with PE has failed prematurely. PE can be damaged during installation if proper care is not taken by the contractor, resulting in rips or tears. These defects and holidays may create holes through which environmental water can reach the DIP and may lead to accelerated corrosive attack of the pipe in the vicinity of these defects. Corrosion under intact PE and in MIC conditions has also been reported.[55] Specific cases are discussed in more detail in Chapter 3.

### *Cathodic Protection*

Cathodic protection is another common method for the reduction of corrosion rates. The two most common types of CP are passive (galvanic) and active (impressed current) systems. CP as a method of corrosion control requires the bonding of DIP joints for electrical continuity. Since DIP is typically installed with push-on or mechanical joints, suitably sized insulated copper wires[56] or straps are installed across each joint and secured to each side of the pipeline joint by exothermic welding or pin-brazing techniques.

For galvanic anode systems, a sacrificial metal (e.g., magnesium or zinc) is attached to the pipe at regular intervals. These prepackaged galvanic anodes are sized and spaced along the pipeline according to design-specified current requirements and pipeline attenuation characteristics. Bare galvanic ribbon anode systems are also used to provide CP protection.

In an active system, an impressed current is applied to the pipeline using a dc power source (typically a rectifier) and impressed current anodes (high-silicon cast iron, graphite, and so on) at intervals according to designed current requirements

1985); J.A. Jakobs and F.W. Hewes, "Underground Corrosion of Water Pipes in Calgary, Canada," *Materials Performance* (May 1987): 42-49; Rajani and Kleiner, "Protecting Ductile Iron Water Mains."

[53] Brander, "Water Pipe Materials in Calgary, 1970-2000."

[54] Michael Szeliga and Debra Simpson, "Evaluating Ductile Iron Pipe Corrosion"; Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[55] Michael Szeliga and Debra Simpson, "Corrosion of Ductile Iron Pipe: Case Histories," Materials Performance, 40(77):22-26 (2001); Michael Szeliga. "Ductile Iron Pipeline Failures," Materials Performance 44(5):26-30 (May 2005); Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[56] DIPRA, "Guidelines for the Electrical Bonding of Ductile Iron Pipe Joints, Thermite Weld Method" (rev. October 1999).

and pipeline attenuation characteristics. These can be electrically remote ground beds or a distributed-type ground bed located next to the pipeline.

In both systems, the dc current produced from the source (galvanic anode or impressed anodes) passes through the soil to the pipeline being protected. A properly designed CP system can reduce corrosion rates to a desired level, thereby extending the useful life of the pipeline.

*Polyethylene Encasement with Cathodic Protection*

In corrosive soils, the combination of CP and PE may be a viable method of corrosion control. The use of PE may reduce the annual operating cost of the active CP system or extend the life of the galvanic anode CP system by reducing the demand on the CP system, allowing the two systems to complement each other.[57]

Theoretically, CP should only be required in those areas where the PE is damaged and direct contact of the DIP with the corrosive soils occurs. However, one concern is that PE may shield the CP system from actively mitigating corrosion under the intact PE.[58] Trapped corrosive materials (organic clays, microbial waters, or soils) can migrate along the loose PE away from damaged areas and create an environment suitable for corrosion and/or MIC. The effectiveness of the CP may be reduced as a function of distance from a holiday or damaged area in the PE. If MIC activity is occurring or corrosive groundwater has traveled, under the PE outside that area of CP influence, the CP system may be ineffective.

If these active corrosion cells are electrically shielded from the CP current by the PE, the corrosion can continue, which is why National Association of Corrosion Engineers (NACE) Standard SP0169 advises against the use of materials or construction practices that create electrical shielding on the pipeline.[59] Similarly, in two separate decisions, the U.S. Department of Transportation's Office of Pipeline Safety ruled against the use of PE with CP for DIP and cast iron in oil and gas lines

---

[57] G. Bell and A. Romer, "Making 'Baggies' Work for Ductile Iron Pipe," ASCE Pipelines 2004 Conference, San Diego, California, August, 2004; D. Lindemuth and D. Kroon, "Cathodic Protection of Pipe Encapsulated in Polyethylene Film," NACE Corrosion, Paper 07040 (2007); M. Schiff and B. McCollum, "Impressed Current Cathodic Protection of Polyethylene-Encased Ductile Iron Pipe," presented at NACE Corrosion 93, Houston, Tex.; J. Schramuk and V. Rash. "Case History: Cathodic Protection for a New Ductile Iron Water Transmission Main," *Materials Performance* 44(10):20-24 (2005).

[58] John H. Fitzgerald III, "Cathodic Protection of Miscellaneous Underground Structures," in *Proceedings of Seventeenth Annual Appalachian Underground Corrosion Short Course* (Morgantown: West Virginia University, 1972); Kevin Garrity, "Corrosion Control Design Considerations for a New Well Water Line."

[59] NACE Standard SP0169, Control of External Corrosion on Underground or Submerged Metallic Piping Systems (NACE International, Cleveland, Ohio, 2007).

because of concerns about electrical shielding and MIC corrosion.[60] One European DIP manufacturer states: "Polyethylene sleeving is not considered an adequate coating for ductile iron pipes subject to cathodic protection."[61]

One of the concerns regarding CP shielding is that problems cannot be detected by means of routine CP-monitoring techniques. If the coating is shielding the current, CP potentials measured along the pipeline will not indicate a problem until a leak occurs. Several authors summarize these problems in regard to disbonded coatings, which are electrically similar to shielding with intact PE.[62] One author concluded, "Electronic (smart) pigging surveys are the best, and only reasonably sure, method for determining corrosion on pipeline surfaces under disbonded coatings."[63]

The ongoing debate about the suitability of DIP with PE and CP in highly corrosive soils is focused on the following: (1) whether moisture and oxygen can be present under undamaged PE, (2) whether PE can be installed without sustaining damage, (3) whether all damaged PE can be identified and repaired before burial, (4) whether electrical shielding can restrict the CP current from reaching the pipe surface in all areas, and (5) whether CP with PE is effective if these conditions occur. Detailed cases of the use of DIP with PE and CP, including examples both of successes and of corrosion of DIP with PE and CP, are presented in Chapter 3.

*Bonded Dielectric Coatings and Cathodic Protection*

Historically, the use of bonded dielectric coatings on DIP has received mixed support.[64] The primary disagreements center on whether DIP can be economically

[60] Office of the Secretary of Transportation ruling: *Federal Register* 36, no. 126 (June 1971): 12297; ruling by Office of the Pipeline Safety: *Federal Register* 36, no. 166 (August 1971): 16949.

[61] St. Gobain Web site, available at www.saint-gobain-pipelines.co.uk. Accessed September 2008.

[62] Spicklemire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective"; F.M. Song, D.W. Kirk, J.W. Graydon, D.E. Cormack, and D. Wong, "Corrosion Under Disbonded Coatings Having Cathodic Protection," *Materials Performance* 42(9):24-26 (2003); Douglas Moore, "Phorgotten Phenomena: Cathodic Shielding Can Be a Major Problem After a Coating Fails," *Materials Performance* 39(4):44-45 (2000).

[63] Duane Tracy, "Disbonded Coatings Influence CP, Pipe Line Risk Assessment," *Pipe Line and Gas Industry* 80(2):27-31 (1997).

[64] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective"; Stroud and Voget, "Corrosion Control Measures for Ductile Iron Pipe"; A.M. Horton, "Special Protective Coatings and Linings for Ductile Iron Pipe," *Proceedings from Second International Conference, Pipeline Division and ASCE-TCLEE* (Reston, Va.: ASCE-TCLEE, 1995), pp. 745-756; Brander, "Water Pipe Materials in Calgary, 1970-2000"; D. Lieu and M. Szeliga, "Protecting Underground Assets with State-of-the-Art Corrosion Control," *Materials Performance* 41(7):24 (2002); "Surface Preparation of Ductile Iron Pipe to Receive Special Coatings," *Ductile Iron Pipe News* (Fall/Winter 1993), p. 17; Shiwei Guan, "Corrosion Protection by Coatings for Water and Wastewater Pipelines," paper

coated and whether the coating will perform satisfactorily. The majority of the reported problems have related to application of the coating. The selection of the correct type of coating and surface preparation are important as, unlike steel pipe which is smooth, the "peened" surface of DIP with scale requires a modification to the specified surface preparation, and the adherence of some coatings has been reported to be poor regardless of the level of surface preparation.[65] The National Association of Pipe Fabricators, in its standard for surface preparation for DIP receiving special external coatings, also specifically notes that the standards developed for steel are not applicable to DIP.[66]

Some of the factors that U.S. pipe manufacturers cite as limiting the feasibility of a bonded coating for DIP include the following: (1) pipe (substrate) damage, including blisters and slivers, caused by abrasive blasting; (2) abrasive blast surface preparation negating the protective effects afforded by the asphaltic shop coating and the annealing oxide layer; (3) difficulty in meeting holiday test requirements because of the rough external surface and as-cast peen pattern; (4) a limited number of knowledgeable coating applicators; (5) susceptibility of the coating to damage during shipment and installation; and (6) adverse impact of the coating on joint configurations and joint tolerances (i.e., field cuts, push-on joints, and restrained joints). These issues are reportedly the reason that North American DIP manufacturers announced in August 2002 that they would no longer provide pipe to be used with bonded coatings.[67] This continues to be the case, and DIPRA notes that none of its member companies will provide pipe with bonded coatings.[68] Some DIP manufacturers discourage end users from using such coatings or even from obtaining pipe without the asphaltic coating (which is taken as an indication of intent to apply a bonded dielectric coating).[69]

In spite of the objections from U.S.-based manufacturers, bonded dielectric coatings for DIP that were used successfully for many years in the United States prior to 2002 are used outside the United States.[70] Coatings that have been speci-

---

presented at Appalachian Underground Corrosion Short Course, Water and Wastewater Program, Morgantown, W.Va., 2001.

65 Guan, "Corrosion Protection by Coatings for Water and Wastewater Pipelines."

66 National Association of Pipe Fabricators, Inc., *NAPF-500-03: Surface Preparation Standard for Ductile Iron Pipe and Fittings in Exposed Locations Receiving Special External Coatings and/or Special Internal Linings* (Edmond, Okla., rev. February 14, 2006).

67 Jose Villalobos, "Successful Coating Applications," *V&A Consulting Engineers Infrastructure Preservation News* 1 (June 2003), available at http://www.vaengr.com/VANewsletter/June2003/Interest-June2003.html. Accessed December 28, 2008.

68 L. Gregg Horn, DIPRA, Letter to John Keys, Commissioner of the Bureau of Reclamation (November 16, 2004).

69 Mike Woodcock, "Review of the Bureau of Reclamation's Technical Memorandum," presentation to the committee, July 29, 2008.

70 Rajani and Kleiner, "Protecting Ductile Iron Water Mains."

fied for DIP include coal tar epoxy, coal tar enamel, extruded polyolefin, sprayed polyolefin, polyurethane, hot- and cold-applied tapes, and cement coatings.[71] Wax-petrolatum tapes have also been reported to have been successfully used on DIP and fittings.[72] Extruded polyethylene-type coatings have been adapted for bell-and-spigot-type DIP joints and have been successfully used since 1975.[73] Tape coatings have been used since the mid-1970s, with use of polyurethane coating beginning in 1988. According to one report, a bonded thermoplastic coating for DIP was used in Seattle, Washington,[74] and this type of coating has also been used successfully in Europe. Liquid epoxy, fusion-bonded epoxy, and thermoplastic-type coatings have been used successfully for ductile- and cast-iron fittings. Brush- and spray-applied coatings, tape, or heat-shrink sleeves have historically been used for pipe joint coatings. A wider variety of bonded dielectric coatings have been used overseas than in North America to protect buried DIP.

In Europe, the primary external coating for corrosion control in use since the 1960s has been metallic zinc spray with a bitumen or epoxy top coat. The two methods of zinc application (metallic zinc or zinc-rich coatings) are covered by International Organization for Standardization (ISO) Standard 8179.[75] This zinc prime coat with a finish coat is used by most European iron pipe manufacturers as well as by the Water Research Centre for mildly and moderately corrosive soils. In more-corrosive soils, the metallic zinc coating and bitumen or epoxy finish coats may be supplemented by PE or bonded dielectric coatings.[76] Other protective coating systems employed by European pipe manufacturers include but are not limited to extruded polyethylene, polyurethane, zinc-aluminum metallic spray with epoxy top coat, tape, and reinforced cementitious coatings.[77] A summary of the use of bonded coatings is presented in Chapter 5 of this report.

---

[71] A.M. Horton, "Special Protective Coatings and Linings for Ductile Iron Pipe," pp. 745-756 in *Advances in Underground Pipeline Engineering II*, Bellevue, Wash.: American Society of Civil Engineers (1995); Rajani and Kleiner, "Protecting Ductile Iron Water Mains"; Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective"; Guan, "Corrosion Protection by Coatings for Water and Wastewater Pipelines."

[72] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective"; Bell and Romer, "Making 'Baggies' Work for Ductile Iron Pipe."

[73] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective"; Brander, "Water Pipe Materials in Calgary, 1970-2000."

[74] J.R. Pimentel, "Bonded Thermoplastic Coating for Ductile Iron Pipe," *Materials Performance* 40(7):36 (2001).

[75] *ISO Standard 8179, Ductile Iron Pipe—External Zinc Coating* (Geneva, Switzerland: ISO, rev. 2007).

[76] J.E. Drew, *Pipe Materials Selection Manual* (Swindon, U.K.: WRc, 1995), p. 128.

[77] Trevor Padley, Saint Gobain Pipelines plc, Derbyshire, England, communication with the committee, 2008; Saint Gobain Web site information, Section 5, Pipe Coatings, available at www.saint-gobain-pipelines.co.uk. Accessed September 2008.

*As-Manufactured DIP with Cathodic Protection*

Since bonded coatings on DIP are not available in the United States, several utilities and corrosion engineers have elected to install bare DIP with CP instead of with PE to minimize the problems with electrical shielding. The city of Seattle, Washington, installed a 40,000-foot section of bare DIP with an impressed current CP system next to a transit authority.[78] Russell Corrosion Consultants reported that it is installing more than 15 miles of bare ductile iron pipeline with CP on 18 different projects in the northeastern United States.[79] The Washington Suburban Sanitary Commission in the Washington, D.C., area has reported that, because of concerns about shielding from PE, it is installing several thousand feet of bare (as-manufactured) DIP with CP.[80]

## Other Methods of Corrosion Control

Other corrosion control methods that may be considered include but are not limited to specifying additional pipe wall thickness in the design of the pipe system to account for a calculated corrosion rate for the life of the system, soil enhancements (e.g., controlled low-strength material), anti-MIC PE, microperforated PE with CP, use of resistance probes or perforated plastic monitoring pipes, and pipeline monitoring and repair. These are discussed in more detail in Appendix D of this report.

## Selection of a Corrosion Control Method

In selecting a method for corrosion control for DIP, the designer and owner should consider all factors, including soil condition, capital costs of construction, operation and maintenance of the CP system, consequences of failure, and cost of repair.

[78] Les Nelson, Seattle Public Utilities, Seattle, Washington, communication with the committee, September 2008.

[79] Michael Szeliga, Russell Corrosion Consultants, communication with the committee, September 2008.

[80] Dick Newell, Washington Suburban Sanitary Commission, communication with the committee, September 2008.

# 3

# Corrosion Performance of Ductile Iron Pipe: Case Histories and Data

The corrosion performance of ductile iron pipe (DIP) in aggressive soils has been the subject of considerable debate, resulting in disagreement on the interpretation of publicly available data on DIP performance. The three underlying causes of the disagreement are these:

1. Material failures in a system, in general, are due to a combination of factors, including variations in the material, installation, environment, and use, and thus often represent the tails of the distribution of behavior, not the averages, when compared with the behavior of most components in a field system or in a more controlled study of system components.
2. Limited field corrosion performance and field failure data are available for water pipelines overall, not just for DIP.
3. Data are reported in the form of averages, but water authorities need to make risk management decisions based on the data in the tail of the distribution.

The Bureau of Reclamation's pipelines are long, cross many different types of terrain and environments, and are required to provide uninterrupted, reliable service. Reclamation's corrosion control decisions have been made to limit the risk of premature corrosion failures while accommodating different types of pipe and environmental conditions. The report of the National Research Council's Transportation Research Board entitled *Transmission Pipelines and Land Use: A Risk-Informed Approach* describes Muhlbauer's analysis of the need for risk assessment for pipelines in the presence of "unmeasureable and unknowable" factors to "systematically and objectively capture everything that is known and use the information to make better decisions."[1] It is with this approach that the data described below have been collected and used as the basis for this report's responses to the questions asked by Reclamation in the charge to the committee (see Chapter 1, the section entitled "Reclamation's Request").

The committee reviewed the available data on the performance of DIP with polyethylene encasement (PE) and cathodic protection (CP) to assess the observed range of material and pipeline system behavior in aggressive soils. As a comparison, the committee also reviewed the available information on the performance of DIP without PE or CP, DIP with PE and without CP, and DIP with CP and without PE, as these data might represent local behavior if local failure of PE or CP in a field system was the underlying cause of observed corrosion and/or pipeline failure. Information was also reviewed for comparison with bonded dielectric coatings on both steel and ductile iron water and sewer pipelines. An additional factor that may come into play in a failure of operating pipelines is the design and installation of other components into the pipeline system.

The committee was asked to use the failure data provided by the U.S. Department of Transportation's (DOT's) Office of Pipeline Safety (OPS) for operating steel pipelines with bonded coatings and CP as the benchmark standard for comparison with data on DIP with PE and CP. Therefore, problems with design and installation failures that lead to external corrosion must be considered as contributing factors to the performance of each system and cannot be discounted.

The following sections present the findings of the data review based on presentations made to the committee; on publicly available documents; and on specific information provided by the Bureau of Reclamation and utilities and on additional data provided by other sources at the request of the committee.

The obtained data on pipeline materials and operating pipelines fall into the following categories of data types. The data type classifications (1 through 5) are listed from the most quantitative to the most qualitative:

1. *Data Type 1—Documented failures of operating pipelines due to external corrosion for pipelines of a given pipeline type, including pipe thickness, pipeline age, and soil condition.* Such information can be converted into a linearized maximum pitting or corrosion rate for that specific failure (assuming that pitting begins upon pipe installation) and into a failure rate per mile per year if the total number of miles of pipeline of that particular age and soil condition are known.

[1] Transportation Research Board, *Transmission Pipelines and Land Use: A Risk-Informed Approach* (Washington, D.C.: The National Academies Press, 2004).

2. *Data Type 2—Measured maximum corrosion pit depths*[2] *in a given pipeline segment with no documented failure as a function of pipeline type, including pipe thickness, pipeline age, and soil conditions.* Such information can be converted into linearized maximum pitting rates and, for measurements from a set of pipe segments, into a distribution of corrosion rates and a distribution of estimated failure times for a pipeline of a given thickness.
3. *Data Type 3—Calculated means and standard deviations from collections of data of maximum pitting or corrosion rates of different pipe segments if and only if the input data fit the statistical model on which the means and standard deviations are based.* If the data fit the model, then the means and standard deviations can be used to estimate the average corrosion rates in the tail of the distribution. For example, from the definition of a standard normal distribution,[3] 2.3 percent of samples are expected to have property values greater than two standard deviations above the mean. For a distribution of maximum observed corrosion rates that fits some distribution, therefore, 2.3 percent of pipeline segments in a system characterized by that distribution would be expected to have maximum observed corrosion rates greater than two standard deviations above the mean. Similar types of statistical statements can be made for other types of distributions, for example, lognormal distributions.
4. *Data Type 4—Calculated averages of averages or calculated mean values assuming data distribution models, if the data do not fit the assumed statistical models or if it is not known whether the data fit the statistical model on which the calculations are based.* The averages are of limited use because the behavior at the tail of the distribution is what is needed for risk assessment. Means and standard deviations are useful only if the data on which the calculations are made follow the model. If the data do not fit such a model, then the calculated mean and standard deviation have limited physical significance. Data Type 4 may provide qualitative support for other sources of Data Types 1 and 2. If the data do not fit such a model, then the calculated mean and standard deviation have little physical meaning. If no information was provided about the validity of the model, the committee assumed that the data did not fit the model, based on the committee's examination of similar data and their fit.
5. *Data Type 5—Qualitative data, including direct physical evidence of disrup-*

[2]Corrosion pit depth measurements are normally taken by examining the pipe surface in question to determine the deepest pit(s), which then are measured with a pit depth gauge. The measured pit depths are then divided by the burial time in years to arrive at a mil per year (mpy) corrosion rate.

[3]The committee recognizes that there are other distributions against which these data can be measured. While the means would likely remain unchanged, these distributions (e.g., lognormal) may impact the tails.

*tion to external corrosion protection systems, such as damage to coatings or PE or failure of CP systems; indirect evidence of disruption to corrosion reduction systems by measured pitting rates or widespread external corrosion deviating from that typically observed; semi-quantitative information on evidence of external corrosion and the frequency of disruption to corrosion reduction systems; and general descriptions of pipeline operator experience with specific pipeline systems where no quantitative information is provided.*

The committee used Data Types 1 and 2 to calculate Data Type 3 as the primary basis for comparison with the OPS benchmark data using a frequentist definition of probability in Chapter 4, which presents the failure criteria derived by the committee.

## OVERVIEW OF PRESENTATIONS TO THE COMMITTEE

As noted in Chapter 1, at its first meeting the committee received several presentations that provided it with a better understanding of the various perspectives and opinions regarding the committee's statement of task. These presentations ranged from summaries of other research to informed opinion and are described in greater detail below.

As summarized in Chapter 1 of this report, the first presentation to the committee was made by representatives of the Bureau of Reclamation on its history, its concerns with the use of DIP with PE and CP, and the development of its Technical Memorandum 8140-CC-2004-1.[4]

A presentation was then made by L. Gregg Horn and his colleagues from the Ductile Iron Pipe Research Association (DIPRA)—an organization that represents the North American DIP manufacturers.[5] Horn reviewed DIPRA's history and described the 85 corrosion-related projects at 27 test sites involving more than 5,200 specimens that DIPRA has carried out since 1928. At present, DIPRA has 33 active corrosion studies under way at 16 test sites involving 2,000 specimens, with ongoing research projects with Corrpro, Schiff & Associates,[6] and the Missouri University of Science and Technology (formerly, the University of Missouri-Rolla). Horn and colleagues stated that DIPRA's empirical data prove that DIP with PE "works," based on more than 150 field investigations of iron pipe with PE, either

[4] Bureau of Reclamation Technical Service Center Staff, U.S. Department of the Interior, "Corrosion Considerations for Buried Ductile Iron Pipe," presentation to the committee, Washington, D.C., July 28, 2008.

[5] L. Gregg Horn, DIPRA, PowerPoint presentation to the committee, Washington, D.C., July 28, 2008.

[6] Corrpro and Schiff & Associates are corrosion engineering and consulting services headquartered in Medina, Ohio, and Claremont, California, respectively.

with or without CP, and that hundreds of millions of feet of iron pipe with PE are in service in the water and wastewater industry throughout North America. Horn and colleagues pointed out that DIPRA had conducted 11 field investigations on DIP with PE and CP on seven different pipeline systems and found no major corrosion. Richard Bonds, a statistician consulting for DIPRA, provided information and summary tables from DIPRA's test data set on corrosion rates.[7] This material included summary information from the test sites, field investigations, member company reports, and Corrpro reports for 1,379 individual data points. A more detailed discussion of DIPRA's data set and the analyses thereof are provided in the section of this chapter entitled "Field Cases."

Horn then provided DIPRA's perspective in answer to the two primary questions comprising the committee's charge. Regarding question 1—whether PE with CP works on DIP installed in highly corrosive soils—Horn stated that based on DIPRA's research and extensive data sets, "polyethylene encasement works in highly corrosive soils without cathodic protection." In response to question 2—whether PE and CP reliably provide a minimum service life of 50 years—DIPRA's answer was "yes." Its consultant for statistical analysis presented information and graphs of corrosion rates to support these positions.[8] Horn and colleagues stated that DIPRA has always recommended against bonded coatings for DIP and that they are not aware of any North American DIP company which is a member of DIPRA that would provide DIP with bonded dielectric coatings.

A presentation was given by Graham E.C. Bell of Schiff & Associates on the use of resistance probes and the success of the three cathodically protected pipelines (totaling 258 miles of DIP with PE and 68 miles of coated steel pipe) in North Dakota and South Dakota:[9] (1) the Southwest Pipeline Project in North Dakota and (2) the WEB (Walworth, Edmunds, and Brown) Development Project and (3) the Mid-Dakota Rural Water Service Project, both in South Dakota. The presentation indicated that DIP wall thicknesses ($t$) will range from 250 to 480 mils depending on pipe diameter and pressure class. Bell pointed out that if the maximum general corrosion limit allowed is 50 percent of the pipe wall, then to reach a 50-year design life the maximum allowable corrosion rate would be 2.5 to 8.7 mils per year (mpy) depending on pipe wall thickness.[10] Bell went on to state that for the pitting corrosion limit (through wall), the maximum allowable pitting rate would be 5.0 to 16.0 mpy. He concluded that CP must reduce or mitigate corrosion to these rates

[7] Richard Bonds, L.M. Barnard, A.M. Horton, and G.L. Oliver, "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research," *AWWA Journal* 97(6):88-98 (2005).

[8] Charles Cowan, Analytical Focus, "Measurements and Standards," presentation to the committee, Washington, D.C., July 28, 2008.

[9] Graham E.C. Bell, Schiff & Associates, "Measurements of Performance of Corrosion Control Mechanisms on DIP," presentation to the committee, Washington, D.C., July 29, 2008.

[10] It should be noted that pressure in water pipes is lower than that in gas pipes.

to "work." He provided information on the historical use of electrical resistance probes for the Southwest Pipeline Project, where 20 steel probes had been installed at eight locations on the 76-mile-long DIP with PE and CP section of this 118-mile-long pipeline. He made the case that since these probes under the PE with CP indicated that the corrosion rate was less than 0.1 mpy, this confirms that CP "works" with PE. He stated that the Southwest Pipeline had only two problems with its corrosion protection systems. The first was due to high groundwater and the use of gravel bedding, which had damaged the PE in those areas and increased the CP current requirements so that a larger rectifier had to be installed. Excavations in one of these areas, even with potentials below protected criteria, indicated no corrosion on the pipeline. The second problem related to a leak on the 16-inch pipeline around Station 283+00 in the Southwest Pipeline Project. This leak is described in more detail in the section below entitled "Summary of Known Cathodically Protected Polyethylene-Encased Pipelines."

Bell also discussed some of the results and problems that he and other consultants had observed with the use of certain steel probes on the Mid-Dakota Water Service Project. Bell and his colleagues found that some of the probes had failed because of manufacturing errors (inadequate seal of the back of the probe), which allowed water to enter the probe body; they concluded that these data could not be used because of faulty probe configurations. Bell also discussed development of a new ductile iron probe that theoretically should more closely represent corrosion rates on DIP.[11]

Another presentation was provided by Mike Woodcock on his experience as a metallurgist with corrosion and corrosion control methods for iron pipe.[12] He discussed the DIP microstructure, showed scanning electron microscope micrographs, and presented his experience with respect to widely varying corrosion rates seen for different DIP over the years. He believes that the corrosion rates are influenced by the chemical makeup of the iron pipe and the amount of trace metals. He said:

> [T]he older ductile iron pipes were made with a higher pig iron content ("pureiron"). The recent iron is predominantly made from scrap iron and steel. The scrap steel can contain chromium, nickel, molybdenum, tungsten, vanadium, titanium, etc. Some DIP being made today is extremely sensitive to corrosion; some is almost corrosion resistant. The presence of the trace metals and their carbides are believed to be a possible source of this wide variation in corrosion sensitivity. DIP is no longer an "iron product" with just Fe, Mn, Si, S, and P.

Woodcock further explained how corrosion activity can be initiated at the

[11] Bell, "Measurements of Performance of Corrosion Control Mechanisms on DIP."

[12] Mike Woodcock, "Review of the Bureau of Reclamation's Technical Memorandum," presentation to the committee, Washington, D.C., July 29, 2008.

pipe surface when the asphaltic shop coating is damaged. He also discussed different types of coatings applied to DIP, including side and circumferential extruded polyethylene, tape coatings, coal tar polyurethanes, epoxy paints and filled epoxies, ceramic epoxies, fusion bonded epoxy coating, PE, and European standards including sprayed zinc metal coating and zinc coatings with coal tar finish coats and PE. He requested that the committee help in allowing end users the option of deciding for themselves what type of corrosion control methods they want. He recommended that an independent national database for all pipeline materials be set up to better track data on each type of pipe. He also asked that intelligent systems (smart pigs) be used on DIP with PE to provide additional information on how PE works. He noted that the effectiveness of PE in test pits and at test locations cannot provide the type of performance information that the end user needs.

A presentation was provided to the committee by Michael Szeliga, a corrosion consultant, who stated that most corrosion occurs on 10 percent of a pipeline, with the most significant corrosion occurring on 10 percent of that 10 percent, so the chance of discovering the worst corrosion with a random test pit is only 1 percent.[13] He presented several papers that discussed corrosion issues involving DIP with PE. These papers included references to 10 papers, authored either by the presenter or by others, that list problems with DIP and PE. This presentation was similar to the information that Szeliga provided in an earlier paper and presentation at the ASCE [American Society of Civil Engineers] 2008 Pipelines Conference.[14] Szeliga concluded that, based on his experience, PE is likely to be damaged during installation regardless of the quality of construction, and the depth of corrosion under intact PE is about the same as the depth of corrosion where the PE is damaged. He also stated that, based on his experience, CP does not prevent corrosion under intact PE, and using external bonded coatings together with CP substantially reduces the number of pipeline failures.

## DATA COMPARISONS OF INTEREST

The primary pipeline type of interest is DIP with PE and CP in highly corrosive soils—defined as soils having a resistivity below 2,000 ohm-cm. The uncertainty about the use of DIP with PE and CP under these conditions arises from various concerns: that CP may fail to be effective due to CP malfunction or electrical shield-

[13] Michael Szeliga, Russell Corrosion Consultants, Inc., "An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe," presentation to the committee, Washington, D.C., July 29, 2008.

[14] Michael Szeliga, Russell Corrosion Consultants, Inc., "An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe," ASCE Pipelines 2008 Conference, Atlanta, Georgia.

ing, that undamaged PE alone may be insufficient to prevent corrosion in highly corrosive soils, that the PE is easily damaged and leads to localized corrosion as a result of holes or tears, and that installation issues, such as damage to the PE or corrosive soil adhering to the pipe remaining between the pipe and the PE during installation, change the local environment surrounding the pipe. The committee therefore performed additional assessments as estimates for the case in which one or both of the corrosion mitigation strategies fail—that is, assessments were made for DIP without PE or CP, for DIP with CP but without PE, and for DIP with PE but without CP.

It is also important to note that all corrosion rates are reported and/or calculated as linear corrosion rates, that is, the corrosion rate is constant over time. For Data Type 1, that is, for pipes that failed, a linearized maximum corrosion rate is calculated from the wall thickness of the pipe divided by the time to failure since installation. For Data Type 2, the measured maximum pit depths are converted into linearized maximum pitting rates by dividing the measured maximum pit depth by the burial time (years) since installation of the corroded pipe. Therefore, all pitting rates noted in this report are based on the assumption that the pit depth grows linearly with time. Corrosion is known to follow kinetics that are nonlinear, in many cases with an incubation time before corrosion begins. A square root of time dependence is often used. However, with the limited data available, the fact that most pitting rates are reported as linear, and with the wide variation of burial conditions that can change over time, a linear model is the simplest and the one commonly used. A study commissioned by DIPRA also made this same simplifying assumption, stating the following:

> Ideally, corrosion rate curves would be generated from the data obtained in this study and mathematical functions developed to predict realistic decreasing corrosion pitting rates for extended times of exposure. However, these functions vary not only with soil type but also with moisture, oxygen content, and bacterial counts, all of which can fluctuate over time. Additionally, the pipes in this study's database were subjected to numerous soils, and these would have their own unique corrosion function. For this reason as well as for simplicity and conservatism, it was decided to treat the corrosion rate as a linear straight-line function. . . .[15]

Therefore, all of the corrosion rates cited in this report were calculated assuming that corrosion pit depths increase linearly with time. In addition, the terminology for pitting corrosion rates has been standardized to "maximum observed pitting rate" for Data Types 1 and 2, "mean maximum pitting rate" and "standard deviation of the mean maximum pitting rate" for data fitting a normal distribution, or

[15] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research."

"average maximum corrosion rate" for an arithmetic average for Data Type 3, and "mean maximum pitting rate" for Data Type 4.

Cast iron and ductile iron corrosion rates were considered to be similar for purposes of comparison in the committee's evaluation. Research by Romanoff of the National Bureau of Standards (NBS, now the National Institute of Standards and Technology) reported in 1964 and 1967 that ductile iron, cast iron, and steel corrode at similar rates in low-resistivity soils.[16] After further testing, NBS reported in 1976 that ductile iron and steel "buried in the same soils . . . corrode at nearly the same rates when encased in some soils. Different soils, however, alter the corrosion rates for both materials." [17] Based on the DIPRA data, Bonds et al. also concluded, "Overall results indicated that the corrosion pitting rates of ductile versus gray-iron pipe were soil specific to an extent but were essentially the same statistically (t-tests, 95% confidence). For this reason, the ductile- and gray-iron pipe data were combined to obtain the benefits of an increased sample size in subsequent analysis."[18] DIPRA indicates that including the cast iron in the ductile iron data set allows information on corrosion rates for older pipelines to be evaluated, since ductile iron has only been commercially available since the mid-1960s.

In the DIPRA report summary, the condition of the PE was divided into two categories, either "undamaged" or "damaged." "Undamaged" refers to the PE being intact at the location being examined and is a term that has generally been used in the field by most corrosion consultants, owners, and by DIPRA in its field summaries. "Damaged" PE may be defined as any opening in the PE that allows a change in the environment at the metal surface that would influence the corrosion rate locally for some easily observable distance from the damaged PE location. "Undamaged" PE in this report refers to having no observed physical damage directly over the pipe location where corrosion was observed and does not refer to any damage of the PE farther away from the corrosion pit that may influence the corrosion rate or environment at the corrosion pit.

The DIPRA data sets of interest to the committee were those for DIPRA's two most corrosive soil conditions, which would generally be under the Reclamation's criterion of less than 2,000 ohm-cm. The committee assumed that these two DIPRA corrosivity soil designations would include the soils identified by the American Water Works Association (AWWA) in Appendix A of ANSI/AWWA Standard C105,

[16] Melvin Romanoff, "Exterior Corrosion of Cast-Iron Pipe," *AWWA Journal* 60(12):1129-1143 (1964); Melvin Romanoff, "Performance of Ductile Iron Pipe in Soils: An 8-year Progress Report," presented at the AWWA Conference, Atlantic City, N.J., 1967; Melvin Romanoff, "Results of National Bureau of Standards Corrosion Investigations in Disturbed and Undisturbed Soils, Technical Bulletin No. 86," presented at the Twelfth Annual Appalachian Underground Corrosion Short Course, 1967.

[17] W.F. Gerhold, "Corrosion Behavior of Ductile Cast-Iron Pipe in Soil Environments," *AWWA Journal* 68(12):674-378 (1976).

[18] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research."

"Polyethylene Encasement for Ductile-Iron Pipe Systems," as case 2 conditions (equal to or above 10 points) and case 3 conditions (uniquely severe soils).[19]

ANSI/AWWA Standard C105, Appendix A, defines the 10-point evaluation procedures and uniquely severe soils. In the 10-point soil classification procedure, soils are tested for five parameters (resistivity, pH, oxidation-reduction potential, sulfides, and moisture); if the assigned point values according to the table in ANSI/AWWA Standard C105, Appendix A, add up to 10 or more, the soil is considered to be corrosive to iron pipe.[20] *Uniquely severe soils* are defined in ANSI/AWWA Standard C105, Appendix A, as soils having the following three characteristics: (1) soil resistivity equal to or below 500 ohm-cm; (2) anaerobic conditions in which sulfate-reducing bacteria thrive—that is, neutral pH 6.5 to 7.5; low or negative redox potential, negative to +100 millivolts (mV); and the presence of sulfides (positive or trace); and (3) the water table intermittently or continually above the invert of the pipe.

In order to evaluate the effectiveness of the different corrosion control methods, the committee sought field data and supportive information from a variety of sources and compared the input received to determine answers to the following questions:

- What is the corrosion rate of bare ductile iron or cast iron compared to iron pipe with PE?
- Has corrosion occurred and at what rate under intact PE on ductile iron or cast iron as a comparison for locations where electrical shielding may occur?
- How does the rate of corrosion compare under intact PE and intentionally damaged PE?
- Is electrical shielding a concern for polyethylene-encased and dielectrically bonded coated pipelines and to what degree?
- Has corrosion occurred and at what rate on DIP with PE and CP?
- How do bonded dielectric-coated steel pipelines compare to bonded dielectric-coated DIP and to DIP with PE?

In terms of the committee's statement of work, note that a corrosion rate of 5 mpy for DIP with a wall thickness of 0.25 inch (6 mm) is a critical value in the simplified linear corrosion rate assumption, as a corrosion rate greater than this could lead to failure in less than 50 years.

The limited amount of data available for this study by the committee was

[19] American Water Works Association, ANSI/AWWA Standard C105/A21.5-05 (2005): "Polyethylene Encasement for Ductile-Iron Pipe Systems," Denver, Colo.

[20] ANSI/AWWA C105/A21.99, "Polyethylene Encasement for Ductile Iron Pipe Systems."

compiled from various sources, including literature search, committee members' experience, presentations to the committee during its first meeting in July 2008, and discussion and correspondence with other sources (consultants, material manufacturers, applicators, and owners). The accuracy of the data provided for this evaluation could not all be independently verified because most of the data were provided by others from various evaluations and testing programs conducted over a number of years. However, every attempt was made by the committee to verify the data and to accurately summarize and present the data provided.

## BARE AND AS-MANUFACTURED IRON PIPE WITHOUT CATHODIC PROTECTION

For comparison purposes, corrosion rates for bare and as-manufactured (shop-applied asphaltic coating) DIP and cast iron pipe (CIP) were reviewed with cases for which the PE was known to be damaged, installed incorrectly, or intentionally damaged. The reason that this is done for comparison purposes is that it is assumed that a properly operating CP system for these types of pipes would protect the limited areas at damaged PE locations and thus exhibit low maximum corrosion rates. If the CP system is not working properly, then the maximum observed pitting rate may be similar to that in as-manufactured DIP (standard asphaltic coating) without CP and in DIP with damaged or intentionally damaged PE without CP. Further, if the shop-applied asphaltic coating is damaged locally, the maximum observed pitting rate may be similar to or higher than that in bare DIP without CP.

### Mean Maximum Pitting Rate for Bare and As-Manufactured DIP

DIPRA provided information to the committee in the form of letters, reports, and articles on its 75-year test study with summary tables for sandblasted, bare, as-manufactured (asphaltic shop-coated), polyethylene-encased (undamaged or intentionally damaged), and vinyl-encased iron pipelines under a range of conditions.[21] Exposure or burial times for the DIPRA ductile iron specimens ranged from 1 to 35 years and for gray iron from 1 to 103 years. This DIPRA study information presented to the committee in terms of "mean maximum pitting rates" is shown in Table 3-1, Rows 1 through 6.[22] The mean maximum pitting rates (referred to by DIPRA as "mean deepest pitting rates") were reported to have been calculated as the arithmetic average of the maximum pitting rates observed for individual pipe

[21] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research"; Richard Bonds et al., "Corrosion Control Statistical Analysis of Iron Pipe," *Materials Performance* 44(1):30-34 (2005).
[22] Cowan, "Measurement and Standards."

TABLE 3-1 Mean Maximum Pitting Rates of Bare and As-Manufactured Iron Pipe

| Row | Reference | Soil Corrosivity Rating | Number of Samples, Pipe Condition, and Data Type | Mean Maximum Pitting Rate | Notes |
|---|---|---|---|---|---|
| 1 | DIPRA study data[a] | Case 2 with soil condition values ≥10 points, per ANSI/AWWA C105[b] | Corrosion rate based on DIPRA Table 8 for 22 samples with bare pipe<br>Data Type 4 | 15.1 mpy | |
| 2 | DIPRA study data[a] | Case 2 with soil condition values ≥10 points, per ANSI/AWWA C105[b] | Corrosion rate based on DIPRA Table 8 for 103 samples with as-manufactured (asphaltic shop-coated) pipe<br>Data Type 4 | 10.5 mpy | |
| 3 | DIPRA study data[a] | Case 3 with uniquely severe soil conditions, per AWWA C105[b] | Corrosion rate based on DIPRA Table 9 for 173 bare-pipe samples<br>Data Type 4 | 44.2 mpy | |
| 4 | DIPRA study data[a] | Case 3 with uniquely severe soil conditions, per ANSI/AWWA C105[b] | Corrosion rate based on DIPRA Table 9 for 70 samples with as-manufactured (asphaltic shop-coated) pipe<br>Data Type 4 | 28.7 mpy | |
| 5 | DIPRA study data[a] | Varies, four test sites combined | Corrosion rate based on DIPRA Table 4 for 4 test sites with 89 samples with bare pipe<br>Data Type 4 | Combined mean pitting rate for 4 sites: 27.3 mpy | Ranged from mean of 9.2 mpy to 42.8 mpy per site. |
| 6 | DIPRA study data[a] | Varies, five test sites combined | Corrosion rate based on DIPRA Table 6 for 5 test sites with 89 samples with as-manufactured (asphaltic shop-coated) pipe<br>Data Type 4 | Combined mean maximum pitting rate for all 5 sites: 24.7 mpy | Ranged from mean of 0.0 to 32.0 mpy per site. |
| 7 | Others—Szeliga[c] | Varies | 45 as-manufactured (asphaltic shop-coated) pipe examples, maximum observed pitting rates between 3.2 mpy and 22.5 mpy, with 17 penetrations<br>Data Types 1 and 2 | Average: 12.3 mpy | Maximum observed pitting rates reported for 45 samples |

NOTE: DIPRA, Ductile Iron Pipe Research Association; mpy, mils per year

[a]Richard Bonds, L.M. Barnard, A.M. Horton, and G.L. Oliver, "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research," *AWWA Journal*, 97(6):88-98 (2005).

[b]American Water Works Association, ANSI/AWWA Standard C105/A21.5-05 (2005): "Polyethyelne Encasement for Ductile-Iron Pipe Systems," Denver, Colo.

[c]Michael Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance," ASCE Pipelines, Advances and Experiences with Trenchless Pipeline Projects Conference, Boston, Mass., 2007.

segments following burial and exhumation. For a 25-year study using 15 pipe segments, for example, three pipe segments were exhumed and examined every 5 years. The maximum pitting depth on each segment was divided by the burial time for that particular pipe segment in order to calculate the maximum observed pitting rate for that segment. Upon completion of an individual study, DIPRA reported only the calculated arithmetic means for the total number of pipe segments in the study, but not the individual data points on which they were based.

In summary from the DIPRA study,[23] the mean maximum pitting rates for bare DIP and as-manufactured DIP for soils with different conditions are as follows:

- For bare pipe in soil conditions with ≥10 points per ANSI/AWWA Standard C105, Appendix A: 15.1 mpy for the 22 samples (see Table 3-1, Row 1).
- For as-manufactured pipe (asphaltic shop-coated) in soil conditions with ≥10 points per ANSI/AWWA Standard C105, Appendix A: 10.5 mpy for 103 samples (see Table 3-1, Row 2).
- For bare pipe in uniquely severe corrosive soils: 44.2 mpy for 173 samples (see Table 3-1, Row 3).
- For as-manufactured (asphaltic shop-coated) pipe in uniquely severe corrosive soils: 28.7 mpy for 70 samples (see Table 3-1, Row 4).

In addition, the "combined mean maximum corrosion pitting rate" of some combination of the mean maximum pitting rates for four selected locations, all with resistivities <2,000 ohm-cm for 215 bare DIP samples, was reported as 27.3 mpy, with the mean maximum pitting rates for the four locations ranging from 9.2 to 42.8 mpy (see Table 3-1, Row 5). The "combined mean maximum pitting rate" of some combination of the mean maximum pitting rates for five selected locations, all with soil resistivities <2,000 ohm-cm for 89 as-manufactured (asphaltic shop-coated) pipe samples, was 24.7 mpy. The five mean deepest pitting rates on which this is based were 0 mpy (Aurora, Colorado), 4.1 mpy (Hughes, Arkansas), 20.5 mpy (Overton, Nevada), 26.8 mpy (Logandale, Nevada), and 32.0 mpy (Everglades, Florida) (see Table 3-1, Row 6).

Additional information provided by the Woolley analysis of the DIPRA data histograms[24] for the bare and as-manufactured DIP showed that the underlying data sets of maximum observed pitting rates for the calculated mean values in Table 3-1, Rows 1 and 2, did not fit normal distributions; therefore the mean values have little physical significance, and these values are Data Type 4. Without additional information on the data distributions or the fit of the distributions for

[23] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research."

[24] Thomas Woolley, Brock School of Business, Samford University, letter to Gregg Horn and attached "Corrosion Database Statistical Analysis" data presentation, April 7, 2008.

other data presented in the Bonds et al. paper,[25] it must be assumed that the other mean values are also Data Type 4 and could not be used in the primary comparison analysis. However, it can be noted that even as mean values, these corrosion rates are very high and would likely result in failure well before the desired 50-year service life of the pipe.

Szeliga compiled a list of maximum observed pitting rates for as-manufactured DIP and DIP with PE based on his and others' experience.[26] Forty-seven examples of as-manufactured (asphaltic shop-coated) DIP on actual pipe installations were examined, in which 24 of the 47 showed penetration. For 2 of 24 penetrated pipe locations, the paper did not provide data on the actual wall thicknesses, so maximum observed pitting rates could not be calculated. The remaining analysis was then performed for the 45 locations for which the pipe thicknesses were known. The pipe ages reported Szeliga's paper ranged from 5 to 35 years.

The 45 as-manufactured pipe examples displayed an average maximum pitting rate based on pit depth per years of burial of 12.3 mpy, with an observed minimum pitting rate of 3.2 mpy and a maximum observed pitting rate of 22.5 mpy. Twenty-eight of the 45 bare-pipe examples had maximum observed pitting rates greater than or equal to 10 mpy, with 22 of the locations displaying through-wall penetrations caused by external corrosion. This information can be considered Data Type 1 and Data Type 2 because, since the distribution of maximum observed pitting rates is known, the average has a physical meaning (see Table 3-1, Row 7).

## Maximum Observed Pitting Rates

A limited amount of additional information on the DIPRA study data sets was provided by DIPRA to Reclamation that allowed the distributions of maximum observed pitting rates to be found.[27] From these data distributions (provided as histograms), the maximum observed pitting rates for bare and as-manufactured DIP pipe samples in soils for which the ANSI/AWWA Standard C105 score is greater than 10 could be estimated. This Data Type 2 information is shown in Rows 1 and 2 of Table 3-2.

These maximum observed pitting rates for bare and as-manufactured pipe samples as shown in Table 3-2 were obtained by the committee from the Woolley graphs, which presented the normal distribution curves from which the means and standard deviations were calculated and the histograms of the raw data were given.

---

[25] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research."

[26] Michael Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance," ASCE Pipelines, Advances and Experiences with Trenchless Pipeline Projects Conference, Boston, Mass., 2007.

[27] Woolley, letter and attached "Corrosion Database Statistical Analysis."

TABLE 3-2 Maximum Observed Pitting Rates of Bare and As-Manufactured Iron Pipe Without Cathodic Protection

| Row | Reference | Project Location or Data Source or Soil Condition | Description (All Data Type 2) | Maximum Observed Pitting Rate | Notes |
|---|---|---|---|---|---|
| 1 | DIPRA study[a] and Woolley analysis report to DIPRA[b] | Case 2 with soil condition values ≥10 points, per ANSI/AWWA C105[c] | Corrosion rate based on DIPRA Table 8 for 22 samples with bare pipe | 26 mpy | Maximum observed pitting rate for individual pipe segments obtained from Woolley analysis of DIPRA data[b] |
| 2 | DIPRA study[a] and Woolley analysis report to DIPRA[b] | Case 2 with soil condition values ≥10 points, per ANSI/AWWA C105[c] | Corrosion rate based on DIPRA Table 8 for 103 samples with bare (asphaltic shop-coated) pipe | 34 mpy | |
| 3 | Szeliga[d] | Varies | Bare pipe with 45 asphaltic shop-coated examples | 22.5 mpy | |

NOTE: DIPRA, Ductile Iron Pipe Research Association; mpy, mils per year.

[a]Richard Bonds, L.M. Barnard, A.M. Horton, and G.L. Oliver, "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research," *AWWA Journal*, 97(6):88-98 (2005).

[b]Thomas Woolley, letter and attached "Corrosion Database Statistical Analysis" data presentation, April 7, 2008.

[c]American Water Works Association, ANSI/AWWA Standard C105/A21.5-05 (2005): "Polyethylene Encasement for Ductile-Iron Pipe Systems," Denver, Colo.

[d]Michael Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance," ASCE Pipelines, Advances and Experiences with Trenchless Pipeline Projects Conference, Boston, Mass., 2007.

The Woolley graphs were provided by DIPRA to Reclamation without numerical scales for maximum corrosion rates on the abscissa. However, as the graphs contained histograms of the raw data along with the normal distribution curves, the graphs of the fitted normal distributions, the reported means, and the reported standard deviations, this information could be used to set a scale to the histograms and thus to determine the maximum observed pitting rates for all five situations in soil conditions ≥10 points.

The maximum observed pitting rate is approximately 26 mpy for bare DIP and approximately 34 mpy for as-manufactured (asphaltic-coated) DIP. This information corresponds to Data Type 2 and is shown as Rows 1 and 2 of Table 3-2.

Unfortunately, the DIPRA data for uniquely severe soils were provided only as mean maximum pitting rates. Without additional information on the data sets that were used to generate the mean values or the fit of the data distributions to a normal distribution, the data for uniquely severe soils in the DIPRA study could not be evaluated further.

The 45 as-manufactured (bare) pipe examples, of which 22 displayed complete wall penetrations, had a maximum observed pitting rate of 22.5 mpy.[28]

## POLYETHYLENE-ENCASED DUCTILE IRON PIPE WITHOUT CATHODIC PROTECTION

### Mean Maximum Pitting Rates for Damaged Polyethylene Encasement

The DIPRA study also compared as-manufactured (asphaltic shop-coated) pipe with pipe with intentionally damaged PE.[29] The "combined" mean maximum pitting rate for a total of 62 pipe samples with intentionally damaged PE from five locations was reported as 11.2 mpy, with the individual mean maximum pitting rates from the five sites being: 0 mpy (Aurora, Colorado—8 pipe samples); 4.5 mpy (Overton, Nevada—3 pipe samples); 5.8 mpy (Hughes, Alaska—3 pipe samples); 12.1 mpy (Everglades, Florida—38 pipe samples); and 20.6 mpy (Logandale, Nevada—10 pipe samples). Unfortunately, no information was provided about the data distributions of the data sets or the fit of the data to normal distributions for any of these five sites. This information is therefore Data Type 4 and has limited physical significance. Data Type 4 may provide qualitative support, which is of limited physical significance, for other sources of Data Types 1 and 2. See Table 3-3.

As noted above, Szeliga compiled a list of maximum observed pitting rates for as-manufactured DIP and DIP with PE based on his and others' experience.[30] The 14 iron pipes with PE included 12 actual pipe installations and 2 examples on 1 pipe sample from a testbed site. Of these 12 pipe installations, 7 showed penetration; of these 7, wall thicknesses were known for only 4 pipes. The maximum observed pitting rates for the 11 samples of DIP with PE for which the pipe wall thicknesses were known ranged from 3.0 to 68.0 mpy, with the four maximum observed pitting rates for penetration ranging from 14.7 to 68 mpy. The maximum observed pitting rate was 68.0 mpy on a DIP-with-PE system that experienced the first leak in 5 years. Six of the data points had corrosion rates equal to or above 10 mpy, and five data points were below 10 mpy. The average rate of corrosion for the 11 samples (arrived at by adding the total reported rates for all of the pipe examples together and dividing by the number of samples) was 16.7 mpy. This information falls into the Data Type 1 and 2 categories and is shown in Row 2 of Table 3-3.

---

[28] Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance."
[29] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research."
[30] Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance."

TABLE 3-3 Mean Maximum Pitting Rates of Damaged Polyethylene-Encased Iron Pipe

| Row | Reference | Soil Corrosivity Rating | Number of Samples and Pipe Condition | Mean Maximum Pitting Rate | Notes |
|---|---|---|---|---|---|
| 1 | DIPRA study data[a] | Varies, five test sites combined | Corrosion rate based on DIPRA Table 6 for 5 test sites with 62 samples with intentionally damaged PE. Data Type 4. | Combined mean maximum pitting rate at 5 sites (62 samples) of 11.2 mpy | Mean maximum pitting rate at 1 site (Florida) of 20.6 mpy for 38 samples |
| 2 | Others—Szeliga[b] | Varies | 11 examples, corrosion rates between 3.00 mpy and 68 mpy with 4 penetrations. Data Types 1 and 2. | Arithmetic average: 16.7 mpy | Maximum and average corrosion rate for all 11 samples |

NOTE: DIPRA, Ductile Iron Pipe Research Association; PE, polyethylene encasement; mpy, mils per year.

[a]Richard Bonds, L.M. Barnard, A.M. Horton, and G.L. Oliver, "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research," *AWWA Journal* 97(6):88-98 (2005).

[b]Michael Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance," ASCE Pipelines, Advances and Experiences with Trenchless Pipeline Projects Conference, Boston, Mass., 2007.

## Maximum Observed Pitting Rates for DIP with Damaged PE

### *Fountain Valley Project*

Reclamation observed corrosion and two leaks on a 24- to 25-year-old, 16-inch (400 mm) DIP with PE on the Fountain Valley Project section of the Fryingpan-Arkansas[31] Project in 2007.[32] This Reclamation project is located in Colorado, south of Colorado Springs. The pipeline with PE experienced corrosion leaks in March and July of 2007. The March leak was at the 5 o'clock position on the pipe and was approximately 1 3/4 inches (44 mm) wide by 2 1/2 inches (63 mm) long. The July leak occurred at the top of the pipe and was approximately 5/8 inch wide by 1 5/8 inches long. Reclamation stated in its report:

> It is not possible to determine for certain whether the pipes perforated due to corrosion under intact polyethylene or whether the polyethylene wrap had been previously damaged at the leak sites. Damage to the polyethylene encasement was present, but could have been caused by the force of the leak.[33]

[31] Per the Bureau of Reclamation Web site, "this is a multipurpose transmountain, transbasin water diversion and delivery project in Colorado." See http://www.usbr.gov/dataweb/html/fryark.html. Accessed April 18, 2009.

[32] U.S. Bureau of Reclamation, Materials Engineering and Research Laboratory, Technical Memorandum No. MERL-08-15, "Fountain Valley Project 2007, Security Lateral 16-inch Ductile Iron Pipe Failures," U.S. Department of the Interior, Denver, Colo. (2007).

[33] U.S. Bureau of Reclamation, Technical Memorandum No. MERL-08-15.

The calculated maximum observed pitting rate at the leak locations was approximately 14 mpy (Data Type 1, Row 1 in Table 3-4). An external corrosion penetration through the DIP wall was also observed at another location, where only the mortar lining was intact. Another corrosion pit location was found under undamaged PE and is discussed in more detail in the next subsection of this report.

*West County Wastewater District, Richmond, California*

Information from a West Coast wastewater district indicated that it observed external corrosion (corrosion from outside in) on an 18,000-foot-long DIP force main at damaged PE locations after 13 years.[34] The pipeline was installed in 1973 and experienced its first corrosion leak in 1986, with a maximum observed pitting rate of 31.6 mpy (Data Type 1, Row 2a in Table 3-4). Additional corrosion damage going two-thirds of the way through the pipe wall was also discovered at another damaged PE location during the forensic investigation; this corrosion occurred within 20 to 30 feet (6 to 9 m) of the first leak location next to a pump station. The maximum observed pitting rate at this location was 21.0 mpy (Data Type 2, Row 2b in Table 3-4). This area was reported to be in very corrosive soils with trash, clay, and bay mud at a former wastewater treatment plant site. Leak clamps were used to repair the pipe and, for approximately 1,300 to 1,500 feet of the pipeline in the most-corrosive low area, a galvanic anode system was installed. This CP system consisted of 65 galvanic anodes that were attached directly to the pipe at approximately 20-foot (6.5-m) spacing. Since the pipeline was not joint-bonded, galvanic anodes had to be installed at each joint of pipe in an effort to provide protection to the DIP with PE. Another leak occurred on the DIP with PE and CP section in 2003 at a bell that required a special leak clamp (bell pack), with a maximum observed pitting rate of 13.7 mpy (Data Type 1, Row 2c in Table 3-4).

*Example by Szeliga*

There are other reports of high pitting rates on DIP with PE or at locations where the PE was not installed correctly in as little as 5 years' time, leading to a maximum pitting rate of 68 mpy (Data Type 1, Row 3 in Table 3-4). Multiple failures have continued to occur during the water main's 21 years of operation.[35]

[34] Paul Winnicki, West County Wastewater District, Richmond, California, communication with the committee, 2008.

[35] Szeliga, "An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe"; Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance."

TABLE 3-4 Maximum Observed Pitting Rates at Damaged Polyethylene-Encased Ductile Iron Pipe (Partial List)

| Row | Reference | Project Location or Data Source | Pipe Size | Pipe Wall Thickness | Approx. Pipe Age | Soil Resistivity | Deepest Pit | Maximum Observed Pitting Rate | Notes (All Data Types 1 and 2) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Bureau | Fountain Valley Project, Colo. | 16-inch | Class 50 340 mils | 24 to 25 years | 520 ohm-cm | 340 mils | 13.6 mpy | 2 leaks and 1 complete wall penetration |
| 2a | Others | West County, Calif. | 18-inch | Class 52 410 mils | 13 years | Very corrosive | 410 mils | 31.6 mpy | First leak |
| 2b | Others | West County, Calif. | 18-inch | Class 52 410 mils | 13 years | Very corrosive | Assume 274 mils | 21.0 mpy | 2/3 wall penetration |
| 2c | Others | West County, Calif. | 18-inch | Class 52 410 mils | 30 years | Very corrosive | 410 mils | 13.7 mpy | 1 additional leak 17 years after galvanic anodes installed |
| 3 | Others | Szeliga[a] | 16-inch | 340 mils | 5 years | No data, assume very corrosive | 340 mils | 68 mpy | First leak, additional multiple later leaks reported |
| 4 | Others | Cape May, N.J. | Varies | Assume 250 mils | 5 years | Very corrosive 500 ohm-cm | 250 mils | 50 mpy | First leak, additional later leaks reported |

NOTE: mpy, mils per year; "Others" refers to data sources other than the Bureau of Reclamation or the Ductile Iron Pipe Research Association.

[a]Michael Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance," ASCE Pipelines, Advances and Experiences with Trenchless Pipeline Projects Conference, Boston, Mass., 2007.

*Cape May, New Jersey*

In Cape May, New Jersey, a corrosion failure on DIP with PE in 500 ohm-cm soils occurred in less than 5 years.[36] If it is assumed that the pipe wall thickness was 250 mils, the thinnest wall thickness, then the corrosion pitting rate would be approximately 50 mpy (Data Type 1, Row 4 in Table 3-4).

Information on the case histories for corrosion on DIP with damaged PE (Data Type 1 and 2) is summarized in Table 3-4.

## INTACT POLYETHYLENE ENCASEMENT

The committee is aware that PE has provided many years of successful protection to many miles of DIP. One recent publication by Crabtree and Breslin[37] presented convincing case studies showing the success of this corrosion protection method. A photograph in that article showed an excavated example of undamaged DIP under PE after 20 years of service. This is not an unusual case, and the committee recognizes that if such pipes were excavated in most locations, similar results of excellent corrosion performance could be documented. However, the committee saw its responsibility as that of finding the cases where DIP with PE did suffer corrosion in order to come to a conclusion concerning the reliability of this system. Thus, the remainder of this section presents cases in which corrosion was evident. Figure 3-1 is an example of DIP in PE.

### Summary of Reports of Corrosion Under Intact or Undamaged Polyethylene Encasement

Although the majority of external corrosion failures on DIP with PE are reported to be a result of damage to the PE or improper installation, studies by DIPRA, Reclamation, and a number of corrosion consultants and utilities also report corrosion of CIP or DIP under intact or undamaged PE. These are summarized below.

The committee's data set was purposely screened to include only information about pipes for which the PE was documented to be undamaged or for which no damage was noted in the field reports, as in some cases it was not known whether the encasement was intact or damaged. In the case of the DIPRA study summary report, the DIP with PE samples were specifically identified as "undamaged PE."

DIPRA provided information to the committee based on its 75 years of test-

[36] W. Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective," *Materials Performance* 41(7):16 (2002).

[37] Daniel Crabtree and Mark Breslin, "Investigating Polyethylene-Encased Ductile Iron Pipelines," *Materials Performance*, October: pp. 2-6 (2008).

FIGURE 3-1 Example of ductile iron pipe encased in polyethylene. SOURCE: Courtesy of Daniel Crabtree, Ductile Iron Pipe Research Association.

ing iron pipe samples with undamaged or intentionally damaged PE.[38] Although this testing is reported as a 75-year study, the data provided by DIPRA for DIP only consisted of performance of 1 to 35 years for ductile iron, 15 years for vinyl encasement, and from 1 to 12 years for intentionally damaged PE pipe samples at the five DIPRA testbed sites. Some of the cast iron samples had longer exposure, from 1 to 103 years, with the oldest CIP pipe with PE reported as being 45 years old for one location.

DIPRA reported that the mean maximum pitting rate of 151 samples with undamaged PE was 0.453 mpy in soils with corrosivity values equal to or greater than 10 points in accordance with the ANSI/AWWA C105 Standard, Appendix A,

[38] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research"; Richard Bonds et al., "Corrosion Control Statistical Analysis of Iron Pipe," *NACE Materials Performance* (January 2005).

evaluation procedures. These studies reported that the mean maximum pitting rate under undamaged PE for 85 samples in uniquely severe conditions as defined in ANSI/AWWA Standard C105, Appendix A, was 6.8 mpy. In the former case, additional information from Woolley[39] demonstrated that the data for the 151 samples were bimodal and did not fit a normal distribution; therefore, the mean maximum pitting rate data are Data Type 4 and have little physical significance.

Unfortunately, the data for uniquely severe soils were also provided only as a mean maximum pitting rate. Without additional information on the data set that was used to generate the mean values or the fit of the data distributions to a normal distribution, the data for uniquely severe soils also corresponds to Data Type 4 and could not be evaluated further. This information is shown in Rows 1 and 2 of Table 3-5.

### Maximum Observed Pitting Rates

A limited amount of additional information on the DIPRA study data sets was provided by DIPRA to Reclamation allowing the distributions of maximum observed pitting rates to be found for DIP with PE, as shown in Table 3-5, Row 1.[40] As noted, the data histogram and the probability plot for DIP with PE indicate a bimodal distribution, with 137 samples showing no pitting corrosion and 14 showing pitting corrosion with a mean maximum pitting rate of 4.9 mpy (for the 14 samples). These mean maximum pitting rate data (Row 3 in Table 3-5) are Data Type 4 and have little physical significance.

From the data distribution provided as a histogram and additional information contained in the Woolley report, the maximum observed pitting rate for DIP with PE pipe samples in soils for which the ANSI/AWWA Standard C105, Appendix A, score is greater than or equal to 10 was estimated to be 8 mpy. This information, classified here as Data Type 2, is shown in Table 3-6.

## FIELD CASES

Since it is frequently difficult to determine during leak repairs of DIP whether the PE was damaged before or after the repair, there is limited information on corrosion under reportedly intact or undamaged PE (see the section entitled "Summary of Bare, As-Manufactured, and Polyethylene-Encased Ductile Iron Pipe Corrosion Rates" later in this chapter for a discussion of "damaged" versus "undamaged" PE). Another challenge of assessing corrosion damage with any pipeline is that of locating corrosion-damaged areas along a pipeline with random digs if no

[39] Woolley, letter and attached "Corrosion Database Statistical Analysis."
[40] Woolley, letter and attached "Corrosion Database Statistical Analysis."

TABLE 3-5 Mean Maximum Pitting Rates Under Intact Polyethylene Encasement Without Cathodic Protection (Partial List)

| Row | Reference | Soil Corrosivity Rating | Number of Samples and Pipe Condition (All Data Type 4) | Mean Maximum Pitting Rate | Notes |
|---|---|---|---|---|---|
| 1 | DIPRA study data[a] | Case 2 with soil condition values ≥10 points, per ANSI/AWWA C105[b] | Corrosion rate based on DIPRA Table 8 for 151 samples with (undamaged) polyethylene-encased pipe | 0.453 mpy | All samples |
| 2 | DIPRA study data[a] | Case 3 with uniquely severe soil conditions, per ANSI/AWWA C105[b] | Corrosion rate based on DIPRA Table 9 for 85 samples with (undamaged) polyethylene-encased pipe | 6.8 mpy | All samples |
| 3 | DIPRA study data[a] | Case 2 with soil condition values ≥10 points, per ANSI/AWWA C105[b] | Corrosion rate based on DIPRA Table 8 for 9% of 151 samples (14 samples which corroded) with (undamaged) polyethylene-encased pipe at an average pitting rate of 4.9 mpy as stated by Woolley[c] | 4.9 mpy | Corroding samples only |

NOTE: DIPRA, Ductile Iron Pipe Research Association; mpy, mils per year.

[a]Richard Bonds, L.M. Barnard, A.M. Horton, and G.L. Oliver, "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research," *AWWA Journal* 97(6):88-98 (2005).

[b]American Water Works Association, ANSI/AWWA Standard C105/A21.5-05 (2005): "Polyethylene Encasement for Ductile-Iron Pipe Systems," Denver, Colo.

[c]Thomas Woolley, letter and attached "Corrosion Database Statistical Analysis," data presentation, April 7, 2008.

TABLE 3-6 Maximum Observed Pitting Rate Under Polyethylene Encasement Without Cathodic Protection

| Reference | Project Location, Data Source or Soil Conditions | Description | Maximum Observed Pitting Rate | Notes and Data Type |
|---|---|---|---|---|
| DIPRA study data[a] and Woolley analysis[b] report to DIPRA | Case 2 with soil condition values ≥10 points, per ANSI/AWWA C105[c] | Corrosion rate based on DIPRA Table 8 for 151 samples with undamaged PE | Approx. 8 mpy | Distribution of observed pitting rates for individual pipe segments obtained from committee analysis of DIPRA data. Data Type 2 |

NOTE: DIPRA, Ductile Iron Pipe Research Association; mpy, mils per year; PE, polyethylene encasement.

[a]Richard Bonds, L.M. Barnard, A.M. Horton, and G.L. Oliver, "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research," *AWWA Journal* 97(6):88-98 (2005).

[b]Thomas Woolley, letter and attached "Corrosion Database Statistical Analysis" data presentation, April 7, 2008

[c]American Water Works Association, ANSI/AWWA Standard C105/A21.5-05 (2005): "Polyethylene Encasement for Ductile-Iron Pipe Systems," Denver, Colo.

failure has occurred. Random digs attempt to access sites of severe corrosion that are at the tail of the distribution, which are difficult to locate. Bearing these issues in mind, representative examples of corrosion reported under undamaged PE are summarized in the subsections that follow. An overview of the field evaluations, field data, and representative photos are included for each data source.

Information from the evaluations reported below for intact or undamaged PE is summarized in Table 3-7. The source, project location, pipe size, pipe wall thickness, approximate age, soil resistivity, deepest pit, and maximum observed pitting rate are included in the table. The maximum observed pitting rate is based on either the estimated time of the leak (years) and wall thickness (or 250 mils if the actual wall thickness is unknown) or on the age of the pipe and the measured deepest pit, and it assumes uniform linear pitting rates. If the actual pipe wall thickness is greater than the assumed wall thickness, then the maximum observed pitting rate will be correspondingly larger than the tabulated value.

Given the size of the corrosion damage at some of the leak locations or where the cement mortar or polyethylene lining was observed to be the only thing resisting the internal fluid pressure, it is likely that the pipe wall had been penetrated at some time prior to detection of the first leak. Therefore, in the case of these pipes, it is likely that the actual corrosion rate may be greater than that listed.

### Marston Lake (Denver), Colorado

At the Marston Lake test location in Denver, Colorado, joint testing with the city of Denver and DIPRA was conducted in moist to wet soils with resistivities in the 400 ohm-cm range. The PE was intentionally damaged to determine the amount of corrosion under damaged and undamaged PE. In 1983, after 8.75 years of soil burial, the last six samples were excavated and examined. After blast cleaning, several pipe samples exhibited corrosion pitting under the undamaged PE. One DIP (sample 12) had a pit depth of 43 mils at the location of the PE damage. However, there was deeper pitting damage (68 mils) on the opposite side of the pipe where no damage to the PE was evident. CIP samples with PE (sample 3) had intermittent pitting (40 mils) along the polyethylene fold line for a distance of about 8 inches (200 mm) and a DIP (sample 21) had five minor pits on the opposite side of the pipe from the intentionally damaged PE.[41]

[41] Deon Fowles, *Report of Pipe Inspection: Denver Test Site (Marston Lake) in conjunction with Denver Water Board* (Birmingham, Ala.: DIPRA, July 15, 1983).

TABLE 3-7 Maximum Observed Pitting Rates Under Polyethylene Encasement (Partial List)

| Row | Reference | Project Location or Data Source | Pipe Size | Pipe Wall Thickness | Approx. Pipe Age | Soil Resistivity | Deepest Pit | Maximum Observed Pitting Rate | Notes (All Data Types 1 and 2) |
|---|---|---|---|---|---|---|---|---|---|
| 1a | DIPRA, 1983 Denver test site joint testing | Marston Lake, Denver, Colo.; city of Denver test site; joint testing with DIPRA 1983 pipe inspection | 6-inch DIP sample no. 12 opposite damaged PE location with 43-mil pit | Est. 250 mils | 8.75 years | 400 ohm-cm | 68 mils | 7.7 mpy | The pitting under undamaged PE was 150% deeper than at damaged PE location (68-mil pit compared to 43-mil pit depth) |
| 1b | DIPRA, 1983 Denver test site joint testing | Marston Lake, Denver, Colo.; city of Denver test site; joint testing with DIPRA 1983 pipe inspection | 6-Inch CIP sample no. 3, damaged PE location with 50-mil pit | Est. 250 mils | 8.75 years | 400 ohm-cm | 40 mils | 4.0 mpy | 40-mil pitting along the polyethylene fold line for 8-inch length |
| 2 | DIPRA[a] | Florida Everglade probes, ductile Iron probes | 6-inch DIP samples | Est. 250 mils | 3 years | 200 ohm-cm | Assumed max pitting rate of 5 to 6 mpy based on report that max rate was never above 6 mpy after first 3 months for all probes under PE, with an average of 1.7 mpy for all probes at bottom of pipe and 0.1 mpy at top of pipe with an average of all polyethylene-encased probes of 0.9 mpy. | | Steel probe data only, no pipe excavations |

*continues*

TABLE 3-7 Continued

| Row | Reference | Project Location or Data Source | Pipe Size | Pipe Wall Thickness | Approx. Pipe Age | Soil Resistivity | Deepest Pit | Maximum Observed Pitting Rate | Notes (All Data Types 1 and 2) |
|---|---|---|---|---|---|---|---|---|---|
| 3 | CIPRA, 1969 test site joint testing | Philadelphia, Pa. | 12-inch CIP | 620 mils | 10 years: December 1959 to August 1969 | 1,700 to 2,800 ohm-cm | 64, 65, and 76 mils | 6.4 to 7.6 mpy | 3 pits. PE not noted as being damaged |
| 4 | Bureau of Reclamation | Fountain Valley Project, Colo. | 16-inch | Class 50, 340 mils | 24 to 25 years | 520 ohm-cm | 130 mils | 5.2 mpy | Pit under undamaged PE |
| 5 | Others | Vancouver, B.C., Canada 1 of 3 sections dug up in 1986-1987 | Section A-B: 100 feet, 6 inches | Class 52, 310 mils | 16 years | 590 ohm-cm | 310 mils | 19.0 mpy | 3 complete wall penetrations to cement lining, with 1 leak |
| 6 | Others | Vancouver, B.C., Canada 1 of 3 sections dug up in 1986-1987 | Section C-D: 100 feet, 6 inches | Class 52, 310 mils | 14 years | 500 ohm-cm | 134 mils | 9.0 mpy | |
| 7 | Others | Vancouver, B.C., Canada 1 of 3 sections dug up in 1986-1987 | Section E-F: 175 feet, 6 inches | Class 52, 310 mils | 16 years | 280 ohm-cm | 118 mils | 7.0 mpy | |
| 8 | Others | Sheridan, Wyo., Marshal Field | 16-inch | Class 50, 340 mils | 14 years | 1,350 ohm-cm | 180 mils | 12.0 mpy | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 9 | Others | San Diego, Calif. | 16-inch CIP | Est. 800 mils | 25 years | 348 ohm-cm | 800 mils | 32.0 mpy | In 1999 averaging 2 leaks per year |
| 10a | Others | San Diego, Calif. | 24-inch DIP | Est. 420 mils | 19 years | 280 ohm-cm | 420 mils | 22.1 mpy | Leaks |
| 10b | Others | San Diego, Calif. | 24-inch DIP | Est. 420 mils | 8 years | 280 ohm-cm | 420 mils | 52.5 mpy | First leak in 8 years |
| 11 | Others | Colorado Springs, Colo. | 10-inch parallel force mains | Est. 380 mils | 14 years | 520 ohm-cm | 380 mils | 27.1 mpy | 5 leaks in this area in 1997, may be influenced by MIC |
| 12 | Others | Anchorage, Alaska | 8-inch | Class 52, assume 310 mils | 9 years: 1994 to 2003 | Most above 2,000 ohm-cm up to 17,000 ohm-cm | Assume 310 mils | 34.5 mpy | Dielectrically bonded coating polyurethane type now being used in these areas |
| 13 | Others | Calgary, Alberta, Canada[b] | 6-inch | 250 mils | 9 years | No data; assume corrosive | 250 mils | 27.8 mpy | From Jakobs and Hewes,[b] Figure 10 on page 48; may have been influenced by galvanic corrosion |

*continues*

TABLE 3-7 Continued

| Row | Reference | Project Location or Data Source | Pipe Size | Pipe Wall Thickness | Approx. Pipe Age | Soil Resistivity | Deepest Pit | Maximum Observed Pitting Rate | Notes (All Data Types 1 and 2) |
|---|---|---|---|---|---|---|---|---|---|
| 14 | Others | Michael Szeliga[c] | 16-inch | 367.3 mils | 21 years | No data on ohm-cm but reported as extremely corrosive soil | 187.3 mils | 8.9 mpy | Over-the-line potential survey did not indicate active corrosion under intact PE |

NOTE: mpy, mils per year; DIP, ductile iron pipe; DIPRA, Ductile Iron Pipe Research Association; "Others" refers to data sources other than the Bureau of Reclamation or DIPRA; CIP, cast iron pipe; CIPRA, Cast Iron Pipe Research Association; PE, polyethylene encasement; NACE, National Association of Corrosion Engineers; MIC, microbiologically influenced corrosion.

[a]A.M. Horton, D. Lindemuth, and G. Ash, "Ductile Iron Pipe Case Study: Corrosion Control Performance Monitoring in a Severely Corrosive Tidal Muck," NACE Corrosion 2005 Paper 05038, Houston, Tex.

[b]J.A. Jakobs and F.W. Hewes, "Underground Corrosion of Water Pipes in Calgary, Canada," *Materials Performance* (May 1987):42-49.

[c]Case History No. 2 from Michael Szeliga, "Ductile Iron Pipeline Failures," *Materials Performance* 44(5):26-30 (May 2005).

### Philadelphia, Pennsylvania

CIP protected with PE and embedded in corrosive soil was excavated and evaluated by the city of Philadelphia, the Cast Iron Pipe Research Association (CIPRA, now DIPRA), and the U.S. Pipe and Foundry after approximately 10 years of service (December 1959 to August 1969). The soils were classified as being contaminated with miscellaneous debris and had resistivities that ranged from 1,700 to 2,800 ohm-cm. The 12-inch (300-mm) CIP with a 620-mil wall thickness had been laid in a sand backfill and encased in an 8-mil tube-type PE. The date of the actual excavation was not stated in the CIPRA inspection summary report. Inspection of approximately 14 feet of the pipe revealed three measurable pits ranging in size from 0.015 to 0.03 square inches. The inspection summary report noted that the depths of the three pits were 64, 65, and 76 mils and stated that otherwise, the surface of the pipe showed insignificant pitting. The report stated that the pitting was probably created by local corrosion cells, and that irregularities in the pipe surface may have contributed to the pit depths. The report also indicated that there was evidence that moisture had been present underneath the PE for considerable periods of time. Damage to the PE was not noted in the inspection report, which also stated that laboratory testing of the PE indicated that the strength characteristics compared favorably with the PE that was being specified at the time of the field investigation in 1969.[42]

### Florida Everglades

The study by Horton and colleagues summarized corrosion control performance of PE for a 3-year period in a severely corrosive area in Florida.[43] Corrosion rates of commercially available steel probes were compared to the DIP both inside and outside the PE. Corrosion of probes inside the PE decreased with time, while those outside the PE and in direct contact with the soil increased with time. The corrosion rates of probes inside tightly wrapped PE were less (all probes averaged 0.6 mpy) compared to loosely wrapped PE (all probes averaged 1.6 mpy). After the initial 3 months of exposure, maximum corrosion rates approached 60 mpy for probes in soils but never exceeded 6 mpy for probes under the PE. Therefore, the committee has assumed that the maximum pitting rate indicated by one or more of the probes under the PE was likely between 5 and 6 mpy. The average corrosion rates for all probes inside the PE at the bottom of the pipe (6 o'clock position) were

[42] Harry Smith, *Inspection of Cast Iron Protected from Corrosive Soils Since December 1959 by Loose Polyethylene Tube* (Philadelphia, Pa.: Cast Iron Pipe Research Association, August 8, 1969).

[43] A.M. Horton, D. Lindemuth, and G. Ash, "Ductile Iron Pipe Case Study: Corrosion Control Performance Monitoring in a Severely Corrosive Tidal Muck," NACE Corrosion 2005 Paper 05038, Houston, Tex.

higher (average 1.7 mpy) than at the top of the pipe (12 o'clock with average of 0.1 mpy). The corrosion rate of the probes under the PE decreased after the initial 3-month exposure. The average corrosion rate after 3 years for all probes under PE was 0.9 mpy and was significantly less than the average of all probes in the soil (9.2 mpy). The study also indicated that additional work would be completed to compare actual corrosion rates of the pipe with those of the probe measurements when the pipe is excavated in the future.

### Fountain Valley Project

As noted earlier, Reclamation observed corrosion and two leaks on a 24- to 25-year-old, 16-inch (400 mm) DIP with PE on the Fountain Valley Project in Colorado in 2007.[44] Corrosion was also discovered under intact PE at a location approximately 6 feet from one of the leaks. This corrosion under the undamaged PE was reported to be 130 mils deep, or 5.2 mpy.

### Vancouver, British Columbia, Canada

In 1986-1987, the city of Vancouver, British Columbia, conducted testing to determine the success of DIP with PE that had been installed between 1970 and 1972 to replace corroding cast iron pipe sections.[45] Three sections of DIP with PE were excavated, two approximately 100 feet (30.48 m) long and the third approximately 170 feet (51.8 m) long. The pipe was approximately 14 years old and was buried in soils with 300 to 900 ohm-cm resistivity values. The pipe sections were pressure tested to 650 psi (~4.5 MPa) with no leaks visible. After abrasive blasting, the pipes were found to have three corrosion penetrations through the pipe wall, with only the cement mortar lining holding the water pressure. The corrosion consultant was of the opinion that some of the pipe corrosion occurred under undamaged PE, since it was difficult to align the PE damage with the corrosion pits.[46] Figure 3-2 shows one of these corrosion penetrations exposing the cement mortar lining.

---

[44] Bureau of Reclamation, Technical Memorandum No. MERL-08-15.

[45] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[46] Jerry Duppong, CH2M HILL. Bellevue, Washington, discussions and correspondence with William Spickelmire, 1997 through 2008.

FIGURE 3-2 In Vancouver, British Columbia, ductile iron pipe with polyethylene encasement after sandblasting where graphitic corrosion and cement mortar lining previously held 650 pounds per square inch water pressure. SOURCE: Courtesy of William Spickelmire, RUSTNOT Corrosion Control Services, Inc.

### Sheridan, Wyoming

In Sheridan, Wyoming, approximately 18 feet (5.486 m) of a 16-inch (40.6-cm) DIP line with PE were excavated for evaluation.[47] The DIP line was approximately 14 years old and was buried in 1,350 ohm-cm resistivity soils. Corrosion under the undamaged PE was found, and a 180-mil-deep pit was located at the 3 o'clock position on the pipe. The pipe was a Class 50 pipe with a nominal wall thickness of 340 mils. Testing of a sample of the PE by DIPRA indicated that the PE material met ANSI/AWWA standards.

[47] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

### San Diego, California

In San Diego, California, a 24-inch (60.96-cm) DIP line with PE was installed in 1967 and described as a successful installation in 1981[48] and 1986 by DIPRA following excavation and evaluation. An example of the corrosion damage observed by the city less than 8 years after burial on what was initially thought to be a previously successful application of PE is shown below in Figure 3-3.[49] This DIP line was reported to be abandoned in 1995.[50] The city of San Diego also reported that a parallel 16-inch (40.64-cm) CIP line installed in San Diego in 1961 was also cited by DIPRA as an example of successful implementation of PE,[51] but it began experiencing corrosion leaks in 1992. According to discussions with city personnel in 1999, the CIP with PE pipeline was averaging two leaks per year in 1997.

### Anchorage, Alaska

Anchorage, Alaska, has reported problems with DIP with PE in its soils with high groundwater and silty clays.[52] It has approximately 820 miles of water and 730 miles of sewer lines with approximately 375 miles of water and 350 miles of sewer lines in what the city classifies as corrosive soils.[53] In 1988-1989, the Anchorage Water and Wastewater Utility started requiring PE on DIP installations. The utility now reports that it has had numerous leaks on its class 52 DIP with PE within the 10- to 12-year burial time, with some failures occurring in as few as 9 years (1994 to 2003). See Figure 3-4 for an example of such a failure. Anchorage has identified failures in DIP buried in soils with higher resistivity values (up to 17,000 ohm-cm) and "corrosive" classifications (per the ANSI/AWWA Standard C105, Appendix A, 10-point system) with values between 2 and 13.5 points with the majority well

[48] Ductile Iron Pipe Research Association, *A Report on Inspection of Cast Iron Pipe and Ductile Iron Pipe Protected by Loose Polyethylene Encasement* (San Diego, California, October 1, 1981).

[49] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[50] William Spickelmire, discussion with Roberto Marigal, City of San Diego, California, November 1997.

[51] Cast Iron Pipe Research Association, *A Report on Observation of Corrosion Protection of Cast Iron Pipe by Loose Polyethylene Wrap* (San Diego, California, December 1968); DIPRA, *A Report on Inspection of Cast Iron Pipe and Ductile Iron Pipe Protected by Loose Polyethylene Encasement*.

[52] Tom Winkler, Anchorage Water and Wastewater Utility, "Corrosion: What AWWU Is Doing About It," Alaska Water and Wastewater Management Association, 46th Annual Statewide Conference, Anchorage, Alaska, 2006.

[53] Mark Corsentino, "Corrosion and Mitigation of AWWU Infrastructure," presentation to Alaska Water and Wastewater Management Association, 48th Annual Statewide Conference, Anchorage, Alaska, May 2008.


FIGURE 3-3 San Diego, California, 8-year-old, 24-inch ductile iron pipe with polyethylene encasement at former test site of the Ductile Iron Pipe Research Association. SOURCE: Courtesy of the City of San Diego, Water Department.

FIGURE 3-4 Nine-year-old 8-inch ductile iron pipe with polyethylene encasement in Anchorage, Alaska. SOURCE: Mark Corsentino, Presentation entitled "Corrosion and Mitigation of AWWU Infrastructure," given at the Alaska Water and Wastewater Management Association 48th Annual Statewide Conference: Anchorage, Alaska, May 2008.

below 10 points. The city is now using bonded polyurethane-coated DIP with CP in its most corrosive soils.[54]

### Colorado Springs, Colorado

Colorado Springs, Colorado, had two parallel 10-inch (250-mm), 18-mile (28.96-km) DIP wastewater force mains with PE and a bonded internal polyethylene lining that experienced severe corrosion problems.[55] In 1982, prior to construction, DIPRA conducted a survey for these routes and indicated that the only external corrosion protection needed was PE. In 1997, when the lines developed two corrosion leaks (Figure 3-5), the city conducted additional testing and evaluations to determine if the leaks were isolated problems or if corrosion threatened the integrity of the wastewater piping system. The pitting corrosion (based on smart pigging test results) was so widespread that the parallel lines could not be considered reliable.

[54] Mark Corsentino, Anchorage Water and Wastewater Utility, communication with the committee, 2008.

[55] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

FIGURE 3-5 In Colorado Springs, Colorado, force main corrosion where only polyethylene lining was holding sewage pressure. SOURCE: Courtesy of William Spickelmire, RUSTNOT Corrosion Control Services, Inc.

The city had to completely replace these pipelines with a high-pressure nonmetallic pipe in fewer than 18 years. In some cases, the internal polyethylene lining was the only material holding the wastewater pressure. Both the consulting engineer and the city's corrosion engineers reported that they observed corrosion under undamaged PE on these sewage force mains.[56] While it is likely that some of the external corrosion was caused by sewage inside the PE, it does show the problem when microbiological influenced corrosion (MIC) under PE may occur.

### Reasons for Variance in Reported Pitting Rates

There seems to be a wide variation in the pitting rates reported in the DIPRA study summary and between DIPRA's random digs and what is actually being seen in some of the field cases cited. One reason may be the difficulty in accurately locating corrosion activity on DIP with PE during random digs. Some researchers believe that, based on their experience, it is difficult if not impossible to locate actual corrosion damage at damaged PE locations on the pipe on the basis of above-

[56] William Spickelmire, discussions with Ron Geist, City of Colorado Springs Corrosion Control Department, Colorado Springs, Colo., 1999 through 2002; William Spickelmire, discussions and correspondence with Ron Skabo, CH2M HILL, Denver, Colo., 1999 through 2008.

grade potential test measurements. For example, Crabtree and Breslin concluded that "cell-to-cell potential surveys and side-drain technique measurements are not reliable in locating corrosion activity on [DIP with PE]. At eight different locations from all three water systems, the potential tests indicated active corrosion where none was found."[57]

Other corrosion consultants have stated that random test digs provide no meaningful information regarding the overall condition of a pipeline. They maintain that soil resistivity data and potential measurements must be analyzed to determine worst-case conditions for field investigations. They have demonstrated with actual digs that corrosion on pipelines at damaged PE locations can be identified with above-grade corrosion testing methods.[58] The same consultants indicated that corrosion under undamaged polyethylene encasement based on a 390-foot cell-to-cell potential over-the-line survey was not successful in locating corrosion damage under intact PE, and corrosion was only found when the entire pipeline was excavated. They further note that the corrosion rate under intact PE was similar to that at damaged PE locations.[59]

These examples are further illustration of the difficulties with electrical shielding in accurately assessing the corrosion activity on pipelines with disbonded coatings or PE. When electrically effective, these may mask the true potentials at the pipe surface and the corrosion activity.

Another reason for differences in corrosion rates may be that the pipe samples in the DIPRA testbeds are short (4- to 8-foot-long) sections of small-diameter pipe that are carefully polyethylene-encased and installed. Also, the testbeds are usually subject to the same uniform types of burial and water levels, which may not be the same conditions as those experienced by DIP with PE in actual installations.[60] Another possible explanation is that random pipe excavations may not result in accurately determining the actual condition of the pipeline or the level of protection provided by a CP system with PE because the probability of actually exposing localized corrosion is less than 1 percent with random digs, and corrosion under intact encasement cannot be detected with above-grade potential measurements.[61]

---

[57] Crabtree and Breslin, "Investigating Polyethylene-Encased Ductile Iron Pipelines."

[58] Michael Szeliga and Debra Simpson, "Corrosion of Ductile Iron Pipe: Case Histories," *Materials Performance* 40(77):22-26, (2001); Michael Szeliga and Debra Simpson, "Evaluating Ductile Iron Pipe Corrosion," *Materials Performance* 42(7):22-28, (2003).

[59] Michael Szeliga, "Ductile Iron Pipeline Failures," *Materials Performance* 44(5):26-30 (2005).

[60] Szeliga, "An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe."

[61] Szeliga, "An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe."

As the San Diego pipelines with PE showed, pipelines randomly excavated may appear good in some places while suffering major corrosion in other areas.[62]

Another possible reason for the wide variance between some of the field examples and the DIPRA study summary data was explained in the Bureau of Reclamation's Fountain Valley report.[63] In this report, Reclamation indicated that DIPRA had provided the Woolley report, which states that the 0.453 mpy rate included in the DIPRA study was based on a weighted mean average for all of the 151 samples in the soils classified as ≥10 points according to the ANSI/AWWA Standard C105, Appendix A, soil evaluation procedure. Reclamation's report stated:

> DIPRA's test bed data was described as bi-modal in nature with 91% of their test bed samples showing no pitting damage during the test period and 9% of their test bed samples exhibiting pitting at an average rate of 4.882 mpy. The 0.453 mpy figure is a weighted average ($0.907 \times 0 + 0.093 \times 4.88 = 0.453$ mpy). Thus, while most of their samples did not show pitting, where corrosion did initiate in the DIPRA test bed samples, it proceeded at a rate similar to the rates observed in the field installations noted above.[64]

Reclamation stated that this may help explain the wide divergence in pitting rates observed for actual field installations and the DIPRA study test data summaries.

Another factor could be that some of the field case studies are in soils that are influenced by MIC or are as corrosive as the uniquely severe soil corrosivity classification. Information was not provided on whether Woolley[65] evaluated the 85 samples of pipe with undamaged PE in "uniquely severe soil conditions" as defined in ANSI/AWWA Standard C105, Appendix A, that showed a 6.8 mpy mean maximum pitting rate in the DIPRA study. The 6.8 mpy mean for undamaged PE in uniquely severe soil conditions is 15 times higher than the reported 0.453 mpy mean rate for undamaged PE in soils of ≥10 points. Likewise, the maximum observed pitting rate for undamaged PE in uniquely severe soil conditions may be much higher than the calculated 8 mpy maximum observed pitting rate for undamaged PE in soils of ≥10 points. Not having the necessary information to calculate the maximum observed pitting rate only allows one to speculate that it may be 10 to 15 times higher based on reported case studies with observed rates of 68 mpy on pipe with PE. Soils of this corrosivity would also be included in Reclamation's classification of highly corrosive soils under 2,000 ohm-cm maximum range.

[62] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[63] U.S. Bureau of Reclamation, Technical Memorandum No. MERL-08-15.

[64] U.S. Bureau of Reclamation, Technical Memorandum No. MERL-08-15.

[65] Woolley, letter and attached "Corrosion Database Statistical Analysis."

## CATHODICALLY PROTECTED POLYETHYLENE-ENCASED DUCTILE IRON PIPELINES

The committee is aware that, as with DIP protected by PE, DIP protected by PE and CP can show excellent corrosion resistance in nearly every place where such a pipeline is buried. However, the committee found it necessary to seek those rare instances in which this protection system failed in order to carry out the committee charge. Thus, the discussion in this section is not intended to imply that such instances are the norm, but rather to document the evidence that the committee evaluated in coming to its conclusions.

There are no industry standards for the use of CP on DIP with PE. It is a controversial issue in the corrosion industry. There are diametrically opposed viewpoints on the performance of this system, with a wide variation in acceptance. The major issue is that no long-term, nonbiased scientific studies have determined whether PE with CP works under all conditions.

There seems to be general agreement in the industry that CP of polyethylene-encased DIP may provide corrosion protection in those areas where localized physical damage to the polyethylene occurs due to poor installation practices, third-party damage, or other damage to the polyethylene, resulting in contact with highly corrosive soil and water environments. There is disagreement, however, as to whether the CP will protect at distances from the damage, due to the potential that the PE may shield the current.

### Field Testing of Five Pipelines: Ductile Iron Pipe with Polyethylene Encasement and Cathodic Protection

Lindemuth provided a summary paper he co-wrote with Kroon and made a presentation to the committee on DIPRA's field testing and pipe examinations completed for four DIP with PE and CP pipelines.[66] The pipelines summarized in the paper were in Montrose, Colorado; Hanna, Wyoming; Aberdeen, South Dakota; and Orange, California. The pipelines were generally installed between 1979 and 1988, with lengths that ranged from 7 to 70 miles. Two of the pipelines were protected with galvanic anodes and two with impressed-current-type CP systems. Short, over-the-line potential surveys (see Appendix D for a discussion of this technology) were made to try to identify possible damaged locations. This testing method consists of conducting pipe-to-soil potential measurements at 2- to 3-foot spaces directly over the pipeline. The field extractions and evaluations, completed

[66] D. Lindemuth and D. Kroon, "Cathodic Protection of Pipe Encapsulated in Polyethylene Film," NACE Corrosion 2007 Paper 07040, Houston, Tex.; D. Lindemuth, "Polyethylene Encasement and Cathodic Protection Proven Synergistic Corrosion Control for Ductile Iron Pipe," presentation to the committee, Washington, D.C., July 28, 2008.

in 2005 and 2006, determined that the DIP with PE and CP pipelines were in very good condition. The authors stated that these field investigations support their contention that CP is compatible with PE and can provide a "synergistic blend of corrosion protection" for ductile iron pipelines. Lindemuth and Kroon state that, while CP and PE have been used together effectively to control external corrosion of ductile iron in very corrosive soils, the CP current will only protect the pipeline surface exposed to the soil, because intact PE may shield CP and not allow it to retard corrosion under intact PE.[67] The authors further stated:

> When used in conjunction with PE, it is important to recognize that cathodic protection only retards corrosion at the DIP surfaces in contact with the soil, i.e. where there is damage to the encasement or where the encasement does not cover the pipe because of improper construction. Corrosion control for the majority of the pipe surface is achieved through the proper installation and maintenance of the encasement, relying on its physical barrier and oxygen reducing characteristics. The electrically high resistant nature of the encasement can significantly reduce the total cathodic protection current demand, which is generally proportional to the exposed pipe surface. The corrosion reducing properties of the cathodic current are typically not expected to further reduce pipe corrosion rates under intact areas of the encasement away from any damage. [68]

A summary describing a fifth, 3-mile-long, 24-inch, 23-year-old pipeline in Vacaville, California, was included in the presentation to the committee in July 2008. No corrosion was noted on this DIP line with PE and CP.[69] The presenter stated that these five pipeline case histories totaling 114 miles with 18-plus years showed satisfactory performance. The soil resistivities reported for four of the five pipelines were below 2,200 ohm-cm in as-received condition and below 500 ohm-cm to 74 ohm-cm when saturated. The soil resistivities for the fifth site, in Vacaville, were 1,200 ohm-cm to 48,000 ohm-cm as-received and 1,000 ohm-cm to 25,000 ohm-cm when saturated. Individual soil resistivity values for these pipelines are summarized in Table 3-8 in the following major section, "Summary of Known Cathodically Protected Polyethylene-Encased Pipelines."

### Southwest Pipeline

One of the earliest-referenced studies of DIP with PE and CP is a large transmission pipeline project in North Dakota, where an impressed current CP system

---

[67] Lindemuth and Kroon, "Cathodic Protection of Pipe Encapsulated in Polyethylene Film."

[68] Lindemuth and Kroon, "Cathodic Protection of Pipe Encapsulated in Polyethylene Film."

[69] Lindemuth, "Polyethylene Encasement and Cathodic Protection Proven Synergistic Corrosion Control for Ductile Iron Pipe."

TABLE 3-8 Partial List of Cathodically Protected Polyethylene-Encased Ductile Iron Pipelines

| Project Location or Data Source | Date of Construction | Pipe Size (Diameter) | Pipe Length |
|---|---|---|---|
| WEB Development Aberdeen, S.Dak. DIPRA Bureau Project | 1984-2008 | 14- to 30-inch | 150 miles |
| Southwest Pipeline Project, N.Dak. DIPRA Bureau Project | 1983-1992 | 12- to 36-inch | 75.8 miles |
| Mid-Dakota Rural Water Service, Miller, S.Dak. DIPRA Bureau Project | 1996-2002 | 20- to 30-inch | 49.6 miles |
| Montrose, Colo. DIPRA Others | 1981 | 24-inch | 27 miles |
| Hanna, Wyo. DIPRA Others | 1986 | 12- to 14-inch | 7 miles |
| Rancho Santa Margarita; Orange County, Calif. DIPRA Others | 1985 | 42-inch | 7 or 8 miles |
| Vacaville, Calif. DIPRA Others | 1984 | 24-inch | 3 miles |
| Akron, Ohio | 2001 | 16-inch | 0.25 miles |
| Trinidad, Trinidad and Tobago | 1979-1982 Heavy-duty polyethylene, 16 to 20 mils thick | 24- to 60-inch | Approximately 10 miles of the 30-mile total were cathodically protected with impressed current distributed anode ground beds |
| California City Others | 1975 | 14- and 16-inch pipeline | Est. 1 to 2 miles |
| Vernal, Utah Others | 1984 Three pipelines: raw water, fire water, and sewer lines | Varies: 4- or 6-inch sewer, 16-inch fire water, and 24-inch raw water pipelines | Sewer line 0.02 mile (100 to 200 feet) Fire water est. 3 to 5 miles Raw water est. 1 mile Total: 4.02 to 6.02 miles for all three lines |

| Route Corrosivity | Notes, Number of Probes, or Excavations |
|---|---|
| Severely corrosive; all reported to be under 2,000 ohm-cm, with most under 1,000 ohm-cm; reported to be 150 to 300 ohm-cm when saturated | No probes installed initially. Installed three DIP probes at one location in 2005. Two excavations by DIPRA (17-year-old pipe), and more than 100 joint bond repair and tap excavation locations. Impressed current CP. No external corrosion leaks reported through 2008. |
| Severely corrosive; all reported to be under 2,000 ohm-cm, with most under 1,000 ohm-cm | Initially eight locations with 20 steel probes, two excavations by DIPRA in 2004, two previous excavations Dickinson, N.Dak., one on June 10, 1989, and one on April 21, 2004, on 1989 pipe. Impressed current CP. One corrosion leak, October 2004. |
| Severely corrosive; all reported to be under 2,000 ohm-cm, with most under 1,000 ohm-cm | Reliability question on steel probes, one excavation by DIPRA, joint bond problems with a large number of excavations. Impressed current CP. No external corrosion leaks reported through 2008. |
| Less than 1,000 ohm-cm; as received, 140 ohm-cm to 2,800 ohm-cm and 140 ohm-cm to 350 ohm-cm when saturated | 450-foot over-the-line-potential-survey; two DIPRA excavations, one with 5 mil rust in 27 years, galvanic anodes. No external corrosion leaks reported through 2008; installation date assumed based on excavation date of 2006 and 25-year pipe age reference. |
| Less than 1,000 ohm-cm with 260 ohm-cm in places. | 582-foot over-the-line potential-survey, one DIPRA excavation, galvanic anode. No external corrosion leaks reported through 2008; installation date assumed based on excavation date of 2007 and 21-year pipe age reference. |
| 2,200 ohm-cm as received and 74 ohm-cm when saturated | One DIPRA excavation; pulse type, impressed current CP. No external corrosion leaks reported through 2008; installation date assumed based on excavation date of 2006 and 21-year pipe age reference. |
| Soil resistivity 1,200 to 48,000 ohm-cm as received and 1,000 to 25,000 ohm-cm when saturated | One DIPRA excavation; pulse type, impressed current CP. No external corrosion leaks reported through 2008; installation date assumed based on excavation date of 2007 and 23-year pipe age reference. |
| 1,200 ohm-cm | One corrosion leak |
| Severe, less than 2,000 ohm-cm, with localized hot spots below 500 to 100 ohm-cm in some locations with high chlorides | Unknown |
| Extremely corrosive, 100 ohm-cm to 250 ohm-cm, with high chlorides | One corrosion leak at 14-inch pipe in 1983, pipeline replaced in 1987. |
| Sewer line 2,000 ohm-cm; plant generally dry and above 3,000 ohm-cm | Corrosion observed on all three lines, with six leaks on sewer line. Sewer line replaced in 2006; two locations of pitting observed on fire water or raw water pipelines. |

*continues*

TABLE 3-8 Continued

| Project Location or Data Source | Date of Construction | Pipe Size (Diameter) | Pipe Length |
|---|---|---|---|
| Denver, Colo.<br>Others | 1984 | 14- and 18-inch parallels | 4.5 miles of dual force mains equaling 9 miles total |
| Sheridan Area-Wide Water Supply Project, Sheridan, Wyo. | 1992 to 1994 | Varies: 16- to 20-inch | 12 miles |
| Bozeman, Mon.<br>Others | 2005 | 24-inch | 4.3 miles |
| Cheyenne, Wyo.<br>Others | 2004 | 30-inch | 1 mile |
| Minneapolis-St. Paul, Minn.<br>Others | 2007-2008 | Dual 18-inch sewer force mains | 2.3 miles of dual force mains equaling 4.6 miles total |
| Totals: Pipeline distance, 369.57 miles; of that, pipelines in soils <2,000 ohm-cm, 352.65 miles | | | |

NOTE: WEB, Walworth, Edmunds, and Brown; DIPRA, Ductile Iron Pipe Research Association; DIP, ductile influenced corrosion.

was employed to provide protection to both coated steel and DIP with PE.[70] This project incorporated steel electrical resistance probes placed both in the pipe backfill and under the PE in an attempt to determine CP levels under the encasement. The authors of the study reported that the corrosion rate of the steel probes with CP current averaged approximately 0.019 mpy for probes located inside and outside the encasement. Their testing indicated that the current requirements for DIP with PE were on average 28 times greater than that for the tape-coated steel.

## SUMMARY OF KNOWN CATHODICALLY PROTECTED POLYETHYLENE-ENCASED PIPELINES

A partial list of DIP lines with PE and CP is presented in Table 3-8.

Although the majority of DIP lines with PE and CP have had no reported leaks, there are a few examples of corrosion on DIP lines with PE and CP. This information is summarized here and in Table 3-9 for reference.

[70] M. Schiff and B. McCollum, "Impressed Current Cathodic Protection of Polyethylene-Encased Ductile Iron Pipe," presented at NACE Corrosion 93, Houston, Tex.

| Route Corrosivity | Notes, Number of Probes, or Excavations |
|---|---|
| Very corrosive; below 2,000 ohm-cm with alkaline salt deposits visible on surface | Parallel force mains, distributed ground bed with three rectifiers. No external corrosion leaks reported through 2008. |
| Varies; most above 1,000 ohm-cm | Surface corrosion seen in 5-year burial on galvanic anode system on two separate DIP PE with CP pipelines. No other external corrosion leaks reported through 2008. |
| Generally above 3,000 ohm-cm | Distributed galvanic ribbon. No external corrosion leaks reported through 2008. |
| Above 3,000 ohm-cm | Distributed galvanic ribbon. No external corrosion leaks reported through 2008. |
| Above 3,000 ohm-cm | Distributed galvanic ribbon and anti-MIC PE. No external corrosion leaks reported through 2008. |

iron pipe; CP, cathodic protection; est., estimated; PE, polyethylene encasement; MIC, microbiologically

## Denver, Colorado

Two 4.5-mile-long parallel force mains with PE in Denver, Colorado, were cathodically protected in 1984.[71] The two parallel force mains (14- and 18-inch diameter) were provided with an impressed-current CP system. A distributed-type impressed-current ground bed was used in an effort to try to minimize electrical shielding problems on the two parallel sewage force mains with PE. In this distributed-type ground bed, the anodes were laid at a specific spacing next to the parallel lines along the entire pipeline route in the same pipe trench between the pipelines. Potential measurements made with both permanent reference electrodes and portable reference electrodes at the ground surface indicated that levels were adequate. Some differences were noted between the inside and outside permanent reference cells.[72] No leaks have been reported on these pipelines up to the time of the writing of this report.

Recent projects in Wyoming, Montana, and Minnesota have used a magnesium

[71] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[72] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

TABLE 3-9 Maximum Observed Pitting Rates of Cathodically Protected Polyethylene-Encased Ductile Iron Pipelines with Observed Corrosion

| Row | Reference | Project Location or Data Source | Pipe Size | Pipe Wall Thickness | Approx. Pipe Age | Soil Resistivity | Deepest Pit | Maximum Observed Pitting Rate | Notes (All Data Types 1 and 2) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Bell[a] | Southwest Pipeline, 75.8 miles of CP PE DIP | 16-inch | Class 250, 300 mils | 19 years: 1985-2004 | 500 to 1,000 ohm-cm | 300 mils | 15.8 mpy | One leak |
| 2 | Others | Akron, Ohio, 0.25 mile | 16-inch | Class 56, 520 mils | 6 years: 2002-2008 | 1,200 ohm-cm | 520 mils | 86.6 mpy | One leak, joint bond problem |
| 3a | Others | Vernal, Utah, Power Plant, sewer line to 6 inches, approx. 100 to 200 feet long | 4- or 6-inch | Assume 250 mils | 22 years: 1984-2006 | Sewer line around 2,000 ohm-cm, with most of the plant above 3,000 ohm-cm | 250 mils | 11.3 mpy | Six leak locations, internal/external corrosion, possible MIC influence |
| 3b | Others | Vernal, Utah, Power Plant, 6-inch fire water or 24-inch raw water line | 6- or 24-inch | Assume 250 mils | 10 years: 1984-1994 | Above 3,000 ohm-cm | 125 mils | 12.5 mpy | Major pitting found during other work |
| 3c | Others | Vernal, Utah, Power Plant, 6-inch fire water or 24-inch raw water line | 6- or 24-inch | Assume 250 mils | 10 years: 1984-1994 | Above 3,000 ohm-cm | 30 to 60 mils | 3 to 6 mpy | Major pitting found during other work |
| 4 | Others | California City, Calif. | 14-inch | 350 mils | 8 years: 1975-1983; CP installed, 1979; pipe replaced, 1987 | 100 ohm-cm | 350 mils | 43.75 mpy | One leak with two other through-wall corrosion penetrations in 1983. Unable to determine if major corrosion occurred before or after CP was installed in 1979. Pipeline abandoned and replaced after only 12 years of service. |

NOTE: CP, cathodic protection; PE, polyethylene encasement; DIP, ductile iron pipe; mpy, mils per year; MIC, microbiologically influenced corrosion; "Others" refers to data sources other than the Bureau of Reclamation or the Ductile Iron Pipe Research Association.

[a]Graham E.C. Bell, Schiff & Associates, "Measurements of Performance of Corrosion Control Mechanisms on DIP," presentation to the committee, Washington, D.C., July 29, 2008.

FIGURE 3-6 Ductile iron pipe with polyethylene encasement and a ribbon galvanic anode cathodic protection system. SOURCE: Courtesy of William Spickelmire, RUSTNOT Corrosion Control Services, Inc.

galvanic ribbon-type anode system on the ductile iron lines in soils generally above 3,000 ohm-cm.[73] To minimize the chance of electrical shielding, the ribbon anode was placed next to the pipe for the entire distance (see Figure 3-6). Specialized polyethylene-encased ductile iron monitoring stations with perforated plastic monitoring pipes placed inside and outside the PE were installed at specified distances along the route. This type of specialized test station has a plastic monitoring pipe installed both inside and outside the PE in an effort to monitor actual potential measurements at the pipe surface for comparison to the measurement outside the PE. Although these cathodically protected pipelines are relatively new (installed between 2004 and 2008), observed potential differences between the inner and outer plastic monitoring pipes range from 10 to 20 mV up to 1 V or more depending on the specific test station and pipeline being tested. As expected, potential measurements outside PE have always been more negative than those under the PE. The reason for this wide variation is likely due, in some degree, to the electrical shielding of the PE. In some cases, the potential levels were below the protected criteria of a −0.85 V to a copper/copper sulfate reference electrode, so the actual level of protection provided under the PE may not be complete. Additional testing and time are needed to explain fully the degree and severity of electrical shielding and the influences on both actual protection levels provided and on potential measurements made inside and outside the PE.

[73] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

**Southwest Pipeline**

One project in North Dakota on a 76-mile DIP line with PE and CP reported a major leak in October 2004.[74] The leak occurred on this 12- to 19-year-old Class 250 (300-mil) walled pipe in the bottom of a small creek drainage. The CP designer stated in his presentation to the committee in July 2008 that he and his colleagues believed that the joint may have been overextended (deflected) and that either the joint leaked or that groundwater flowing through the low creek area locally increased the oxygen level and CP current requirements in that area.

In 2004, the manufacturer of the ruptured DIP conducted a forensic analysis to evaluate the metallurgical and mechanical properties of the 16-inch-diameter section of pipe that had been returned to it.[75] The inspection found that although the joint was overdeflected (6.6 degrees compared to a 5.0-degree design maximum), based on the manufacturer's examination of the gasket and gasket sealing surface on both the spigot and the bell gasket recess area, it had not leaked. The manufacturer also examined the thermite weld connections for the joint bond wires and found that the cadweld connection and mastic coating were in good condition and showed no evidence of galvanic corrosion. The pipe thickness in an undamaged area was measured and found to be greater (318 mils) than the specified Class 250 pipe thickness of 300 mils. The testing indicated that the pipe met the mechanical and metallurgical property requirements of ANSI/AWWA Standard C151.[76] The manufacturer concluded that "the pipe showed no evidence of any type of leakage until it ruptured."

The pipe manufacturer also conducted additional testing and a scanning electron microscope analysis of the leak area,[77] concluding that the nature of the pipe wall failure was indicative of a catastrophic-type event as opposed to a leak over a long period of time. The manufacturer based this conclusion on the observations that the pipe was sufficiently thin that it ruptured due to stress overload; the failure area was jagged, which is indicative of a relatively recent event; the edges could fit back together completely; the surface of the breach exhibited less corrosion than the pipe surface; and the increased metal thickness on each end of the failure was sufficient to stop the rupture and handle the hydrostatic pressure. The manufacturer described the external corrosion damage as a large area where the pipe wall

[74] Bell, presentation to the committee, July 29, 2008.

[75] American Cast Iron Pipe Company, *Investigation of the Fracture of a 16" DIP from SWPP Station 283+: Scanning Electron Microscope Evaluation of Fracture* (Birmingham, Ala.: American Cast Iron Pipe Company-Technical Division, October 11, 2004).

[76] American Water Works Association, ANSI/AWWA Standard C151/A21.51-96, "American National Standard for Ductile-Iron Pipe, Centrifugally Cast, for Water" (Denver, Colo., 1996).

[77] American Cast Iron Pipe Company, *Investigation of the Fracture of a 16" DIP from SWPP Station 283+*.

FIGURE 3-7 Location of 2004 leak on 16-inch Class 250 (300 mil thick) ductile iron pipe with polyethylene encasement and cathodic protection in North Dakota. SOURCE: Courtesy of Joe Bichler, Bartlett and West Engineers.

had been thinned down and stated, "The thinnest area consisted of a 2-[inch] wide band covering 120 degrees of the circumference adjacent to the face of the bell and the other area was about 1 sq. ft. at the very bottom of the pipe where the [pipe wall failure] occurred."[78] It concluded that the area of thin metal was due to external corrosion and that the rupture probably occurred when a transient pressure event took place in the water pipe system. The photo provided in the presentation of the leak is shown in Figure 3-7.

### Akron, Ohio

The committee received information about a corrosion leak that occurred on a 16-inch DIP with PE and CP in Ohio in a less-than 6-year burial time.[79] Historically, a 7-mile section of CIP had experienced corrosion breaks in the same area. After a third leak occurred in the same area on the cast iron pipeline, a short, 1,300-foot section was replaced with Class 56 (520 mil thick) DIP with PE and galvanic anodes in 2001. Early in 2008 (after approximately 6 years of burial), the pipeline experienced a leak at a joint where the single joint bond was loose. From the information received by the committee, it is not possible to determine both whether that section of the pipe was the side with the anode and whether the joint

[78] American Cast Iron Pipe Company, *Investigation of the Fracture of a 16" DIP from SWPP Station 283+*.

[79] Gregg Loesch, Akron Public Utilities Bureau, communication and correspondence with the committee, September 2008.

FIGURE 3-8 Location of leak on bottom of cathodically protected 16-inch ductile iron pipe with polyethylene encasement in Ohio. SOURCE: Courtesy of Gregg Loesch, Akron Public Utilities Bureau.

bond had been broken before excavation, during the pipe excavation, or as a result of pipe movement due to the pipeline leak. It was also not possible to determine the level of CP provided to the pipeline. The owner did confirm that the leak was on the bottom of the pipe and that there were no interference sources (rectifiers) in that area. See Figure 3-8.

### Vernal, Utah

Three different types of DIP lines with PE (fire water, raw water, and sewer lines) were installed at a power plant in Vernal, Utah, in 1984, and CP was installed and operating by 1985.[80] The raw-water and fire-water pipelines were excavated

[80] William Spickelmire, discussions and correspondence with Jeff Mattson, Corrosion Control Technologies, Sandy, Utah, 1997 through 2008.

to repair broken test leads in 1995. Surface corrosion was found at two locations under intact PE, one on the raw-water line and one on the fire-water lines. The corrosion engineer, who observed the external corrosion damage, stated that "it was not from polyethylene-encasement coating defects, soil under the polyethylene, or [CP] stray currents at a broken joint bond."[81] The soil resistivities at these locations were approximately 3,000 ohm-cm. The estimated pit depths were 30 to 60 mils at one location and 125 mils at the second location and occurred in less than 10 years of burial on the raw-water and fire-water pipelines.[82]

In 2006, a DIP sewer line at this power plant was replaced because of six leaks.[83] The corrosion engineer stated that it was not possible to determine whether the damage was due to internal or external corrosion or to a combination. The pipe was replaced and discarded before additional forensic testing could be performed to determine the actual depth of external corrosion. The engineer also reported that the pipeline displayed a thick black layer and severe graphitic corrosion, even with a measured protected potential of −1.10 V at the ground surface. Some of the corrosion damage may have been due to MIC activity, which indicates that CP may not be able to provide protection in cases of MIC if the PE is electrically shielding the pipeline. The sewer line case is included here for completeness but is not included in the failure analysis to be presented in Chapter 4. However, the maximum observed pitting rate for this line was 11.3 mpy, which is very similar to the 12.5 mpy maximum observed pitting rates on one of the water lines; the latter is known to be entirely from external corrosion.

### California City, California

Corrosion was observed at three locations in California in 1983 on a section of a 14-inch DIP with PE and CP that had been removed because of a large leak.[84] The pipeline potential measurements were slightly below adequate protection levels (−0.760 V potential range at the pipeline leak repair location) because of a short at an insulator on the opposite end of the pipeline. The 14- and 16-inch pipeline had been installed in 1975, and CP was added in 1979. The soils were extremely aggressive tidal mudflats with high chlorides (38,600 ppm) and a soil resistivity of 100 ohm-cm. The 14-inch DIP wall was perforated in three locations at the bot-

[81] Spickelmire, discussions and correspondence with Mattson.
[82] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."
[83] Spickelmire, discussions and correspondence with Mattson.
[84] CH2M HILL, *California City Corrosion Control Study*, March 1983, with field observations by George Richards and William Spickelmire, (CH2MHILL: Engelwood, Colo.); California City Engineering Department, communication with the committee, September 2008.

tom of the pipe near the spigot end of the joint. The pit that caused the leak was approximately 2.75 inches (69 mm) wide and 5.75 inches (144 mm) long. The other two locations where the corrosion pits had completely perforated the pipe wall were both approximately 1.5 to 2.0 inches (37 to 50 mm) in diameter. Only the cement mortar lining at these other two penetrations appeared to be holding the water pressure. The bond wires were tested and appeared to be functioning correctly, and the DIP was electrically continuous.[85] It was not possible to determine whether the damage to the DIP wall had occurred prior to or after installation of the CP system (see Figure 3-9). Two other locations on this same pipeline were also excavated and examined, but no corrosion pitting was observed. Follow-up communication with the city's engineering department revealed that this pipeline was abandoned and replaced with a new, 14-inch lined concrete cylinder pipe in 1987.

## SUMMARY OF BARE, AS-MANUFACTURED, AND POLYETHYLENE-ENCASED DUCTILE IRON PIPE CORROSION RATES

This section presents published corrosion rates for bare, as-manufactured DIP and DIP with PE and derived corrosion rates for Data Types 1, 2, 3, and 4 in corrosive soils. It should be noted that the data presented are for both "undamaged" PE and "damaged" PE. The term "undamaged" refers to conditions in which there is no observed physical damage to the PE directly over the location on the pipe if corrosion has occurred. As a result of the PE damage, water or aggressive ions may enter at the damage site and influence the corrosion rate at a point away from the damage location. This general definition has been used by DIPRA and others and is also used in this report. Since some suggest[86] that PE alone is ineffective because it cannot be constructed without damage, the committee chose to evaluate corrosion for DIP with both "undamaged" and "damaged" PE. Of specific note is that, for a more realistic comparison, data on both DIP and CIP were included.

Stroud from DIPRA stated, "The number of documented failures of polyethylene encased pipelines—the vast majority of which are the result of improper installation—is insignificant compared to the miles of Cast and Ductile Iron pipe that are afforded excellent protection with this method of corrosion prevention."[87]

[85] CH2M HILL, *California City Corrosion Control Study*; California City Engineering Department, communication with the committee, September 2008.

[86] Szeliga, "An Independent Evaluation of the Effectiveness of Polyethylene Encasement as a Corrosion Control Measure for Ductile Iron Pipe"; Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[87] Troy Stroud, "Polyethylene Encasement Versus Cathodic Protection: A View on Corrosion Protection," *Ductile Iron Pipe News* (Spring/Summer 1998).

FIGURE 3-9 In California City, California, major corrosion damage on ductile iron pipe with polyethylene encasement and cathodic protection with joint bond on opposite side of pipe. SOURCE: Courtesy of William Spickelmire, RUSTNOT Corrosion Control Services, Inc.

However, a concern of Reclamation[88] is that if corrosion occurs under undamaged PE and application of CP is deemed necessary, electrical shielding of the CP currents to those areas that are experiencing corrosion may reduce the CP current below what is required to mitigate the corrosion. It is also possible that, even in the absence of shielding, CP may malfunction.

Corrosion can occur at some distance from a break or flaw in the PE if oxygen is being replenished at a sufficient rate to continue the corrosion activity. This is similar to what has been observed on disbonded dielectric coatings. However, under anaerobic conditions, in the presence of sulfate reducing bacteria, MIC can occur under undamaged PE even when the pipe is under cathodic protection. MIC under disbonded pipeline coatings is a serious problem in the oil and gas industry and is not fully understood.[89] Pikas points out that while CP can be effective at

[88] Bureau of Reclamation Technical Service Center Staff, U.S. Department of the Interior, "Corrosion Considerations for Buried Ductile Iron Pipe," presentation to the committee, Washington, D.C., July 28, 2008.

[89] Joseph Pikas, "Case Histories of External Microbiologically Influenced Corrosion Underneath Disbonded Coatings," NACE International Corrosion 1996, Paper No. 198, Houston, Tex.

damaged coating locations, it becomes more limited when MIC activity occurs farther away from the damaged area, primarily due to the reduction of the current densities to those areas to provide adequate levels of CP effectively.

*Electrical shielding*, defined as any insulating barrier that will prevent or divert the CP current from the structure that it was intended to protect,[90] occurs if the disbonded coating or PE has sufficient dielectric strength to form a barrier that electrically restricts or isolates the pipe surface from the CP current. Although the CP current does not reach the pipe surface under the disbonded coating or PE, corrosion can still occur even when CP levels measure adequate at the ground surface.

The amount of current reaching the pipe surface from a coating defect under either a disbonded coating or loose bonded coating such as PE is a function of the distance from the defect and the longitudinal resistance of the layer of soil or water between the insulating barrier and the pipe through which the CP current must pass to the active corrosion location. The smaller this annular space (separation distance) between the pipe and the insulating barrier, the higher will be the longitudinal resistance by unit length of the electrolyte (soil or water). This is because the reduced cross-sectional area of the electrolyte that will carry the protective CP current is smaller, and therefore there is a higher resistance per unit length. The distance that the current is able to penetrate from a coating defect or damaged PE location is therefore a function of the current density, the electrolyte, and the longitudinal resistance. This means that the ability of the protective current to penetrate small, annular spaces is limited. From a practical standpoint, according to Peabody, the distance that one can project current into a small space is approximately about 3 to 10 times the thickness of the annular space between the insulating barrier and the pipeline surface.[91]

If the insulating barrier is not an effective electrical insulator (e.g., if water absorption allows it to become conductive and current to pass through it, or if there are a number of damaged locations), then enough CP current may flow to the corrosion location to provide partial or complete protection. This is the principle behind perforated rock shield or microperforated PE (described later).

## Pitting Rates

When looking at the pitting rate, it is of particular relevance to the committee's work that if the rate is above 5 mpy for a pipe with a 250-mil wall thickness, then

[90] A.W. Peabody, *Peabody's Control of Pipeline Corrosion, Second Edition*, Ronald Bianchetti, ed. (Houston, Tex.: NACE International, The Corrosion Society, 2001).

[91] Peabody, *Peabody's Control of Pipeline Corrosion, Second Edition*.

the desired 50-year pipeline design life would not be met.[92] As noted by Bell,[93] if a general corrosion limit of 50 percent of the wall thickness is the maximum allowed, then depending on the DIP wall thickness (250 to 870 mils), the maximum general corrosion rates to meet a 50-year life would be 2.5 to 8.7 mpy. He also points out that if the pitting corrosion limit of 100 percent of the wall thickness is the maximum allowed, then depending on the DIP wall thickness, the maximum pitting rate to meet the 50-year design life would be 5 to 16 mpy.

Table 3-10 summarizes these data sets. For the testbed samples in the DIPRA study,[94] mean maximum pitting rates for soils ≥10 points and uniquely severe conditions as defined by ANSI/AWWA Standard C105, Appendix A,[95] were included. However, for the other data sources no soil designation was reported. The DIPRA data used in conjunction with the Woolley report[96] allowed the distributions of maximum observed pitting rates to be determined for the five pipe conditions reported in Bonds et al.[97] For the other mean maximum pitting rates reported by DIPRA, the data distributions were not available to the committee, so the maximum observed pitting rates could not be determined. It should be noted, however, that the DIPRA study mean maximum pitting rate for the uniquely severe soils with undamaged PE was 6.8 mpy, which is 15 times the comparable mean maximum pitting rate of 0.453 mpy for soils ≥10 points as defined by ANSI/AWWA Standard C105, Appendix A.[98] Therefore, the maximum observed pitting rate of DIP with damaged PE should be much higher than the 8 mpy maximum observed pitting rate for undamaged PE in ≥10 corrosive soils. It should also be noted that the corrosion rate data are available as various data types—mean or average maximum (Data Types 4), maximum observed (Data Types 1 and 2), and minimum and maximum ranges (Data Types 1 and 2)—depending on the data source. In most cases, there were insufficient data provided to the committee to convert all of the mean maximum pitting rate data in the DIPRA study to the maximum observed pitting rate that is needed to compare various corrosion protection methods and to predict pipeline life. So although the data are not of the same types, the mean maximum pitting rates and the maximum observed pitting rates, where known, are included in Table 3-10 for reference purposes.

[92] Bureau of Reclamation Technical Service Center Staff, presentation to the committee, July 28, 2008.

[93] Bell, "Measurements of Performance of Corrosion Control Mechanisms on DIP."

[94] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research."

[95] American Water Works Association, ANSI/AWWA Standard C105 (2005), "Polyethylene Encasement for Ductile-Iron Pipe Systems," Denver, Colo.

[96] Woolley, letter and attached "Corrosion Database Statistical Analysis."

[97] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research."

[98] Bonds et al., "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research."

TABLE 3-10 Corrosion Rate Summary

| Row | Pipe Conditions | DIPRA Study Data with Mean Maximum Pitting Rate[a] (Data Type 4) | DIPRA Study and Woolley Analysis Report to DIPRA[b] (Data Types 2 and 4) | Szeliga Data[c] (Data Types 1 and 2) | Case Studies (Partial List): From Summary Tables (Data Types 1 and 2) |
|---|---|---|---|---|---|
| 1a | Bare | Table 3-1, soils ≥10 points, 22 samples with mean of 15.1 mpy | Table 3-2 soils ≥10 points, 22 samples with estimated maximum observed pitting rate of 26 mpy | No data; assumed all pipes were as-manufactured (asphaltic shop-coated) | No data sought |
| 1b | | Table 3-1, soils uniquely severe, 173 samples with mean of 44.2 mpy | See Note 1 | | |
| 2a | As-manufactured (asphaltic shop-coated) | Table 3-1, soils ≥10 points, 103 samples with mean of 10.5 mpy | Table 3-2, soils ≥10 points, 103 samples with estimated maximum observed pitting rate of 34 mpy | Tables 3-1 and 3-2, varied soils, 45 pipe examples with maximum observed pitting rate of 22.5 mpy. Maximum observed pitting rates ranged from 3.182 mpy to 22.5 mpy for 45 pipe examples with measured pitting rates including 17 penetrations | No data sought |
| 2b | | Table 3-1, soils uniquely severe, 70 samples with mean of 28.7 mpy | See Note 1 | | |
| 2c | | Table 3-1, varied soils, 89 samples in five testbed sites with “combined mean” of 24.7 mpy for all five, all sites and the means for the individual sites ranging from 0 to 32 mpy depending on individual site | See Note 1 | | No data sought |
| 3 | Damaged PE | Table 3-3, varied soils, 69 samples in five testbed sites, with “combined mean” of 11.2 mpy for all five sites, with the means for the individual sites ranging from 0 to 20.6 mpy depending on individual site | See Note 1 | Tables 3-3 and 3-4, varied soils, 11 examples with maximum observed pitting rate of 68 mpy. Corrosion rates ranged from 3 to 68 mpy for 11 pipe examples with measured pitting rates including four penetrations | Table 3-4, varied soils, maximum observed pitting rate of 68 mpy for Szeliga site and 50 mpy for Cape May, N.J., location. Maximum observed pitting rates ranged from 13.6 to 68 mpy for four pipelines |

| | | | | | |
|---|---|---|---|---|---|
| 4a | Undamaged PE | Table 3-5, soils ≥10 points, 151 samples with mean of 0.453 mpy | Table 3-5, soils ≥10 points, for the 14 samples that showed corrosion. Mean maximum pitting rate of 4.9 mpy[d] per Woolley analysis; Table 3-6, soils ≥10 points, 151 samples with calculated maximum observed pitting rate of 8 mpy | No data; assumed all pipe examples had damaged PE, as there was no designation in original Szeliga article summary chart for undamaged PE | Table 3-7, varied soils, maximum observed pitting rate of 52.5 mpy. Maximum observed pitting rates ranged from 4.6 to 52.5 mpy for 14 examples with measured rates |
| 4b | | Table 3-5, soils uniquely severe, 85 samples with mean of 6.8 mpy | See Note 1 | | |
| 5 | PE with CP | No data | No data | No data | Table 3-9, varied soils, maximum observed pitting rate of 86.6 mpy. Maximum observed pitting rates ranged from 3 to 86.6 mpy for six different DIP with PE and CP pipelines with measurable corrosion; pitting based on known 369 miles with 353 in soils below 2,000 ohm-cm (Table 3-8) of DIP with PE and CP. Four of the pipelines experienced leaks (with one sewer pipeline in Utah having six penetrations). The one pipeline in California was abandoned and replaced in 1987 after only 12 years of service |

NOTE: Table numbers refer to tables in this chapter of the present report. DIPRA, Ductile Iron Pipe Research Association; PE, polyethylene encasement; CP cathodic protection; DIP, ductile iron pipe; mpy, mils per year.

NOTE 1: Insufficient data provided to convert uniquely severe soil mean rates or individual test site mean rate data to maximum observed pitting rates.

[a]Richard Bonds, L.M. Barnard, A.M. Horton, and G.L. Oliver, "Corrosion and Corrosion Control of Iron Pipe: 75 Years of Research," *AWWA Journal*, 97(6):88-98 (2005).

[b]Thomas Woolley, letter and attached "Corrosion Database Statistical Analysis" data presentation, April 7, 2008.

[c]Michael Szeliga, "Analysis of Ductile Iron Corrosion Data from Operating Mains and Its Significance," ASCE Pipelines, Advances and Experiences with Trenchless Pipeline Projects Conference, Boston, Mass., 2007.

[d]U.S. Bureau of Reclamation, Materials Engineering and Research Laboratory, Technical Memorandum No. MERL-08-15, "Fountain Valley Project 2007, Security Lateral 16-inch Ductile Iron Pipe Failures," U.S. Department of the Interior, Denver, Colo. (2007).

### Data Evaluation for Ductile Iron Pipe with Polyethylene Encasement and Cathodic Protection in Soil ≥10 Points

The maximum observed pitting rates for bare, as-manufactured, and damaged DIP with PE in corrosive soils was observed to range from 13.6 to 68.0 mpy, depending on the study. The maximum observed pitting rates for undamaged PE ranged from 4.0 to 52.5 mpy, depending on the study. These results indicate that, for whatever underlying reason (e.g., PE damage, damage to the asphaltic coating, MIC, and so on), DIP with PE installed in corrosive soils can be found to exhibit the maximum pitting rates characteristic of bare and as-manufactured DIP and DIP with damaged PE. The maximum observed pitting rates for DIP with PE and CP ranged from 3.0 to 86.6 mpy for the seven studies represented in Tables 3-1 through 3-10. These results indicate that, for whatever underlying reason (e.g., shielding, joint bonds, insufficient CP current, PE damage, damage to the asphaltic coating, MIC, and so on), DIP with PE and CP in pipeline installations can be found to exhibit the maximum observed pitting rates characteristic of bare and as-manufactured DIP and DIP with damaged PE.

These data indicate that DIP with PE and CP will not meet the target 50-year pipeline lifetime when installed in highly corrosive soils. For a nominal pipeline thickness of 250 mils, pipeline leaks can be expected in the worst case as soon as 3 years after installation. It should be remembered that lifetime is based on the behavior of the tail of the corrosion rate distribution, not on average values. There will be many pipe segments in a pipeline that will meet the target 50-year lifetime, but those in the tail of the distribution will not. The large number of high maximum observed pitting rates seen for this small number of total miles is indicative of the rates seen in the tail of the distribution and can be used to make risk management decisions.

# 4

# Failure Criteria

## OBJECTIVE AND APPROACH

One objective of this committee is to determine whether ductile iron pipe (DIP) with polyethylene encasement (PE) and cathodic protection (CP) can reliably provide a 50-year service life when used in underground buried water projects. As already noted, the Bureau of Reclamation initially requested a failure rate of zero in this regard. Clearly this desire was an indication that Reclamation is very concerned with pipeline failures and with the potential costs associated with pipeline failure and having pipelines out of service.

This committee asked Reclamation to provide a quantitative benchmark against which it could measure the performance of DIP with PE and CP installed in severely corrosive soils. The committee also asked whether failure rates of other systems would be acceptable benchmarks. The objective of these questions was simply to obtain from Reclamation a threshold value other than zero so that a comparative analysis could be performed by the committee.

In responding to the committee, Reclamation noted that an average annual failure rate of 0.000044 failures per mile per year was computed from gas pipeline performance data from the Department of Transportation's (DOT's) Office of Pipeline Safety (OPS). Reclamation also noted that this database did not provide information on soil conditions and that "some adjustment to the computed failure rate may be warranted to compensate for this uncertainty in soil conditions."[1] The bureau provided no specific guidance on how to adjust the data, but it did state that, regarding an average annual failure rate of 0.000044 failures per mile per year, "we believe this analysis supports Reclamation's original response to the Committee's question of what we define as reliably providing a minimum service life of 50 years for our pipelines."[2] This statement indicates that the threshold value that Reclamation provided (0.000044) is within its risk-tolerance range.

The committee believes that a threshold value must be defined by Reclamation, and whether this information is based on pipe failures of other pipe systems or on an economic risk-based procedure, some value is necessary to allow a comparative analysis to be performed. Without discussing whether the analysis for determining the threshold value used by Reclamation is appropriate, but realizing that Reclamation accepts the 0.000044 value as within its risk tolerance, the committee first uses the threshold value of 0.000044 failures per mile per year as suggested by Reclamation. This value is identified as Threshold 1. This threshold value can change based on other assumptions, so the committee examined two additional possible threshold values derived from the gas pipeline data set for comparison with the performance of DIP with PE and CP in soils with soil resistivity values less than 2,000 ohm-cm. The two additional gas pipeline-based thresholds are listed below with Threshold 1:

- *Threshold 1:* Gas pipeline failure data from 2002 to 2008.
- *Threshold 2:* Gas pipeline failure data from 2002 to 2008 (data for Threshold 1) that include four additional leaks associated with external corrosion of welds, elimination of leaks for pipeline in service for more than 50 years, and the use of all mileage for bonded dielectric steel gas pipeline.
- *Threshold 3:* Gas pipeline failure data from 1974 to 1983, a time period during which regular inspections were not required by law.

The threshold provided by Reclamation of 0.000044 (Threshold 1) articulates the bureau's risk tolerance. The two additional threshold values derived from gas pipeline data are necessarily estimates, owing to the lack of information on the corrosivity of the soils where the failures occurred; they may not be representative of Reclamation's risk tolerance. However, the committee believed that it was necessary to develop additional threshold values to identify the potential variation

[1] Michael Gabaldon, Bureau of Reclamation, letter to Emily Ann Meyer, National Research Council, re: National Academies Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe—A Response to the Committee's Request for Clarification on Project Scope, August 21, 2008.

[2] Gabaldon, letter to Meyer, August 21, 2008.

TABLE 4-1 Gas Pipeline Failure Data from the U.S. Department of Transportation, Office of Pipeline Safety

| Event No. | Year Installed | Nominal Pipe Size (in.) | Pipe Wall Thickness (in.) | Years to Incident |
|---|---|---|---|---|
| 1 | 1990 | 48 | 0.42 | 17 |
| 2 | 1978 | 20 | 0.25 | 29 |
| 3 | 1975 | 6.62 | 0.19 | 30 |
| 4 | 1975 | 30 | 0.31 | 30 |
| 5 | 1971 | 20 | 0.26 | 31 |
| 6 | 1967 | 4 | 0.19 | 35 |
| 7 | 1968 | 36 | 0.38 | 37 |
| 8 | 1967 | 36 | 0.33 | 39 |
| 9 | 1967 | 12.75 | 0.25 | 40 |
| 10 | 1966 | 36 | 0.33 | 41 |
| 11 | 1965 | 36 | 0.34 | 42 |
| 12 | 1965 | 30 | 0.31 | 42 |
| 13 | 1964 | 16 | 0.22 | 42 |
| 14 | 1964 | 24 | 0.25 | 44 |
| 15 | 1960 | 6.63 | 0.19 | 44 |
| 16 | 1960 | 20 | 0.28 | 44 |
| 17 | 1960 | 24 | 0.28 | 44 |
| 18 | 1959 | 20 | 0.25 | 47 |
| 19 | 1956 | 26 | 0.28 | 47 |
| 20 | 1953 | 24 | 0.25 | 50 |
| 21 | 1957 | 26 | 0.25 | 50 |
| 22 | 1947 | 26 | 0.3 | 58 |
| 23 | 1947 | 26 | 0.29 | 58 |
| 24 | 1947 | 20 | 0.31 | 59 |
| 25 | 1944 | 8 | 0.19 | 60 |
| 26 | 1943 | 24 | 0.38 | 60 |
| 27 | 1928 | 18 | 0.28 | 74 |
| 28 | 1964 | 36 | 0.42 | 38 |
| 29 | 1961 | 16 | 0.22 | 42 |
| 30 | 1961 | 12 | 0.19 | 42 |
| 31 | 1962 | 30 | 0.31 | 45 |

SOURCE: U.S. Department of Transportation, Office of Pipeline Safety.

that might result from using different methods. Table 4-1 shows the failure data for the gas pipeline system.

Another approach to determining a rational threshold for comparison with DIP with PE and CP is to use the failure rates of pipelines for conditions as reported in Table 2 entitled, "Corrosion Prevention Criteria and Minimum Requirements," in the Bureau of Reclamation's Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe."[3] If the failure rates for

[3] Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipes," Washington, D.C., July 2004.

pipelines in soils with resistivity values between 2,000 and 3,000 ohm-cm and for pipelines in soils with resistivity values greater than 3,000 ohm-cm could be determined, this same threshold value could be used for pipelines embedded in soils with resistivity values less than 2,000 ohm-cm. The use of the specific pipeline system in these specific soil conditions is an implicit statement of a threshold for pipeline system performance for such soils.

It should be noted that the corrosion protection required by Reclamation is modified according to the soil conditions. However, there is no comprehensive database on the performance and failure rates for the different types of pipelines when embedded in soils with resistivity values less than 2,000 ohm-cm, so no quantitative threshold for such data could be obtained. If this information were available, it could constitute a fourth threshold value.

## VARIATIONS OF GAS PIPELINE THRESHOLD VALUES

Threshold values are necessary to establish the probability of pipeline failure. Although Reclamation provided a benchmark, or threshold value, in response to the committee request, it noted that "some adjustment to the computed failure rate may be warranted to compensate for this uncertainty in soil conditions."[4] In addition, changes may be needed so as to include only the failures that occurred prior to 50 years of service life and to include pipelines that had no failures. The following subsections provide a brief review of how Thresholds 1 through 3 were determined.

### Threshold 1: Reclamation's Reported Threshold Value

The threshold value reported by the Bureau of Reclamation was given in terms of failures per mile per year based on data shown in Table 4-1. As explained by the bureau, this threshold value was based on the number of failures (27) resulting from external corrosion on the body of the pipe, observed from 2002 through mid-2008, and did not consider the age of the pipe. Also, the length of the gas pipeline used in the calculation included only the lengths of the pipeline systems that exhibited failures (93,523 miles).[5] The reporting period was 6.5 years (2002 to mid-2008). The calculation and threshold value provided by Reclamation were as follows:

[4] Gabaldon, letter to Meyer, August 21, 2008.
[5] Gabaldon, letter to Meyer, August 21, 2008.

$$\begin{aligned}\text{Threshold } 1 &= \frac{\text{number of failures}}{(\text{reporting period})\times(\text{pipe mileage})}\\ &= \frac{27 \text{ failures}}{(6.5 \text{ years})\times(93{,}523 \text{ miles})}\\ &= 0.00044 \text{ failures/mile per year}\end{aligned} \qquad \text{(Eq. 4-1)}$$

### Threshold 2: Threshold 1 Adjusted for Pipe Age and Length

Several potential challenges arise from the values used by Reclamation for determining the Threshold 1 value:

1. The number of failures did not include failures identified on the welds (four additional failures were identified);
2. The number of failures used in the calculation included failures that occurred after or at 50 years (27 failures were reported, but only 19 occurred before 50 years); and
3. Pipelines that did not exhibit failures were not included in the pipe mileage (an additional 206,877 miles were identified with no reported failures).

Modifying the number of failures (4 + 19) and the total length of pipeline in service (300,400 miles) results in the following threshold value:

$$\begin{aligned}\text{Threshold } 2 &= \frac{23 \text{ failures}}{(6.5 \text{ years})\times(300{,}400 \text{ miles})}\\ &= 0.000012 \text{ failures/mile per year}\end{aligned} \qquad \text{(Eq. 4-2)}$$

It should be noted that the total mileage listed is only an estimate, which could vary depending on the amount of pipe in service at a specific time and on the amount of pipe that has been installed for fewer than 50 years. However, this information was not readily available to the committee, and because the objective is to assess the potential variability in the threshold value, the committee believes that this is a reasonable estimate. In addition, Reclamation noted:

> The DOT database does not include information on the soil conditions in which the pipelines are installed, so we are unable to further screen the data to include only pipe installed in severely corrosive soils. We are not able to quantify the impact this issue has on the calculated performance data noted above, but some adjustment to the computed

failure rate may be warranted to compensate for this uncertainty in soil conditions across the data set.[6]

Applying factors to Equation 4-2 could change the threshold but, after significant searching, the committee was unable to determine these factors.

### Threshold 3: Based on Early Gas Pipeline Failure Rates

Current regulations[7] require that oil and gas steel pipelines be stringently inspected. This strategy has been found to be very effective at locating potential corrosion problems before failures occur. Advanced technology coupled with rigorous internal and aboveground inspections has resulted in significant reductions in failure rates of steel pipelines used for gas or hazardous liquids in the past few decades. Because water lines are not inspected at the same level or with the same frequency as pipelines carrying gas or other hazardous liquids, the threshold provided by Reclamation (Threshold 1) could be considered to be low. To assess this, the committee reviewed results from the Eiber study, an evaluation of DOT data collected between 1972 and 1984, inclusive.[8]

At the time (1972 to 1984) of Eiber's study, the reporting requirements included any leak that required immediate repair or any incident that required removal from service of any segment of transmission pipeline. Furthermore, while inspection was required at that time, the requirements were minimal, had recently been imposed, and used technologies that were much less effective than those currently available. Thus, the inspections did not have a significant influence on the failure rate. The pipeline inventory included pipe buried in the 1930s through the 1970s; thus most ages of pipe relevant to this study were available (up to 54 years of service life). These pipes consisted of bonded dielectric coatings with CP, but many may not have been cathodically protected for their entire life. Some of the steel gas pipelines, depending on company policy, may not have been adequately cathodically protected for the first 30 or 40 years of their life, until this was required by DOT regulations.

The Eiber study eliminated duplicate and clearly invalid reports and reported nearly 400 service failures caused by external corrosion out of 5,872 incidents. The failure rate for these failures is plotted versus the age of the pipe in Figure 4-1. (The

[6] Gabaldon, letter to Meyer, August 21, 2008.

[7] Pipeline and Hazardous Materials Safety Administration, *Code of Federal Regulations*, Title 49, Part 192.

[8] D.J. Jones, G.S. Kramer, D.N. Gideon, and R.J. Eiber, American Gas Association, "An Analysis of Reportable Incidents for Natural Gas Transportation and Gathering Lines 1970 Through June 1984," NG-18 Report No. 158 (Washington, D.C.: Pipeline Research Committee of the American Gas Association, 1986).

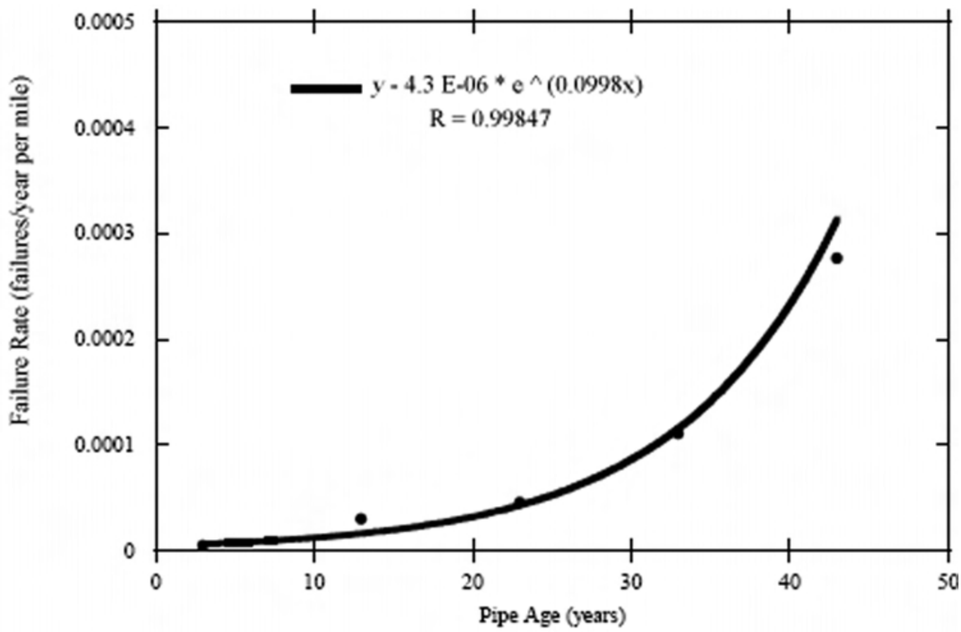


FIGURE 4-1 Pipe age versus failure rate for older steel pipe with bonded dielectric coating and cathodic protection.

age of the pipe was deduced from the decade of installation, so there are only 5 points—one per decade—with each point representing about 80 failures.) The figure shows that, as expected, the failure rate from external corrosion (a time-dependent degradation) increases as the pipes age. Furthermore, this increase is well predicted, with an exponential increase with time. Note that the rate is rapidly increasing as 50 years is approached. This is one reason that coated steel with CP may not eliminate the need for additional mitigation methods to minimize loss of service.

The mileage-weighted average age of the 353 miles of DIP with PE and CP in corrosive soil (Table 4-2) was determined to be 22.5 years.[9] Using the best-fit curve shown in Figure 4-1, the equivalent-age failure rate for the older steel pipes with an average age of 22.5 years was determined to be 0.000041 failures per mile per

[9]This mileage-weighted average can be calculated using the following equation:

$$\text{mileage-weighted average age} = \frac{[\Sigma(m_i a_i)]}{[\Sigma m_i]'}$$, where $m_i$ is the mileage of pipe age $a^i$.

TABLE 4-2 Data from Table 3-8 in This Report on All Relevant Ductile Iron Pipe with Polyethylene Encasement and Cathodic Protection in Corrosive Soils

| Abbreviated Project Name | Total Project Age, $t_i$ (years) | Average Age (years) | Length, $l_i$ (miles) | $t_i \times l_i$ | Failures | Failure Rate (failures/mile/year) |
|---|---|---|---|---|---|---|
| WEB | 24 | 12 | 150 | 3,600 | 0 | 0 |
| Southwest | 25 | 20.5 | 75.8 | 1,895 | 1 | 0.000528 |
| Mid-Dakota | 12 | 9 | 49.6 | 595.2 | 0 | 0 |
| Montrose | 27 | 27 | 27 | 729 | 0 | 0 |
| Hanna | 20 | 20 | 7 | 140 | 0 | 0 |
| Santa Margarita | 23 | 23 | 7.5 | 172.5 | 0 | 0 |
| Vacaville | 24 | 24 | 3 | 72 | 0 | 0 |
| Akron | 7 | 7 | 0.25 | 1.75 | 1 | 0.571429 |
| Trinidad | 29 | 27.5 | 10 | 290 | 0 | 0 |
| California City | 25 | 16.5 | 1.5 | 37.5 | 1 | 0.026667 |
| Denver | 24 | 24 | 9 | 216 | 0 | 0 |
| Sheridan | 16 | 15 | 12 | 192 | 0 | 0 |
| TOTALS | | | 352.65 | 7,940.95 | | |

SOURCE: In Chapter 3 of this report, see Table 3-8, "Partial List of Cathodically Protected Polyethylene-Encased Ductile Iron Pipelines."

year. This threshold value is only slightly lower than that provided by Reclamation (Threshold 1).

*Probability Analysis for Threshold Value*

The thresholds estimated in the previous subsections can be used to calculate the probability of having no failures over a 50-year period. Also, the data can be used to estimate the probability of having one or more failures. Assuming that the annual probability of failure per mile remains constant over time[10] and that each year is statistically independent, the probability of having zero failures over a 50-year period for a given mile of pipe can be determined as follows:

$$P_{50\text{ years, 1 mile, 0 failures}} = (1 - \text{Benchmark Failure Threshold})^{50} \quad \text{(Eq. 4-3)}$$

Using the threshold values determined in the previous subsections and Equation 4-3, the probability of having no failures for a given mile of pipe over a 50-year period for each threshold value is shown in Table 4-3, and the trend in the probability with threshold is linear, as shown in Figure 4-2. The probability of

[10]The failure rate generally increases over time. However, the failure rate here is for pipe having an average age near 50 years. Therefore, calculating the probability of failure using this rate will be conservative (i.e., it should overpredict the number of failures in 50 years).

TABLE 4-3 Summary of Possible Failure Rates and Resultant Probabilities

| Threshold No. | Failure Rate (failures/mile per year) | Probability of No Failures in 50 Years | Probability of One or More Failures in 50 Years |
|---|---|---|---|
| 1 | 0.000044 | 99.78% | 0.22% |
| 2 | 0.000012 | 99.94% | 0.06% |
| 3 | 0.000041 | 99.80% | 0.20% |

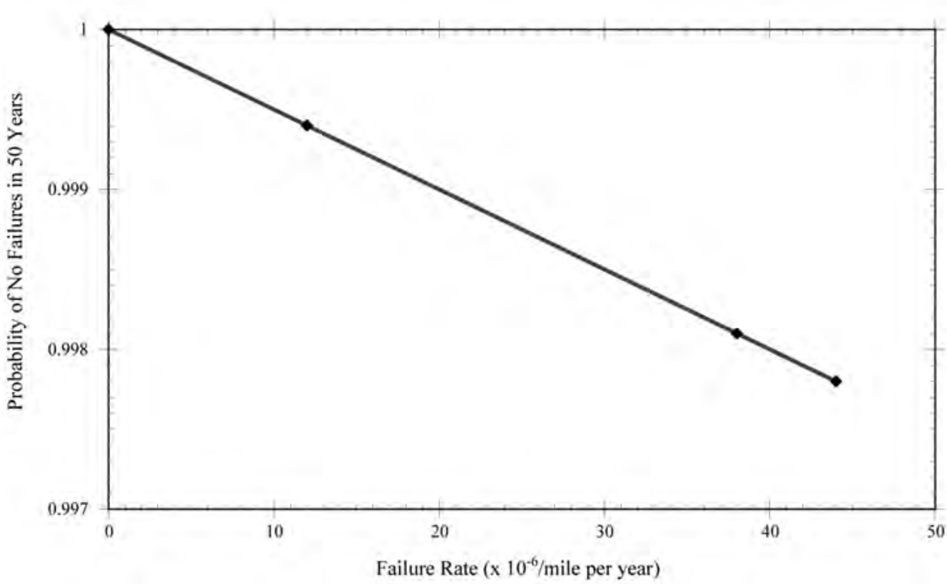


FIGURE 4-2 Trend of probability of no failures in 50 years, with failure rate.

having at least one failure on a given mile over a 50-year period is then 1 minus the probability of having no failures; these values are also shown in Table 4-3. They are used in this report as benchmark probability values for failures. If the estimated probability of failure of DIP with PE and CP is greater than the values shown in Table 4-3, it will be concluded that the DIP with PE and CP does not meet Reclamation's performance requirements. Alternatively, if the probability is lower than the values shown in Table 4-3, it will be concluded that the DIP with PE and CP meets Reclamation's performance requirements.

Although the committee evaluated alternative methods for assessing failure rates, it does not know whether these failure rates fall within Reclamation's risk tolerance. Reclamation did note that it believes that its analysis supports the original response to the committee's question of what it defines as reliably providing a minimum service life of 50 years for its pipelines, and this desired value was reported to be 0.000044 failures per mile per year. To put this number in perspective, using the 150 miles of South Dakota's Walworth, Edmunds, and Brown (WEB) Project as a hypothetical system, the failure rate would be 0.0066 failures across the system per year, or 0.33 failures in the system over Reclamation's desired 50-year service lifetime.

*Probability Analysis of DIP with PE and CP*

The committee deliberated extensively regarding the number of corrosion failures on the DOT gas steel and DIP pipelines and ultimately decided that the failure data for both types of pipelines should be treated in the same manner. The committee did not have any specific information (e.g., level of CP, date of CP installation, soil corrosivity, or disbonded coatings) about individual gas pipeline failures in the DOT data set that could be used to disqualify specific failures.

The committee thus applied the same standards to the failure of DIP pipelines with CP and PE. As has been noted, if the cathodic protection systems on the gas pipelines were working correctly, the number of failures should theoretically be near zero. However, because of other factors, there have been—and will continue to be—corrosion failures on dielectrically bonded steel pipelines with CP. Therefore, the committee elected to treat the DIP failure data in a manner consistent with the treatment of the DOT gas pipeline failure data.

A detailed review of case histories was performed earlier in the report that included an assessment of all known pipelines of DIP with PE and CP. Within this data set, pipeline failures of DIP with PE and CP were identified. It should be noted that there were not widespread failures of DIP with PE and CP. Table 3-8 in Chapter 3 documented that the total pipeline length buried in highly corrosive soils was approximately 353 miles. Table 3-9 indicated that a total of nine cases of failures on DIP with PE and CP from 1983 to 2006 occurred at four different locations. Of the nine failures reported, six occurred at the Vernal, Utah, site (Chapter 3, Table 3-9, Rows 3a, 3b, and 3c). This pipeline was a DIP sewer line and was protected with PE and CP. Because this was a sewer line and the possible effects of sewage leaks under the PE on the corrosion could not be determined, the committee could not reach agreement on whether to use these failures in the analysis, and they were therefore excluded.

There was a consensus among the committee members that the Southwest Pipeline leak (Table 3-9, Row 1) should be included as a valid failure location.

For the Akron, Ohio, location (Table 3-9, Row 2), there was some concern that the CP may not have been functioning correctly and that the side of the joint with the leak may not have been cathodically protected. There is an equal chance that the side of the pipe joint with the leak was connected to the same side as the anode(s) and therefore connected into the CP system. Alternatively, if the leak was located between the anodes, there is an equal chance that the joint was protected from both directions.

The type of joint bond used in Akron appears to be a solid- or rigid-type bond wire, as shown in the photos in the failure report (see Figure 3-8 in Chapter 3). This type of joint bond, once recommended by DIP manufacturers, has historically had problems (breaking or coming loose from pipe) if the pipe moves. It looks as though it broke in this instance, but the timing of the break is not known. Because the committee could not identify how or when the joint bond broke, it also could not ascertain what effect this break may have had on the level of CP at the leak location. To discount this location because of these reasons would be inconsistent with how the DOT pipeline data (which did not eliminate any breaks) was interpreted. Therefore, the majority of the committee members agreed that this location should be considered a failure.

For the California City site (Table 3-9, Row No. 4), some committee members argued that because the CP was not installed concurrent to the pipe installation (4 years difference), this failure location should be discounted. However, as noted by Graham Bell in his presentation to the committee,[11] it is normal to have some delay (up to several years) in installing CP on water pipelines. For the DOT gas pipelines with which these data are being compared, many of the DOT gas pipelines were not cathodically protected until the DOT regulations mandated the use of CP in the 1970s. Thus, it is likely that the DOT gas pipeline database includes some older pipelines (pre-1970) that did not have CP for 30 to 40 years, until the DOT regulations went into effect.

Based on this reasoning, the initial failure analysis will be performed assuming three failures (failures in Rows No. 1, 2, and 4 from Table 3-9). It should also be noted that the same approach was used by Reclamation to determine the failure rate for the DOT gas pipelines that is used for this initial analysis. As described below, the committee used an alternative analysis to verify the procedure.

Employing the methodology used by Reclamation, the number of failures (three), the reporting period (23 years), and the pipe length in corrosive soils (353 miles), the probability of having at least one failure on a given mile over a 50-year period can be determined using Equation 4-3. It should be noted that the three failures occurred at 6 years, 8 years, and 19 years, respectively—all significantly less than 50 years—and it is known from Table 3-8 that all 353 miles of DIP with PE and CP were embedded in highly corrosive soils. Using this information, the annual probability of failure for a given mile of DIP with PE and CP embedded in highly corrosive soils can be determined as follows:

[11] Graham E.C. Bell, Schiff Associates, "Measurements of Performance of Corrosion Control Mechanisms on DIP," presentation to the committee, Washington, D.C., July 29, 2008.

$$\text{Failure Rate}_{\text{DIP with PE and CP}} = \frac{3 \text{ failures}}{23 \text{ years} \times 353 \text{ miles}}$$
$$= 0.0003 \text{ failures/mile per year} \qquad \text{(Eq. 4-4)}$$

The probability of having zero failures in a 50-year period for a given mile of DIP with PE and CP embedded in highly corrosive soils can then be determined as follows:

$$P\,(0 \text{ failures})_{\text{DIP, PE, CP 50 years, 1 mile}}\,(\%) = 100 \times (1 - \text{Failure Rate})^{50}$$
$$= 100 \times (1 - 0.00037)^{50} = 98.2\% \qquad \text{(Eq. 4-5)}$$

The percent probability of having zero failures for DIP with PE and CP is less than all values shown in Table 4-3, indicating that DIP with PE and CP will likely not meet Reclamation's requirement. However, to assess this further, the committee considered an alternative approach.

An alternative approach to compare the performance of the DIP with PE and CP with the Reclamation benchmark is to estimate a weighted average of the failure rate of the DIP with PE and CP. Data from Table 3-9 are shown again in Table 4-2, with individual failure rates for each pipeline. Given the small mileage of DIP that is relevant to this analysis and the fact that only three failures were deemed valid, a determination of failure rate is difficult. The committee considered this problem for some time to arrive at the following alternative approach to estimate the failure rate. The failure rate for each pipeline project can be calculated based on the number of failures, $N$ (1 or 0 here), its length, $l$, and the time from its installation to the present date or date of removal from service, $t$:

$$\text{Failure Rate}'_{\text{DIP with PE and CP}} = \frac{N}{l \times t} \qquad \text{(Eq. 4-6)}$$

For example, for the Southwest Pipeline,

$$\text{Failure Rate}'_{\text{DIP with PE and CP}} = \frac{1}{75.8 \text{ miles} \times 25 \text{ years}}$$
$$= 0.000528 \text{ failures/mile per year} \qquad \text{(Eq. 4-7)}$$

For the Akron pipeline,

$$\text{Failure Rate}'_{\text{DIP with PE and CP}} = \frac{1}{0.25\ \text{miles} \times 7\ \text{years}}$$
$$= 0.571\ \text{failures/mile per year} \qquad \text{(Eq. 4-8)}$$

And for the California City pipeline,

$$\text{Failure Rate}'_{\text{DIP with PE and CP}} = \frac{1}{1.5\ \text{miles} \times 25\ \text{years}}$$
$$= 0.0266\ \text{failures/mile per year} \qquad \text{(Eq. 4-9)}$$

For the remaining mileage, RM, of pipeline,

$$\text{Failure Rate}'_{\text{DIP with PE and CP}} = \frac{0}{1 \times t} = 0\ \text{failures/mile per year} \qquad \text{(Eq. 4-10)}$$

The various failure rates can then be averaged using a weighting based on the length of each pipeline ($l_i$) multiplied by its years of service ($t_i$) divided by the sum of the products of the length of each project the age of that project and ($\Sigma(l_i \times t_i)$), to obtain an average failure rate:

$$\text{Failure Rate}'_{\text{DIP with PE and CP}} = \frac{l_i \times t_i}{\Sigma(l_i \times t_i)} \times \text{(Failure Rate)} \qquad \text{(Eq. 4-11)}$$

Using these data, Equation 4-11 was evaluated to obtain a length-time-weighted average failure rate for DIP with PE and CP in corrosive soils:

$$\text{Failure Rate}'_{\text{Average DIP with PE and CP}} = \frac{1{,}895}{7{,}941} \times \text{Failure Rate}_1 +$$
$$\frac{1.75}{7{,}931} \times \text{Failure Rate}_2 + \frac{37.5}{7{,}941} \times \text{Failure Rate}_3 + \frac{6{,}607}{7{,}941} \times \text{Failure Rate}_4 \qquad \text{(Eq. 4-12)}$$

$$\text{Failure Rate}'_{\text{Average DIP with PE and CP}} = 0.00126 + 0.000126 + 0.000126$$
$$= 0.000378\ \text{failures/mile per year} \qquad \text{(Eq. 4-13)}$$

This is also the failure rate that would have been obtained if all of the pipelines had been combined into one 353-mile pipeline and three failures had occurred during a period of 22.5 years (the length-weighted average age of all the pipelines). Comparing this average failure rate to the Reclamation benchmark threshold of 0.000044 failures/mile per year indicates (Threshold 1) that DIP with PE and CP has a significantly higher failure rate than that desired by Reclamation.

The average failure rate for DIP with PE and CP in corrosive soils is about the best estimate that the committee could deduce given the paucity of data. As noted in the earlier discussion, there were other failures of DIP, but they were not considered. Probability estimates were also made to determine if the three failures could be reasonably expected if DIP had the same behavior as the benchmark. In fact, the committee examined many facts that could not be well quantified.

*Comparison of DIP with PE and CP with Threshold Values*

Using the data in Table 4-3 for steel pipe with bonded dielectric coating and CP and the probability of having no failures over a 50-year period determined in Equation 4-5, the committee can provide a reasonable comparison of likely performance. For the DIP with PE and CP, the probability of having at least one failure on a given mile over a 50-year period is 1.8 percent (100 percent – 98.2 percent). Because 1.8 percent is much greater than all alternate values reported in Table 4-3, the probability of having at least one failure on a given mile of DIP with PE and CP is likely significantly higher than the benchmark threshold values reported in Table 4-3 for steel pipe with bonded dielectric coatings and CP. In addition, 1.8 percent is significantly higher than the 0.22 percent value determined from Reclamation's desired failure rate (Threshold 1). This suggests that DIP with PE and CP does not provide a reliable 50-year service life, as defined by Reclamation, when embedded in highly corrosive soils (less than 2,000 ohm-cm).

It should be noted that the assumptions used in this analysis are based on the data identified during the time of this study. Even though considerable effort was spent on identifying relevant data, there is limited information on pipe failures. DIP with PE and CP is relatively new, with the oldest such pipeline being 29 years old, with only 353 miles in corrosive soils, and three failures in water transmission pipelines. Although the committee used different approaches to evaluate the threshold failure rate provided by Reclamation, it realizes that the overall assessment is based on limited data.

To assess how small variations in the data used to assess the probability of having at least one failure on a given mile of DIP with PE and CP over a 50-year period affect the comparison with the benchmark values, a sensitivity analysis was performed. A *sensitivity analysis* is a tool used to determine how changes in the input variables (in this analysis, the number of failures, the reporting period, and the length of pipe in highly corrosive soil conditions) can influence the outcome of an analysis (in this case the probability of having one failure in 50 years).

To perform a sensitivity analysis, baseline values are used. The baseline values for this analysis were three failures, a 23-year reporting period, and 353 miles of DIP with PE and CP embedded in highly corrosive soil. Baseline values are varied as a percentage from the original value and plotted against the outcome, reported as a percentage of the original value—the original value in this case being 1.8 percent. Figure 4-3 shows the sensitivity analysis.[12] Note that if only two failures were valid, the *number of failures* would be reduced by 33 percent:

$$\left(\frac{3-2}{3}\times 100\right)$$

which would in turn reduce the probability of one failure by 33 percent to approximately 1.2 percent—if one failure were valid the probability of failure would be approximately 0.6 percent. Of significance is that both values (one and two failures) result in greater probabilities of failure than the threshold value of 0.22 percent defined by Reclamation.

The initial calculation used the maximum known length of DIP with PE and CP and 23 years as the reporting period. It can be seen that if the length of pipe embedded in highly corrosive soil is reduced or the reporting period is shortened (while keeping the other variables constant—for example, the three failures) the probability of failure increases at a significant rate, indicating that the probability of failure is sensitive to these variables. Reducing either of these two values makes it less likely that DIP with PE and CP will meet the required threshold limits shown in Table 4-2, and more specifically that set by Reclamation. Alternatively, increasing the length of pipe embedded in highly corrosive soil or increasing the reporting period decreases the probability of failure. However, it can be seen that the probability of failure is less influenced as the length of pipe and reporting period increase (i.e., the slope of the lines are lower). As already noted, the number of failures is a significant variable for both positive and negative changes and, as expected, is directly correlated to the probability of failure.

What is important to note is that the failure rate of the DIP with PE and CP would have to be decreased by almost 90 percent (to 0 failures) to meet the highest threshold value (Threshold 1) shown in Table 4-3. The threshold values from

[12] As an example of how to use Figure 4-3: assume that an additional 353 miles of DIP with PE and CP embedded in highly corrosive soils were identified and that this pipe exhibited no failures; this would increase the pipe length from 353 to 706 miles, a 100 percent increase in pipe length; from this 100 percent change in variable point on the abscissa, draw a line up to the curve that represents "length of pipe"; at this intersection draw a horizontal line to the ordinate, indicating that the original probability of failure of 0.018 will be reduced by 50 percent to 0.009.

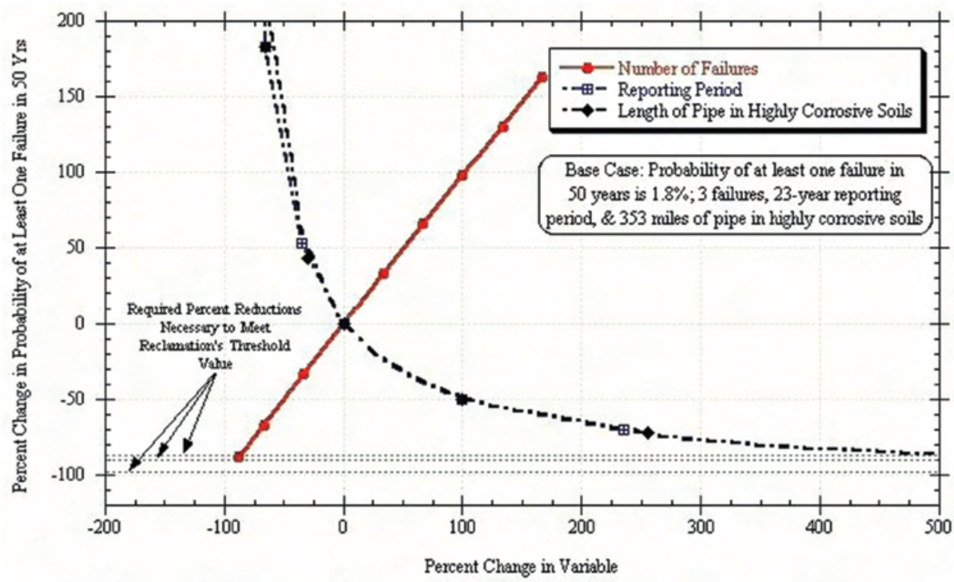


FIGURE 4-3 Sensitivity plot for probability of failure of ductile iron pipe with polyethylene encasement and cathodic protection.

Table 4-3 are shown in Figure 4-3 as the dashed horizontal lines. The length of pipe embedded in highly corrosive soil would have to increase by over 750 percent (to almost 3,000 miles) to meet the highest threshold value shown in Table 4-3 (Threshold 1) and almost 2,900 percent (11,000 miles) to meet the lowest threshold value shown in Table 4-3 (Threshold 2). The reporting period would have to range between approximately 200 and 700 years to meet the three threshold values shown in Table 4-3.

Based on the pipeline data described in Chapter 3, it is unlikely that any of the variables (number of failures, pipe length, or reporting period) would change sufficiently to make the probability of having one failure less than the threshold values shown in Table 4-3. Moreover, it is less likely that the data would change sufficiently for the probability of having one failure to be less than that originally required by Reclamation (Threshold 1). This indicates that the analysis is sufficiently robust and not sensitive to the assumptions made in this analysis. Or, stated otherwise, reasonable changes in the input variables (three failures, 353 miles of DIP with PE and CP, and a 23-year reporting period) will not reduce the probability of failure of DIP with PE and CP below the threshold values shown in Table 4-3, or, more importantly, below the threshold values desired by Reclamation.

*Comparison of Corrosion Rates*

To further examine the finding that DIP with PE and CP does not meet the Reclamation threshold, the committee considered the maximum observed linearized corrosion rates from Tables 3-2, 3-4, 3-7, and 3-9 in Chapter 3. Table 3-9 treats data for DIP protected with PE and CP. Most of the data available were for failed pipes, for which the corrosion rate was calculated by dividing the wall thickness by the years of service before failure. Table 3-9 includes data on the failed wastewater lines not used in the failure analysis earlier, but those data represent the lowest corrosion rates in the table.

When the maximum corrosion rate data available for bare and as-manufactured DIP (Table 3-2), DIP with damaged PE (Table 3-4), and DIP with undamaged PE (Table 3-7) are examined, it is found that in these categories as well as in the subject category of DIP with PE and CP above, the worst-case corrosion rate can well exceed the corrosion rate thought to be acceptable for reliable service. The committee recognizes that all of these data were selected as the *maximum* observed corrosion rates and therefore are not typical of the expected performance of most pipeline segments; they represent the tails of the failure distributions. All data in these tables suggest that there are conditions in which these pipes will corrode at undesirable rates and that these data reinforce the conclusion that it cannot be ensured that DIP with PE and CP will achieve the reliability expected by Reclamation.

## SUMMARY

The committee used various assumptions and methods to calculate different threshold values. These threshold values were then used to compare the performance of DIP with PE and CP and to determine whether DIP with PE and CP meet the various threshold requirements, but more specifically the threshold requirement provided by the Bureau of Reclamation. The probability analysis based on annual failure rates indicated that DIP with PE and CP does not meet any of the alternative threshold values as reported in Table 4-3 and that it is almost an order of magnitude higher than the threshold value requested by Reclamation. Two sensitivity analyses based on three valid failures supported the conclusion that DIP with PE and CP likely exhibits poorer performance than the threshold requirement provided by Reclamation. Comparison of maximum observed pitting rates for various DIP systems indicates that rates at the tail of the distribution can be similar for bare DIP pipe systems, as-manufactured DIP pipe systems, DIP with damaged PE, DIP with undamaged PE, and DIP with PE and CP. In summary, based on the information collected for this report, DIP with PE and CP will not "reliably" (quoting the committee's statement of work) provide a minimum service life of 50 years and will not meet the threshold requirement set by Reclamation.

# 5

# Evaluation of Other Corrosion Control Alternatives

Since it did not appear that ductile iron pipe (DIP) with polyethylene encasement (PE) and cathodic protection (CP) would meet the necessary reliability threshold values of the Bureau of Reclamation, the committee considered other corrosion control measures with the goal of determining whether they would do so. The results of this evaluation are summarized in this chapter.

## BONDED DIELECTRIC COATINGS ON STEEL PIPELINES WITH CATHODIC PROTECTION

Although the majority of dielectrically bonded steel pipes with CP are reported not to have a history of leaks, in a few instances corrosion resulted in leaks. This information is summarized below by the four source classifications (U.S. Department of Transportation [DOT], steel water pipe manufacturers, the Bureau of Reclamation, and others) and in Table 5-1.

### Department of Transportation

As explained earlier in this report, the committee used a large data set published by DOT's Office of Pipeline Safety (OPS), which categorizes all reported leaks for liquid and gas pipelines regulated under the Pipelines and Hazardous Materials

TABLE 5-1 Partial List of Bonded Dielectric Coatings on Steel Water Pipelines

| Project and/or Source | Date of Construction and Type of Coating | Pipe Diameter | Pipe Length | Route Corrosivity | Notes (Any Problems or Corrosion Activity Reported) |
|---|---|---|---|---|---|
| Bureau of Reclamation Technical Memorandum 8140-CC-2004-1[a] | 1960s to present | Varies | 320 miles | Varies | No external corrosion leaks reported through 2008. |
| Southwest Pipeline Project, N.Dak.; Bureau | 1983-1992 Tape | Varies; assume 24- to 36-inch | 43 miles | Severely corrosive below 2,000 ohm-cm | No external corrosion leaks reported through 2008. |
| Mid-Dakota Rural Water System, Miller, S.Dak.; Bureau | 1996 to 2002 | Varies; assume 24-to 30-inch | 25.4 miles | Severely corrosive | No external corrosion leaks reported through 2008. |
| Mni Wiconi, Pierre, S.Dak.; Bureau | 1993 to 2007 Polyurethane | Varies; 24- to 30-inch | 100 miles | Below 2,000 ohm-cm | No external corrosion leaks reported through 2008. |
| Lewis and Clark, Sioux Falls, South Dakota; Bureau | 2003 to present | Varies; 24- to 54-inch | 78.5 miles | Below 2,000 ohm-cm | No external corrosion leaks reported through 2008. |
| East Bay Municipal Utility District, Calif. | 1920s, Aqueduct No. 1 | 65-inch riveted steel | 90 miles | Varies | Leaks. Stopped after adequate cathodic protection (CP) levels were restored; no external corrosion leaks reported through 2008. |
| Cheyenne, Wyo. | 1964, Stage 1 Coal tar enamel | 26-inch | 40 miles | Portions less than 1,000 ohm-cm | In 1987, 23 leaks on Stage I pipeline. After joint bonding and CP improvements were made and adequate CP levels were restored in 1990, no external corrosion leaks were reported between 1990 and 2008. |
| Shoshone Pipeline, Cody, Wyo. | 1988-1990 Tape | 24- to 36-inch | 50 miles | Portions less than 1,000 ohm-cm | No external corrosion leaks reported through 2008. |

[a]Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, “Corrosion Considerations for Buried Metallic Water Pipe,” Washington, D.C., July 2004.

Safety Administration (PHMSA).[1] This data set provides a basis for determining a documented failure rate for steel pipelines with bonded dielectric coatings and CP.

Theoretically, with the incorporation of CP on buried metallic pipelines and its ability to mitigate corrosion to acceptable levels, the incidence of corrosion failure should be near zero. In fact, however, the OPS data present a history of external-corrosion-related failures (leaks) on steel pipelines with CP. Although CP is extremely effective in the mitigation of corrosion, it is not perfect. The external corrosion leaks reported by OPS can be categorized as being caused by one or more of the following:

- Disbonded coating,
- Interference or stray currents,
- Improper levels of CP at or near the leak area, and/or
- CP system failure.

To reduce the number of leaks, the regulations and PHMSA require liquid and gas pipeline operators to implement an Integrity Management Program (IMP), which incorporates a proactive system of evaluation protocols in an attempt to provide corrosion monitoring and assessment methodologies to further reduce the leak rates. At a minimum, for regulatory compliance the following are required:

- Bimonthly rectifier and critical bond monitoring and
- Annual surveys of the CP levels at test locations.

In addition, IMP includes expanded monitoring such as the following:

- Detailed, close-interval surveys,
- Direct assessment of the pipeline in suspect areas,
- Intelligent pigging of pipeline segments, and
- Direct current voltage gradient or alternating current voltage gradient.

PHMSA has shown that with the incorporation of IMP, many of the pipeline segments experiencing corrosion due to the causes listed above can be located and mitigated before a leak occurs. The overall number of reported leaks has significantly decreased since PHSMA implemented IMP as part of the regulations in 2002.

Typically, installation of CP on an existing steel pipeline will reduce the cumulative number of leaks as long as the CP system is designed, adjusted, and main-

[1] Pipeline and Hazardous Materials Safety Administration, *Code of Federal Regulations*, Title 49, Parts 192 and 195.

tained correctly. A classic example of the ability of CP to reduce corrosion leaks is shown for the East Bay Municipal Utility District for its Aqueduct No. 1. This line is a 90-mile, 65-inch (1,650-mm)-diameter riveted steel transmission pipeline installed near Oakland, California, in the early 1920s. Corrosion leaks occurred until the line was put under adequate CP, at which time all leaks stopped. A chart of cumulative leaks versus time for almost 70 years of service clearly shows the benefit of CP in extending the service life of this water transmission pipeline.[2]

In the paper containing the chart of leaks versus time, the author discusses the positive experience that Canadian cities have had with hot-spot protection of existing ductile iron and cast iron mains in reducing the number of leaks and presents corresponding cumulative leak charts versus time of CP installation. Similarly, a paper on "Protecting Ductile Iron Water Mains" describes a number of examples of the effectiveness of CP in minimizing corrosion leaks on corroding or new pipelines.[3]

Another example of how CP can reduce corrosion is demonstrated by the city of Cheyenne, Wyoming, which had a high-pressure 1964 steel water line in which some sections had inadequate CP levels. That pipeline experienced a high number of leaks (23 in the first half of 1987) due to a localized failure of the CP system caused by highly resistant or broken joint bonds. After the steel pipeline's electrical continuity was restored by conducting joint bond repairs, the existing CP system was upgraded in 1990, providing enhanced potential levels to the entire pipeline. This 650-psi water pipeline has not had a corrosion leak since then.

### Steel Water Pipeline Manufacturers

Based on information that the committee received from U.S. steel pipe manufacturers, more than 500 miles of bonded dielectric coated steel pipe are manufactured and installed each year for water transmission pipelines.

### Bureau of Reclamation

The Bureau of Reclamation reports that, since the 1960s, approximately 320 miles of bonded dielectric coated steel pipe on Reclamation projects have been designed and installed.[4] The bureau has stated that, to date, it is unaware of any cor-

[2] R.A. Gummow, "Corrosion Control of Iron and Steel Water Piping—A Historical Perspective," NACE International Northern Area Eastern Conference, Quebec City, Canada, August 26-27, 2007.

[3] B. Rajani and Y. Kleiner, "Protecting Ductile Iron Water Mains: What Protection Method Works Best for What Soil Condition," *Journal of the American Water Works Association* 95(11):110-125 (2003).

[4] Bureau of Reclamation, U.S. Department of the Interior, Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe," Washington, D.C., July 2004.

rosion failures for bonded dielectric coated steel pipeline with CP on Reclamation-designed projects. A partial list of bonded, dielectric coated steel pipeline projects is listed in Table 5-1.

## BONDED DIELECTRIC-COATED DUCTILE IRON PIPELINES WITH CATHODIC PROTECTION

Bonded dielectric coatings for use on DIP have been provided since the mid-1970s.[5] According to Horton, external coatings for DIP that historically have been used "include, but are not limited to: polyurethane, coal tar epoxy, coal tar enamel, tapewrap, extruded polyethylene, metallic zinc, zinc/epoxy/polyurethane, and fusion bonded epoxy."[6] Information provided by the Ductile Iron Pipe Research Association (DIPRA) for a 5-year period indicates that less than 1 percent of DIP produced has been provided with bonded, dielectric coatings.[7]

Most of the dielectric bonded coatings require some type of surface preparation of the DIP prior to application of the coating; this may include abrasive blasting and removal of the epidermal layer or simply cleaning the pipe and applying the coating directly to the epidermal layer, depending on the type of coating. Most bonded dielectric coatings applied in the United States have been added by third-party applicators, although one U.S. DIP manufacturer did apply them for a short period of time.[8] By contrast, international DIP manufacturers primarily apply the bonded dielectric coatings in-house.

Bonded dielectric coatings for DIP have not been used widely in the United States for the past 5 or 6 years. New bonded dielectric coated DIP installations have been curtailed because of the refusal by the U.S manufacturers of DIP to provide

[5] D. Lieu and M. Szeliga, "Protecting Underground Assets with State-of-the-Art Corrosion Control," *Materials Performance* 41(7):24 (2002); Shiwei Guan, "Corrosion Protection by Coatings for Water and Wastewater Pipelines," paper presented at Appalachian Underground Corrosion Short Course, Water and Wastewater Program, Morgantown, W.Va., 2001; Rajani and Kleiner, "Protecting Ductile Iron Water Mains"; J.R. Pimentel, "Bonded Thermoplastic Coating for Ductile Iron Pipe," *Materials Performance* 40(7):36 (2001); William Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective," *Materials Performance* 41(7):16 (2002); Sasan Hosein, "Ductile Iron Pipes—Inorganic Zinc Application Project Review," Corrpro Companies, Conyers, Ga.

[6] A.M. Horton, "Special Protective Coatings and Linings for Ductile Iron Pipe," pp. 745-756 in *Advances in Underground Pipeline Engineering II,* Bellevue, Wash.: American Society of Civil Engineers (1995).

[7] Information provided by DIPRA to NACE International TG 14 Committee on Corrosion and Corrosion Control for Buried Cast- and Ductile-Iron Pipe.

[8] *CorroNews: A Newsletter of Protective Coating Information from Madison Chemical*, Vol. 9 (Summer 1997).

pipe for the application of bonded dielectric coatings.[9] As described earlier in this report, the U.S.-based DIP manufacturers cite problems with surface preparation and coating application as the reasons for not providing bonded dielectric coatings when requested.[10]

Based on a literature search performed by the committee as well as on discussions with and correspondence from coating manufacturers, applicators, and European DIP manufacturers, it appears that most major coating manufacturers believe that they have developed standard surface preparation and coating application techniques and specifications for ductile iron or cast iron that allow successful bonded dielectric coating for DIP.[11] A number of U.S. applicators indicated that they also believe that they have successfully resolved the technical issues of surface preparation and applying bonded coatings to DIP.[12] One polyurethane manufacturer stated that as far as applying coating to DIP, "for a knowledgeable applicator it is really no more difficult than coating steel." As to the difficulty in coating of joints, the manufacturer stated that "the coating thickness needs to be decreased in close tolerance areas and there is a very simple method for doing so. This method was developed about 20 years ago and worked well throughout the period that DIP manufacturers were willing to use bonded coatings."[13]

As noted earlier in this report, a wider variety of bonded dielectric coatings are still used and being developed on the international DIP market. According to one

---

[9] Jose Villalobos, "Assessing DIPRA's New Corrosion Standards," *V&A Newsletter, Infrastructure Protection News* (June 2003).

[10] DIPRA, "Surface Preparation of Ductile Iron Pipe to Receive Special Coatings," *DIPRA Ductile Iron Pipe News* (Fall/Winter 1993); Gregg Horn, "Product Advisory: Tape Coat," *DIPRA Ductile Iron Pipe News* (Fall/Winter 1992); Troy Stroud and James Voget, "Corrosion Control Measures for Ductile Iron Pipe," 46th Annual Appalachian Underground Corrosion Short Course (Morgantown, W.Va.: West Virginia University, 2001).

[11] Polyken Pipe Coatings Technical Reports, *Technical Review of Bonded Tape Coatings on Ductile Iron Pipe* (Gardena, Calif.); Madison Chemical Industries, Inc., *Long Form Specification Polyurethane Coatings for the Internal Lining and External Coating of Ductile Iron Pipe and Fittings*, Specification No. SP-LF 1997-03, Milton, Ontario, Canada; Berry Plastics Corporation Corrosion Protection Group, *Polyken YGIII System for Ductile Iron Pipe Application Specifications*, Franklin, Mass.; Tek-Rap Inc., DI-4 Ductile Iron Coating System Specification, Houston, Tex.; Polyken Bonded Tape Coating Procedures for Small Diameter Bare Steel or Ductile Pipe (when plant applied application is not possible), Specification 2003, Chase Construction Products Tapecoat/Royston: Evanston, Ill.

[12] Don Barder, Liberty Coating Company, LLC, Morrisville, Pa., communication with the committee, 2008; Dick Brunst, Western Pipe Coaters and Engineers, Orem, Utah, communication with the committee, 2008; Delor Baumann, Baumann Coatings, Inc., Bessemer, Ala., communication with the committee, 2008; Ross Mitchell, Madison Chemical Industries, Inc., Milton, Ontario, Canada, communication with the committee, 2008; Jim Havey, Mobile Pipe Wrappers and Coatings, Inc., Adelanto, Calif., communication with the committee, 2008.

[13] Mitchell, communication with the committee, September 2008.

coating manufacturer, more than 3,000 miles of the polyurethane-type coatings have been applied to DIP in the Asian market alone.[14]

For pipe-surface preparation in Europe, the standard as-cast external surface (with or without the zinc or zinc/aluminum) forms the basis for additional top coatings, with the exception of polyurethane, which requires an abrasive blast. Joints are normally coated with a thin (six-thousandths of an inch) epoxy coating. In more aggressive soils, the joints are protected by epoxy coatings, or by rubber boots, petrolatum tape, or heat shrink sleeves.[15]

DIP, fittings, accessories, and their joints for water or gas applications are covered in ISO 2531, under Paragraph 4.4,[16] "Coatings and Linings for Pipes," which states:

> Pipes shall normally be delivered internally and externally coated. External coatings depending on the external conditions and taking into account existing national standards, the following coatings may be supplied:
>
> - metallic zinc with finishing layer, in accordance with ISO 8179-1;
> - zinc rich paint with finishing layer, in accordance with ISO 8179-2;
> - thicker metallic zinc with finishing layer;
> - polyethylene sleeving, in accordance with ISO 8180;
> - polyurethane;
> - polyethylene;
> - fibre cement mortar;
> - adhesive tapes;
> - bituminous paint;
> - epoxy.
>
> When ISO standards do not exist, these coatings shall comply with national standards, or with an agreed technical specification.

Within Europe there is a general consensus with respect to pipe protection, which is described in British Standard (BS) EN 545,[17] the specification for DIP, which states that specific coatings may be used in soil conditions with different ratings. External coatings and standards in the United Kingdom are reported to include extruded polyethylene (BS EN 14628),[18] polyurethane (BS EN 15189),[19]

[14] Shiwei Guan, Brederow Shaw, communication and correspondence with the committee, September 24, 2008.

[15] Trevor Padley, Saint Gobain Pipelines plc, Derbyshire, England, communication with the committee, 2008.

[16] International Organization for Standardization, "Ductile Iron Pipes, Fittings, Accessories and Their Joints for Water or Gas Applications" (2004).

[17] British Standards Institute, BS EN 545, "Ductile Iron Pipes, Fittings, Accessories and Their Joints for Water Pipelines. Requirements and Test Methods" (2006).

[18] British Standards Institute, BS EN 14628, "Ductile Iron Pipes, Fittings and Accessories. External Polyethylene Coating for Pipes. Requirements and Test Methods" (2005).

[19] British Standards Institute, BS EN 15189 "Ductile Iron Pipes, Fittings and Accessories. External Polyurethane Coating for Pipes. Requirements and Test Methods" (2006).

and fiber cement coating (BS EN 15542)[20] or adhesive tapes. Pipes with these more robust types of external coatings (extruded polyethylene, polyurethane, fiber cement or adhesive tapes) are allowed to be buried in soils of all levels of corrosivity according to the BS EN 545 standards.

According to a DIP manufacturer in England, the standard approach is to coat DIP with a zinc or zinc/aluminum plus epoxy or bitumen top coats.[21] In more aggressive soils, options include (1) the zinc coating with an epoxy or bitumen-type finish coat augmented with PE or tape or (2) the zinc/aluminum coating with an epoxy top coat. PE is only used for larger-diameter DIP (>800 diameter nominal). The zinc/aluminum epoxy option is now being recommended more and more by the pipe manufacturers for these types of applications, except for larger-diameter pipe. For highly aggressive soils, pipes are protected with thick, adherent barrier coatings, such as extruded polyethylene, polyurethane, or fiber cement, mortar. Another approximately 3 to 5 percent of the DIP produced annually is coated with either extruded polyethylene or polyurethane-type bonded dielectric coatings.[22]

Fiber cement mortar is reported to be used mainly in Germany where the soil is extremely rocky or for directional drill and direct-pipe-insertion-type installations. The other countries in Europe have reportedly used bonded dielectric polymeric-barrier-type coatings since the 1980s.[23] Zinc coatings have been used in France since the early 1950s.

Although the majority of North American DIP is covered with PE, there are examples of bonded, dielectric coated ductile iron pipelines with CP. The committee collected information on more than 225 bonded dielectric coated DIP projects from tape and coating manufacturers, applicators, owners, and corrosion and engineering firms, and obtained information on DIP lines with different types of coatings, some of which are exemplified in the subsections that follow.[24] The projects described are primarily projects for which contact information was known and the corrosion performance of the coated DIP with CP could be confirmed. Various North American projects are summarized in Table 5-2.

---

[20] British Standards Institute, BS EN 15542, "Ductile Iron Pipes, Fittings and Accessories. External Cement Mortar Coating for Pipes. Requirements and Test Methods" (2008).

[21] Padley, communication with the committee, 2008.

[22] Padley, communication with the committee, 2008.

[23] Padley, communication with the committee, 2008.

[24] Rod Jackson and Jerry Duppong, CH2M Hill, communication with the committee, 2008; Bob Hayes and Galloway, communication with the committee, 2008; Ross Mitchell, communication with the committee, 2008; Tek Rap, Inc., fax to customers on D.I. Cold Applied System List, November 1998; Corrpro fax to customers on List of Ductile Iron Pipe with Bonded Coatings, June 1998; Scott Smith, CANUSA, communication with the committee, September 2008; Richard Newell, Washington Suburban Sanitary Commission, communication with the committee, 2008; Jeff Mattson, Corrosion Control Technologies, communication with the committee, 2008; Les Nelson, Seattle Public Utilities, communication with the committee, 2008.

Reclamation's records indicate that it has been specifying dielectric bonded coatings for iron pipe since 1954.[25] The bureau has used dielectric bonded, tape-coated DIP on the Mni Wiconi Regional Water System Water Treatment Plant (Pierre, South Dakota) since the mid-1990s. Polyurethane coated, 6-inch fire hydrant DIP stubs were also provided until 2003-2004 when the U.S. DIP manufacturers' moratorium on the use of bonded dielectric coating was instituted.

A review of the data that the committee was able to gather indicates that even for a partial list there is actually more bonded dielectric coated DIP with CP in North America (877 miles) than there is DIP with PE and CP (369 miles). In 1999, there were no reported failures or leaks on 860.4 miles of coated DIP. Of the 860.4 miles of coated DIP, the committee confirmed that 525.9 miles had experienced no failures or leaks up to the writing of this report. For the remaining 334.5 miles, the committee was not able to obtain updated information. It should also be noted that the coated pipe in Canada was 33 years old, almost 10 years older than the previously referenced DIP with PE and CP projects in North and South Dakota. This partial list of projects with coated DIP does not include the bonded, dielectric coated pipe used internationally, which may amount to thousands of additional miles.

### Calgary, Alberta, Canada

The city of Calgary was facing an alarming increase in the number of corrosion leaks on its bare and polyethylene-encased iron pipelines in the 1970s.[26] The city started an aggressive campaign of pipe replacement and the use of a bonded dielectric coating on its DIP, working with a local coating applicator to develop a process to apply an extruded polyethylene coating (yellow jacket) on its DIP. In the early 1970s Calgary experimented with several different types of DIP external coatings, including taped urethane, yellow-jacket urethane, and yellow-jacket extruded polyethylene. In 1975, the city started to aggressively coat its DIP with extruded polyethylene. In a paper in 2001, it was reported that the largest portion of Calgary's DIP (373 miles [600 km]) was coated with yellow jacket. The city stated that its yellow-jacketed ductile iron (YDI) "is especially well protected against corrosion, both with coating and cathodic protection." The city went on to note that it still uses YDI where DIP is used and that it had no corrosion problems with its YDI pipe. The city verified in 2008 that it has had no corrosion leaks in its coated DIP and was beginning a program to replace the CP galvanic anodes on the YDI pipelines.[27]

---

[25] Technical Memorandum 8140-CC-2004-1, "Corrosion Considerations for Buried Metallic Water Pipe."

[26] Roy Brander, "Water Pipe Materials in Calgary, 1970-2000," *2001 Infrastructure Conference*, Orlando, Fla.

[27] Jim Buker, The City of Calgary Project, communication with the committee, 2008.

TABLE 5-2 Partial List of Bonded Dielectric Coated Ductile Iron Pipelines

| Project and/or Source | Date of Construction and Type of Coating | Pipe Diameter | Pipe Length | Route Corrosivity | Known Failures |
|---|---|---|---|---|---|
| Mni Wiconi, Pierre, S.Dak.; Bureau | Tape on water treatment plant piping and polyurethane coating on 6-inch fire hydrant stubs | Varies | Est. less than 1 mile | Less than 2,000 ohm-cm | No external corrosion leaks reported through 2008. |
| Calgary, Alberta, Canada | Begun in 1975; extruded polyethylene | Varies | 373 miles (600 km) | Very corrosive, typically previous leak locations | No external corrosion leaks reported through 2008. |
| Washington Suburban Sanitary Commission, Washington, D.C. | Begun in 1982; coal tar epoxy and tape; would like to use extruded polyurethane | Varies; 6- to 60-inch | 27 miles | Varies, very corrosive and/or stray current locations | No external corrosion leaks reported through 2008. |
| City of Philadelphia | Tape and extruded polyurethane | 8- to 12-inch | 18 miles | Unknown | No reported failures based on Corrpro fax in 1999.[a] |
| Philadelphia Suburban Water Company | Varies | 8- to 10-inch | 1.5 miles | Unknown | No reported failures based on Corrpro fax in 1999.[a] |
| Russell Corrosion, various locations | Late 1970s, small-diameter, and 1990s, larger-diameter; fusion bonded epoxy, liquid epoxy, tape, extruded polyethylene | 6- to 48-inch | Est. 30 miles | Varies; very corrosive | No external corrosion leaks reported through 2008. |
| Seattle, Wash. | Varies; tape and thermoplastic | Varies | 31 miles | Varies, very corrosive | No external corrosion leaks reported through 2008. |
| Price, Utah | 2003; tape with taped joints | 24-inch | 11 miles | Very corrosive | No external corrosion leaks reported through 2008. |
| San Diego, Calif. | 1995; polyurethane and coal tar epoxy[b] | Varies, 10- to 36-inch, some high-pressure (450 psi) sewage lines | 50 miles | Very corrosive | No external corrosion leaks reported through 2008. |

*continues*

TABLE 5-2 Continued

| Project and/or Source | Date of Construction and Type of Coating | Pipe Diameter | Pipe Length | Route Corrosivity | Known Failures |
|---|---|---|---|---|---|
| San Jose, Calif. | Varies;[c] tape | | 315 miles | Unknown | No external corrosion leaks reported through 1999. |
| Santa Rosa, Calif. | Unknown | 24-inch water reuse pipeline | 15.5 miles | 500 ohm-cm with high chlorides | Unknown |
| City of Renton, Wash. | 1994; tape coating, wax tape joints and galvanic anodes | 8- to 16-inch water transmission main | 0.4 mile | Stray current | No external corrosion leaks reported through 2008. |
| Puget Sound, Wash. Private manufacturing facility | 1994; 100% solid polyurethane and galvanic anodes | 14-inch water transmission main | 0.5 mile | <10,000 with pockets of lower-resistivity soils | No external corrosion leaks reported through 2008. |
| Puget Sound Municipality, Wash. | ca. 1983; coal tar epoxy and galvanic anodes | 18-inch underwater wastewater force mains | 0.23 mile | <1,000 (crossing under saltwater inlet) | Unknown |
| Puget Sound Municipality, Wash. | ca. 1983; coal tar epoxy and galvanic anodes | 8- to 12-inch wastewater force mains | Est. 1 mile plus | <1,000 (saltwater beach) | Unknown |
| City of Vancouver, B.C., Canada | ca. 1986; galvanic anodes | 10-inch to 12-inch water distribution mains | Unknown | <1,000 (wet/heavy clays) | Unknown |
| City of Aurora, Colo. | Estimated 15 to 20 years; tape coated | 16-inch water supply to military facility | 2 miles | Corrosive | No external corrosion leaks reported through 2008. |

[a]Corrpro fax on List of Ductile Iron Pipe with Bonded Coatings, June 1998.
[b]Approximately 46 miles polyurethane and 4 miles coal tar epoxy.
[c]Were doing approximately 15 miles a year in 1999.

### Washington Suburban Sanitary Commission, Washington, D.C.

In discussions with the committee, corrosion control experts within the Washington Suburban Sanitary Commission (WSSC) in Washington, D.C., indicated that the WSSC had historically used coal tar epoxy and tape coating systems. In its decision tree with respect to installing bare DIP, DIP with PE, or coated DIP for larger-diameter pipelines, the WSSC employs a risk assessment procedure that evaluates soil corrosivity, size of pipe, and presence of groundwater or interference. The WSSC claims that it was able to obtain holiday-free coating applications by doing two or more coats of the epoxy coating or by using the multilayer tape systems. The commission completed more than 50 projects from 1987 to 2002, at which time U.S. DIP manufacturers ceased applying bonded dielectric coating to its product. Since the corrosion control project managers at WSSC at present cannot obtain DIP with bonded dielectric coating, they have installed several thousand feet of bare DIP with CP; they do not use DIP with PE and CP for fear of electrical shielding.[28]

### San Diego, California

Based on its historical problems with pipelines with PE, the city of San Diego now requires bonded dielectric coatings (polyurethane) and CP on its DIP lines.[29] The city also reported good success with the use of petrolatum wax tape for wrapping valves and fittings since beginning its use in 1989.[30] San Diego reports that it has had good success with bonded dielectric coatings on pipelines and has done a number of bonded dielectric coatings on DIP with polyurethane and on one pipeline with coal tar epoxy. San Diego continues to coat DIP with fusion-bonded epoxy coatings and linings for pump stations and small piping.[31] San Diego's present corrosion consultant stated that the city's high-pressure (above 400 psi) polyurethane-coated ductile iron force main, which is both buried in highly corrosive soils and exposed above grade on a bridge, demonstrates that one can successfully coat and line DIP.[32]

### Price, Utah

An example of a tape-coated DIP project is the 11-mile, 24-inch pipeline for Price, Utah, that was completed in 2003. Adhesion pull tests were completed on the tape-coated DIP throughout the project and were well above the acceptable range. The pipeline joints were coated with a field-applied joint wrap tape that conformed

[28] Richard Newell and Mike Woodcock, Washington Suburban Sanitary Commission, communication with the committee, 2008.
[29] Martin Fogata, City of San Diego Water Department, communication with the committee, 2008.
[30] Fogata, communication with the committee, 2008.
[31] Ernesto Fernandez, City of San Diego Water Department, communication with the committee, 2008.
[32] Jose Villalobos, V&A Consulting Engineers, communication with the committee, 2008.

to the changing size of the ductile iron bell.[33] The tape applicator reported that the DIP tape coating project was very successful, with just a few problems with overblasting (slivers, scars, pockets, and so on), even with the DIP in the abrasive blaster for up to 5 minutes in order to obtain a near-white blast on the DIP. The tape applicator also added that there had been few problems with tape coating of the bells and that the adhesion values were very good on the entire project.[34] The corrosion engineer confirmed that they were pleased, that there was little problem with the coated DIP, and that a second phase with coated DIP had been planned, but the DIP manufacturers would not provide pipe to be coated so the second phase of the project used plastic pipe instead.[35]

### Cairo, Egypt

Another approach to applying a dielectric bonded coating to DIP is to tape coat the pipe without abrasive blasting of the DIP surfaces. On a large-diameter DIP pipeline installed in Cairo, Egypt, the U.S.-made DIP was primed with the standard asphaltic primer before being shipped. When it arrived in Egypt, the DIP was cleaned and refreshed with a tape primer that was compatible with the DIP plant-applied asphaltic primer to provide a 100 percent primed surface. The pipe was then inserted in a rack- or lathe-type system that spun the pipe, and the three-coat tape system was applied with tensioned tape spindles. The tape-coated DIP was holiday tested and installed with copper strap bonds, and the joints were provided with mastic filler and a hot-melt adhesive, heat-shrink sleeve. The technical representative of this tape-coating process stated that there had been minimal-to-no problems with the tape application and that there were good bonds to the pipe and bell. He also stated that joint coating with the mastic bar and the hot-melt adhesive, heat-shrink sleeve performed well, with no voids or problems observed at the joints.[36] The corrosion engineer and tape manufacturer also reported that the DIP tape-coating project went very well.[37]

### Seattle, Washington

Since the early 1980s, Seattle, Washington, has required bonded dielectric coatings on DIP in soils below 2,500 ohm-cm; in less-corrosive soils, DIP with PE is

[33] Berry Plastics, "Job Site Report Polyken Tape 24″ Ductile Iron Transmission–Main" (Norwood, Mass.: Tyco Adhesives).

[34] Dick Brunst, Western Pipe Coaters, communication with the committee, 2008.

[35] Jeff Mattson, Corrosion Control Technologies, communication with the committee, 2008.

[36] Don Hoff, John Hoff Co., Inc., communication with the committee, September 2008.

[37] Rod Jackson, CH2M Hill, communication with the committee, 2008; Tek-Rap Inc., Houston, Tex., previous communication and correspondence with committee member.

allowed. The city estimated that it has more tape-coated DIP (26.5 miles) than DIP with PE (14.9 miles).[38] Because of some problems with tape coatings on uneven appurtenances at valve bodies, tees, bends and joints, damage due to soil stresses, and the fact that the tape will degrade over time if exposed to sunlight, the city investigated and tried a thermoplastic coating[39] that had been used with positive results internationally.

In 1998, the city engineers visited the water utility in Gothenburg, Sweden, to evaluate that city's 15 years of experience with the thermoplastic-type coating and excavated and examined a section of DIP that had been buried for 12 years. Based on this evaluation and on the advantages of this type of coating with good adhesion, good impact and ultraviolet resistance, ease of repair, and the ability to coat the entire pipe and appurtenances including the bell-and-spigot-type joints, Seattle elected to try this coating on DIP. The city first conducted testing of the coating on four small projects (1,500 feet or less) to make sure that there were no unforeseen problems in the use of this type of coating in the United States. Based on the success of this trial project, the city added the thermoplastic-type coating to the types of coating options that it would consider, and used it on a 4.5-mile project in the late 1990s in the Port of Seattle area. The city reports that it experienced minor to little difficulty in surface preparation and application of the thermoplastic coating and was very satisfied with the installation of the coated DIP. Because of the advantages of thermoplastic coating—including but not limited to the ability to coat the entire bell-and-spigot assembly including the bell face, and the physical properties and characteristics of the coating—it was selected as the standard DIP coating system.[40] However, since Seattle can no longer obtain DIP on which to apply this type of dielectric coating and because of its concerns with electrical shielding with PE, it has installed approximately 40,000 feet of bare DIP with CP. The city is still investigating other types of coatings that may be applied over unblasted ductile iron.[41]

## OTHER CORROSION MITIGATION METHODS

The committee considered other corrosion mitigation methods that might have potential for providing the needed level of reliability for DIP (some of these are discussed in greater detail in Appendix D). The simple system of protecting bare DIP with CP alone has the advantage of likely providing a very high level of

[38] Les Nelson, Seattle Public Utilities, Seattle, Wash., communication with the committee, September 2008.
[39] Pimentel, "Bonded Thermoplastic Coating for Ductile Iron Pipe."
[40] Pimentel, "Bonded Thermoplastic Coating for Ductile Iron Pipe."
[41] Nelson, communication with the committee.

corrosion protection without the concerns of shielding, provided the CP system remains reliable. That method is frequently not practical because of the high level of CP current required, particularly in highly corrosive soils, and may be best suited for short lengths of pipe. It may be possible to improve on this method by using controlled low strength material (CLSM) bedding and backfill, although some concerns have been reported on its use in areas where the ground freezes.[42] The use of CLSM will likely reduce the currents needed, but this is a very untested method and cannot be endorsed by the committee as a reliable method. However, it is deserving of additional study and evaluation.

The use of perforated PE is one of the current research directions of which the committee is aware. In this case, the polyethylene is intentionally perforated on a grid that has the potential to minimize shielding of the CP currents. Like the PE currently being used, this method has the potential of being easy and inexpensive to install, but there is insufficient information available about the needed current levels and the degree of corrosion protection provided to endorse it at this time. In principle, PE or perforated PE could be used in conjunction with CLSM bedding and backfill for additional protection, but again, these methods are only in the conceptual stage. The committee believes that these methods are worthy of additional study.

Galvanized zinc coatings with various top coats have been used for DIP in Europe. There are ISO (International Organization for Standardization) standards for both metal coatings and high-zinc-content paint coatings, but the committee is not aware of how reliable these may be for the applications at hand. Based on their long-term use and acceptance in Europe, however, these coatings may show some promise that should be investigated further.

Finally, the committee considered the possibility of manufacturing DIP with excess wall thickness to extend the time to failure from external corrosion. The committee decided that this is not a viable solution because it would impose costs with no real assurance of protection—corrosion could still lead to local failure despite the higher wall thickness. Some of these options are discussed in more detail in Appendix D.

[42] K. Sepehr and L.E. Goodrich, "Frost Protection of Buried PVC Water Mains in Western Canada," *Canadian Geotechnical Journal* 31:491-501 (1994).

# 6

# Findings, Conclusions, and Recommendations

The Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe reviewed and discussed the information and data presented to it and sought out by the committee in order to come to the findings, conclusions, and recommendations presented in this chapter. The information and data referred to above were classified as Data Types 1 through 5 in terms of their relevance to predictions of the first failures to occur in a pipeline system. Specifically, the first failures are expected to be represented by corrosion behavior at the tails of the distribution, where the corrosion is fastest, and not by average behavior. Data Types 1 through 3 as defined in Chapter 3 were therefore used as the primary basis for the findings, conclusions, and recommendations presented here.

The charge of the committee included a responsibility to reply to two specific questions:

- *Question 1*—Does polyethylene encasement with cathodic protection work on ductile iron pipe installed in highly corrosive soils?
- *Question 2*—Will polyethylene encasement and cathodic protection reliably provide a minimum service life of 50 years?

The committee charge went on to pose another alternative responsibility depending on the answers to questions 1 and 2:

- *Alternative Responsibility*—If the committee answers either of the above questions in the negative, the committee will provide recommendations for alternative standards that would provide a service life of 50 years.

With respect to question 1, after its review of the question, including oral and written clarifications from the Bureau of Reclamation, **the committee finds that if manufactured and installed correctly, polyethylene encasement with cathodic protection provides *a betterment* to bare and as-manufactured ductile iron pipe without cathodic protection in highly corrosive soils.**

There is little controversy over the statement that polyethylene encasement (PE) alone will serve to provide an improved level of corrosion protection over bare or as-manufactured (asphaltic-coated) ductile iron pipe (DIP). Studies sponsored by the Ductile Iron Pipe Research Association (DIPRA) and cited in this report provide convincing evidence of this general result. These studies compared pitting rates in test sections of as-manufactured DIP buried in highly corrosive soils to rates for equivalent pipes with PE, also in highly corrosive soils. It should be noted, however, that the committee does not endorse some of the data evaluation methods used by DIPRA in these studies.[1]

That said, when comparing the reported mean maximum pitting rates of the 103 as-manufactured DIP samples to those of DIP with PE (Data Type 4), the DIPRA study results indicate that the mean maximum pitting rate of all 151 samples is decreased by a factor of about 23 (10.5 mils per year [mpy] compared to 0.5 mpy) compared to as-manufactured pipe without PE. According to histograms of this data set, the maximum observed pitting rates in the distributions dropped by a factor of approximately 4 (from 34 mpy to 8 mpy) by adding PE. The committee found this to be convincing evidence that intact PE alone may offer significant corrosion protection to bare DIP.

The committee believes that if cathodic protection (CP) is added to DIP with PE, evidence and experience from various sources lead to the conclusion that this may provide further improved levels of corrosion protection. While there is controversy as to whether CP can be relied on to protect DIP with PE at all distances from a defect or holiday in the PE, that does not detract from the finding that DIP with PE and CP may offer significant improvement in corrosion protection compared with bare and as-manufactured DIP (without PE or CP). In spite of the improvement obtained by the addition of PE and CP to DIP, the pipeline failures seen for DIP with PE and CP have occurred with maximum linearized pitting rates

[1] Particularly troubling to the committee were the use of the weighted average or mean maximum pitting depths without maximum and minimum pitting depths, or the distribution of pitting depths reported, the combination of pitting data from various sites with very different corrosion behavior, the lack of reported time-dependent pitting depths (when such results are available), and unrealistically short burial times before excavation (as short as 1 year) combined with total study times as short as 3 years, for example, for the study of DIP with intentionally damaged PE.

that are characteristic of bare or as-manufactured DIP in the same soils. From this information, the localized failures of the corrosion protection systems of PE and CP are inferred. However, for DIP with PE and CP, it is expected that the frequency of failure could be significantly lower than for bare and as-manufactured DIP without PE and for DIP with PE and no CP.

With respect to question 2 in the charge to the committee, after its review of the question, including oral and written clarifications from Reclamation, **the committee finds that the limited data available and the scientific understanding of corrosion mechanisms show that ductile iron pipe with polyethylene encasement and cathodic protection is not likely to provide a reliable 50-year service life in highly corrosive soils (<2,000 ohm-cm).**

In order to reach a finding with respect to question 2, the committee needed to know what threshold level of failures would be acceptable to Reclamation. In discussions with the committee, Reclamation expressed a desire to have no failures over the 50-year life of its systems because failures that interrupt service are very serious events. However, it is understood by Reclamation that it is never possible to engineer any system that will not have some probability of failure, and in answer to the committee's asking Reclamation to define a level of failure risk that the bureau would like to attain for its pipeline systems, Reclamation responded by using data from the U.S. Department of Transportation's (DOT's) Office of Pipeline Safety (OPS) on welded steel gas pipelines with bonded dielectric coatings and CP to calculate a failure rate for that system of gas pipelines. Regarding such pipelines, Reclamation stated the following: "We have concluded that the level of performance provided by steel pipe, installed in severely corrosive soils with cathodic protection and bonded dielectric coating, is a *reasonable benchmark* (emphasis added) against which to measure the performance of ductile iron pipe installed in severely corrosive soils with polyethylene encasement and cathodic protection."[2]

From the OPS data set, Reclamation calculated a failure rate of 0.000044 failures per mile per year. The most important aspect of this failure rate is that despite many shortcomings considered and discussed earlier in this report and mentioned below, it did set a threshold level of *risk tolerance* for Reclamation.

Perhaps one of the most obvious shortcomings of the calculated failure rate of 0.000044 failures per mile per year is that it does not consider the corrosivity of the soils. Reclamation noted this in its letter of August 21, 2008, with the statement: "However, the DOT database does not include information on the soil conditions in which the pipelines are installed, so we are unable to further screen the data to

[2]Michael Gabaldon, Bureau of Reclamation, letter to Emily Ann Meyer, National Research Council, re: National Academies Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe—A Response to the Committee's Request for Clarification on Project Scope, August 21, 2008.

include only pipe installed in severely corrosive soils. We are not able to quantify the impact this issue has on the calculated performance data noted above, but some adjustment to the computed failure rate may be warranted to compensate for this uncertainty in soil conditions across the data set."[3]

The committee also noted early in its study that these data do not account for soil corrosivity. DIPRA has criticized the Reclamation benchmark on these grounds as well.

The committee spent considerable effort in attempts to correct the calculated failure rates from the DOT OPS data for soil corrosivity. Searches for definitive data on the fraction of gas pipelines in highly corrosive soils (below 2,000 ohm-cm) were not successful. Attempts were made to estimate the fraction of soils that are highly corrosive and the fraction of failures that would have occurred in such highly corrosive soils where gas pipelines are located, but these attempts ended with the realization that these estimates were highly speculative and not well supported by any engineering data available to the committee. Therefore, the committee understands that the failure rate for pipelines buried in highly corrosive soils will likely be higher than the rate for the entire system, but it has no means of quantifying the degree of that likely increase.

In further analysis of the rate of 0.000044 failures per mile per year calculated by Reclamation, the committee believed that the number of failures counted should be decreased since failures for pipe over 50 years of age should not be considered. By contrast, DIPRA criticized the number of failures as being too low because four failures in welded pipe seams due to external corrosion were not counted. The committee then counted those four failures and removed the failures in pipelines equal to or more than 50 years of age in a revised calculation. The committee also revised the total mileage of pipeline to recognize the total length of pipe, both failed pipe and pipe that did not fail. With these corrections, the committee calculated an additional threshold of about 0.000012 failures per mile per year.

The pipeline data used for the Reclamation calculation included failures identified between 2002 and 2008. DIPRA objected to that window as one in which stringent pipeline monitoring was in place for DOT pipelines, and it contended that if pipelines were monitored less stringently (as is generally the case for water pipelines), a higher failure rate would have been seen. The committee agreed with this contention and studied the gas pipeline data taken for pipelines before the current stringent monitoring guidelines were imposed.[4] To establish an alternative threshold, a different calculation method was used, based on the failure data for external corrosion of gas pipelines before monitoring systems were imposed. The

[3] Gabaldon, letter to Meyer, August 21, 2008.

[4] Pipeline and Hazardous Materials Safety Administration, *Code of Federal Regulations*, Title 49, Part 192.

committee calculated a threshold failure rate of 0.000041 failures per mile per year for gas pipelines 22.5 years old, the age characteristic of current pipelines of DIP with PE and CP in water systems.

Both of the recalculated thresholds (0.000012 and 0.000041 failures per mile per year) are lower than Reclamation's benchmark (and presumed risk-tolerance level) of 0.000044 failures per mile per year.

The committee then sought to find failure data on DIP with PE and CP to compare to the benchmark. Only about 350 miles of such water pipeline that was buried in highly corrosive soils could be found. Much of these data are for Reclamation projects, and within that set one failure was known.

The committee also sought data from other pipeline users who were reported to use DIP with PE and CP. From these users, several other failures were reported. Some of these were for DIP with PE and CP used in a sewer application. The committee recognized that, while these corrosion failures probably should not have occurred in a well-protected system, the application was sufficiently different from those used by Reclamation systems that this sewer pipe and its failures were not used in the calculations.

Two other failures were reported to the committee in water-carrying DIP protected by PE and CP in highly corrosive soils. Both were on pipeline systems that were short compared to those of Reclamation but nevertheless were failures of water-carrying pipelines.

Using the three failures referred to above on 353 miles of total pipeline, the committee calculated a failure rate for DIP with PE and CP. This was done two ways, both yielding about the same failure rate. In one method, a 23-year window of time was used (similar to the use of a time window for the OPS calculations), representing the reporting time for failures. This yielded a failure rate of 0.00037 failures per mile per year (see Eq. 4-4 in Chapter 4). The other method used a weighted average (weighted by the product of the time that the pipeline had been in service times the length of the pipeline) of the individual failures. This method is mathematically the same as considering the 353 miles of pipeline to have a weighted average age of 22.5 years. This method yielded a nearly identical failure rate of 0.00038 failures per mile per year (see Eq. 4-13).

The committee found these failure rates, when compared to the Reclamation benchmark of 0.000044 failures per mile per year, to be sufficiently large (and even larger than the recalculated benchmarks from the committee) that it was concluded that DIP with PE and CP was not likely to meet the expectations of Reclamation for 50-year reliability or the risk-tolerance threshold set by Reclamation. This is particularly true considering that none of the pipelines studied were yet approaching the expected 50-year service life, and the number of failures is expected to rise further with age. Conducting two different sensitivity analyses based on three valid failures led to the same conclusion: DIP with PE and CP is not likely to meet the threshold set by Reclamation.

The committee also reviewed pitting data on DIP with PE (without CP) in highly corrosive soils, as those data could be viewed as the conditions experienced by a pipe at a distance from a damaged area (holiday) in the PE where the pipe is shielded from the protective CP current. There was no consensus in the committee on how to interpret such data, since the data are presented as linear pitting rates. Some committee members would argue that linearized pitting rates are a commonly used metric for anticipating failure, whereas others contend that since pitting is not expected to proceed at a linear rate with time, such analysis is not firmly rooted in good science. This disagreement might lead to the conclusion that only full data sets with the time dependence of pitting and corrosion up to failure may be used for analyses. For the purposes of this report, the observations of failures and the linearized rates that result are the only available information on DIP with PE and CP. The committee had to work with the data available. In doing so, it also recognizes that linear pitting rate data do not follow any accepted model of corrosion but nevertheless can give a conservative estimate of time to failure for comparison. This linear model is a common engineering practice and predicts a conservative estimate of time to failure, because actual corrosion that has an induction period and/or slows with depth of corrosion would result in actual lifetimes longer than those predicted by linear extrapolation.

DIPRA has conducted burial and excavation studies of DIP in highly corrosive soils and shared limited aspects of its linearized data and its statistical analysis of the data with the committee. DIPRA studies involved burying 4- to 8-foot sections of bare DIP, as-manufactured DIP, DIP with intentionally damaged PE, and DIP with PE in corrosive soils in various locations and excavating sets of the pipes at regular intervals to evaluate maximum pit depth at each burial time. Mean maximum pitting rates were calculated on the basis of aggregate data for all burial times, and in many cases by aggregating information for multiple sites. The mean maximum pitting rate of DIP with PE are compared to pipes buried without the protection of PE, and the data as presented make a case for showing that mean maximum pitting rates are reduced by intact PE. The committee agrees with that qualitative conclusion. Of more interest to the committee were the actual data on observed pitting depths, but these data are considered proprietary to DIPRA and full details were not shared. However, DIPRA has reported (in Chapter 3 of the present report, see Table 3-5, Row 3) that of the 151 pipes (representing less than 1,000 feet of pipe), 14 exhibited measurable pitting corrosion and that the mean maximum pitting rate for these 14 samples is about 5 mpy. These data also suggest that the most extreme corrosion rate exceeded the mean of 5 mpy, and further analysis (see Table 3-6) showed maximum observed pitting rates that may be as much as 8 mpy.

The committee believes that it is the extreme values (Data Types 1 and 2) that need to be considered rather than the reported mean maximum pitting rates (Data Type 4), because it will always be the point of most rapid corrosion on a length of pipe that will lead to the first failure. In this case, if there is a maximum observed pitting rate of at least 5 mpy, a linear extrapolation of that rate would suggest a corrosion depth of at least 250 mils in 50 years. Again, the committee does not accept that a linear maximum observed corrosion rate reflects scientific understanding of corrosion mechanisms, but such linear extrapolations are used in the absence of more comprehensive data. One DIPRA study reports a mean maximum pitting rate for this measurement on all 151 pipe sections as 0.45 mpy leading to a projected time to corrosion penetration of over 500 years.[5] Using the mean maximum pitting rate (5 mpy) for the 14 corroding sample pipes, however, this projected time to failure would be only about 50 years. Anticipating that the maximum pitting rate for this distribution will be greater than the mean of 5 mpy and could be at least 8 mpy based on reported values, the projected time to first failure for this agglomeration of 151 short sections of pipe would be 32 years, well less than 50 years.

Considering the DIPRA data referred to above on the pipe measuring between 600 and 1,200 feet (151 samples at 4- to 8-foot lengths) that is presumably installed with ideal care, the committee does not find that the studies of DIPRA confirm that DIP with PE can meet the expected reliability of over 50 years of service life. The committee recognizes that, based on an understanding of scientific principles, adding CP to DIP with PE will likely lead to an improved reliability over DIP with PE alone. However, the shielding effect of the PE at some distance from damage or a holiday suggests that in those areas the maximum observed pitting rates may not differ from DIP with PE only. Indeed, the oxygen depletion encountered in most of the pipe will protect it from much of the corrosion, but there remain questions as to whether this mechanism and the CP will protect the entire pipe. Therefore, the available limited data from the DIPRA studies do not lead the committee to the conclusion that DIP with PE and CP will necessarily have the required level of reliability over the 50-year service life.

The committee also collected data on maximum observed pitting rates of DIP with PE from various other field studies, as summarized in Tables 3-7 and 3-9 in Chapter 3. The data in Table 3-7 for maximum observed pitting rates under PE frequently give linear pitting depth rates significantly greater than 5 mpy, indicating that by conventional industry extrapolations, these pipes could fail in much less than 50 years and will not meet the Reclamation threshold in corrosive soils. Likewise field data, summarized in Table 3-9, for DIP with PE and CP provided data

[5] Charles Cowen, Analytical Focus, "Measurements and Standards," presentation to the committee, Washington, D.C., July 28, 2008.

on actual wall penetrations and linear maximum observed pitting rates greater than 5 mpy. Therefore, these field data do not contradict the fundamental understanding of corrosion mechanisms which suggests that DIP with PE and CP will not offer the level of pipeline reliability desired by Reclamation.

Finally, although this corrosion protection system should work in ideal conditions, fundamental scientific principles also indicate that there can be problems with the use of DIP with PE and CP. The shielding of the CP current at points away from damage or a holiday in the PE is a concern to many. Shielding prevents reliable calculation of anticipated corrosion rates and can make the normal monitoring systems used to show pipeline health less reliable. However, there continues to be disagreement in the pipeline community on the importance of current shielding. There are those who believe that shielding does make CP less effective and that corrosion mechanisms such as microbiologically influenced corrosion (MIC) are favored in the anaerobic environments when a food source is present underneath the PE. However, others who recognize these principles would argue that experience has shown them to be unimportant or not contributing to significant corrosion.

With respect to the alternative responsibility in the committee's charge, since the committee answered question 2 in the negative, it is asked by the Bureau of Reclamation to "provide recommendations for alternative standards that would provide a service life of 50 years." **After considerable study and deliberation, the committee finds that using the performance of bonded dielectric coatings on steel pipe with cathodic protection as a benchmark for reliability, and based on available information, it is unable to identify *any* corrosion control method for DIP that would provide reliable 50-year service in highly corrosive soils.**

This finding does not mean that any of the corrosion mitigation systems *will not* meet the required benchmark, but rather that the data are insufficient to draw a conclusion in either the affirmative or the negative.

In arriving at this finding, the committee naturally looked at the corrosion control method currently required in the Bureau of Reclamation's Technical Memorandum 8140-CC-2004-1 for highly corrosive soils—a bonded dielectric coating on DIP with CP. Indeed, there is evidence to support a conclusion that this method of protection is superior to that of DIP with PE and CP, but the data on each system are so insufficient that it is not possible to ensure that this system will provide corrosion protection for a service life of 50 years. This is particularly true in view of the fact that the benchmark of meeting the reliability of the gas pipelines is a high standard and one supported by years of experience with many miles of pipe. Also, the DOT system represents the state of the art in pipeline maintenance, including periodic studies of pipeline with technology such as intelligent in-line inspection ("smart pigging"), in which a remotely controlled measuring device is sent down the pipe to collect data such as pipeline wall thickness. The industry serving the water pipeline infrastructure seldom uses such advanced monitoring methods.

The committee considered that a very simple argument might have led to a conclusion that DIP with bonded dielectric coatings could provide the desired level of reliability. That simple reasoning is that DIP, cast iron, and steel pipe are often thought to corrode at roughly the same rates. Therefore, if bonded dielectric coatings on steel pipe offer the desired level of reliability, bonded dielectric coatings on DIP would also provide the desired level of reliability. However, the committee could not rely on this reasoning because some of the committee members were of the opinion that coatings on DIP are bonded to a surface that is quite different from the surface of steel and that therefore there could be no assurance that the coatings would perform equivalently. Also, some members believed that the difference in the nature of the joints in steel and DIP might also affect the overall performance of the corrosion protection. Others thought that these coatings would provide performance similar to that of bonded dielectric coatings on steel pipe. The committee believed that adequate data were not available to fully endorse bonded coatings with CP for corrosion protection of DIP because of these uncertainties in the performance of bonded dielectric coatings on DIP.

There is limited experience with bonded dielectric coatings for DIP in the United States, and some pipelines were installed as long as 33 years ago. To the committee's knowledge, none of these pipelines has failed, but the length of pipe involved and the length of service for the pipeline prevent the committee from endorsing this as a method leading to the desired level of reliability.

Beyond the lack of data for DIP with bonded dielectric coatings and CP, the principles used to understand the mechanisms that may prevent DIP with PE and CP from meeting the needed pipeline reliability criteria can in some cases be used to question the ability of DIP with bonded dielectric coatings and CP to meet the reliability benchmark. For instance, a criticism of PE has been that if the encasement is damaged, the CP will protect the pipe in the immediate vicinity of the damage but may not protect the pipe away from the damage due to shielding of the current. In principle, the same argument can apply to bonded dielectric coatings where, due to current shielding, CP may not protect a pipe from corrosion away from the damage if the coating is disbonded. Of course, not all damage to bonded dielectric coatings includes significant disbonding of the coating in the vicinity of the damage, so it is anticipated that DIP with bonded dielectric coatings and CP should perform better than PE with CP in these cases. This leads to a conclusion that DIP with bonded dielectric coatings and CP is likely to provide a higher level of protection to DIP compared to that provided by PE with CP, but this does not equate to a finding that DIP with bonded dielectric coatings and CP will meet Reclamation's desired level of reliability.

The committee considered other corrosion mitigation methods such as anti-MIC PE, microperforated PE, zinc coatings with epoxy or other types of top coats, controlled low strength material backfill, and building in a corrosion allowance.

**The committee finds that these other corrosion mitigation methods show promise, but the evidence is too limited to make any recommendations for their use at this time.**

**In summary, the committee finds that PE with CP can provide improved corrosion protection to DIP when compared to bare DIP or as-manufactured DIP in highly corrosive soils.** However, the committee does not believe that DIP with PE and CP is assured to provide the level of reliability expected by Reclamation over the 50-year pipeline service life in highly corrosive soils. The committee considered alternative corrosion control methods that would provide the desired level of reliability of DIP in highly corrosive soils. In view of the low level of experience on alternative systems, the committee cannot provide assurance that any corrosion control method for DIP will provide a reliable 50-year service in highly corrosive soils. Of the alternatives considered, the committee was of the opinion that because DIP systems with bonded dielectric coatings and CP that are in use are performing well, this corrosion control system for DIP was most favored.

The data on the corrosion mitigation systems were limited for a variety of reasons, chief among them being limited sample size—that is, the total length of pipelines with DIP with PE and CP in corrosive soils is 353 miles, with a maximum age of 29 years. Unfortunately, significantly more data are not expected to be forthcoming other than some indicating additional experience on pipelines remaining in service. One promising way of protecting DIP in highly corrosive soils is to use bonded dielectric coatings with CP; it would be useful if more data on the efficacy of this protection method would also be forthcoming. Unfortunately, it is unlikely that significant amounts of DIP will be installed with bonded dielectric coatings and CP because the domestic DIP manufacturing industry will not supply DIP with bonded coatings and resists allowing customers to apply such coatings. Therefore, the prospect of amassing the data that would be needed to test the efficacy of bonded dielectric coatings with CP for DIP is limited (with the possible exception of DIP with bonded dielectric coatings manufactured outside the United States). Therefore, the committee concludes that making a more extensive analysis of the reliability of both DIP with PE and CP and DIP with bonded dielectric coatings and CP will not likely be possible in the foreseeable future.

The committee recommends several areas in which additional studies could clarify its findings and provide data to improve the reliability of water-carrying pipe systems.

- **The committee recommends that to improve the reliability of existing pipelines, modern testing systems such as intelligent in-line inspection ("smart pigging") should be studied and introduced in order to monitor more closely the corrosion of pipes and permit the repair of pipe systems prior to failure.**

The adoption of such pipeline monitoring systems is not common in the water industry, but if adopted, they could enhance the reliability of these pipelines, particularly where failure would have large negative impacts. The method of random digging to diagnose the corrosion behavior of pipelines is inadequate to predict the state of corrosion for the total pipeline and thus will seldom identify the fastest corrosion rates at the tail of the distribution. Studies should be initiated to evaluate some of the promising corrosion control systems considered in this study for water pipelines in order to determine whether the adoption of any of these systems would permit the system to meet the desired level of pipeline reliability.

- **The committee recommends that data on pipeline reliability be assembled for all types of pipe specified by the Bureau of Reclamation in Table 2, entitled "Corrosion Protection Criteria and Minimum Requirements," in Technical Memorandum 8140-CC-2004-1 along with the specified corrosion protection applied in the various soil types.**

While the challenge to Reclamation's specifications concerned only DIP in highly corrosive soils, there are other categories of pipes (steel, pretensioned concrete, and reinforced concrete) and corrosion mitigation methods (including mortar/coal tar epoxy, mortar, concrete, and concrete/coal tar/epoxy depending on the pipe material) that are not challenged, and implicit is the assumption that these pipe types and corrosion mitigation methods meet Reclamation's expectations for reliability. With a quantitative analysis of the behavior of these pipeline types in the other two soil conditions, future consideration of benchmarks for needed reliability will be much clearer, and the appropriateness of the corrosion protection measures specified can be better understood. Also, the committee believes that Reclamation can enhance the reliability of existing systems by adopting some of the modern pipeline monitoring systems in use on natural gas pipelines. There is evidence that better monitoring has led to enhanced reliability on the gas pipeline system. It is expected that a similar asset management program for critical water pipelines would enhance the reliability of these systems as well.

# Appendixes

# Appendix A

# Biographies of Committee Members

**David W. Johnson, Jr.**, Chair, retired from his position as director of the Materials Research Department at Agere Systems. Previously he had been director of the Materials Research Department at Bell Laboratories. He continues as an adjunct professor of materials engineering at the Stevens Institute of Technology and editor of the Journal of the American Ceramic Society. His expertise is in ceramic materials development and processing, specifically, electronic, magnetic, and optical materials. His research focused on bulk and thin-film fabrication and processing of materials for communications technologies. He was awarded a B.S. and Ph.D. in ceramic science from the Pennsylvania State University. He is a member of the National Academy of Engineering and a fellow and past president of the American Ceramic Society.

**Ronald Bianchetti** is principal/owner of Blackstone Group, Ltd., a corrosion engineering consulting firm located in El Dorado Hills, California. He is a registered corrosion engineer in the state of California and is a certified National Association of Corrosion Engineers (NACE) cathodic protection specialist. Mr. Bianchetti has been a member of NACE for 30 years, during which time he has been extremely active. He currently serves as Western Area director for the 2006-2009 term. He has served as chair for the San Francisco Section (1984-1986); vice chair, San Francisco Section (1984-1985); secretary/treasurer, San Francisco Section (1983-1984); membership chair, San Francisco Section (1980-1983); and chair, NACE Program-Golden Gate Metals and Welding Conference-1985. He has also held the positions of trustee, San Francisco Section (1990-1992); chair, Western Region (1994-1996);

and vice chair, Western Region (1994-1995). He has served in various NACE services offices, including as a member of the board of directors (1992-1995); chair, Publications Committee (1992-1995); past chair, Publications Committee (1994-1997); and chair of Symposium, Corrosion/91 on “Corrosion and Its Control in Reinforced Concrete Structures.” For his many contributions, Mr. Bianchetti received the T.J. Hull Award and the NACE Distinguished Service Award. He received his B.S. in engineering in 1975 from the University of California, Davis. In 1981, he obtained his Executive M.B.A. from St. Mary’s College of California. He has served as chair, co-chair, and active member on a variety of technical and board-level committees throughout his tenure with NACE.

**Richard J. Fields** is metallurgy consultant with KT Consulting. Previously he worked at the National Institute of Standards and Technology (NIST) (formerly the National Bureau of Standards [NBS]), where he supervised groups of scientists doing research in metal forming, nanolaminates, and powder metallurgy. He was the principal technical investigator on metallurgical aspects of the congressionally mandated investigation of the collapse of the World Trade Center’s Twin Towers and was supervisory metallurgist managing the Time Dependent Failure Group in NBS’s Fracture and Deformation Division. This group ran the metallographic facilities as well as carrying out mechanical testing research programs for the U.S. Navy, the Federal Railroad Administration, the National Transportation Safety Board, and the Nuclear Regulatory Commission. Dr. Fields was group leader for the Materials Performance Group in NIST’s Metallurgy Division. Part of this group of 11 professionals runs the U.S. National Hardness Standardization Facility, certifying primary hardness standards. As the supervisor of the Materials Performance Group, he started a program on sheet metal forming with the auto industry. He also started a program on modeling bullets and armor for the National Institute of Justice and a program on fire-resistant structural steels. He has an extensive list of publications, patents, and awards available on request. He has performed research and written numerous papers relevant to the prediction of fracture behavior in pipeline steels. In particular, he was principal author on NIST Report 89-4136, *An Assessment of the Performance and Reliability of Older ERW Pipelines*, written at the request of Senators Kit Bond and John Danforth. He was appointed by Secretary of Transportation Elizabeth Dole to the Office of Pipeline Safety’s Hazardous Liquid Pipeline Safety Committee and served for 6 years, 3 of these as secretary. He is now part of a research team that is developing experimental and analytical methods to assess the high-rate fracture- and crack-arrest behavior of high-strength pipeline steels. Dr. Fields received his undergraduate degrees in chemistry and metallurgical engineering from the University of Pennsylvania. He received an M.S. in engineering and applied physics from Harvard University and a Ph.D. in engineering materials from Cambridge University. He has conducted metallurgical research and participated in mechanical test standards development activities for nearly 40 years. He is currently the U.S. representative on the Ductility Subcommittee of the International Organization for Standardization. Dr. Fields is a member of ASTM (American Society for Testing and Materials) International and of the American Academy of Mechanics and is chair of the ASTM Subcommittee on Ductility and Formability. He is an active member of the Fire Resistive Steel Task Group. He received a Bronze Medal from the National Bureau of Standards for his research on fracture and crack arrest in high-strength steels, and a silver medal from the Department of Commerce for scientific achievement in materials properties measurements and modeling.

**Carol A. Handwerker** is a professor of materials engineering at Purdue University, having joined Purdue in August 2005 after serving for 9 years as chief of the NIST Metallurgy Division. Professor Handwerker's research is focused on the thermodynamics and kinetics of interface processes, with applications to microelectronics, nanoelectronics, and printed electronics. She received a B.A. in art history from Wellesley College, and an S.B. in materials science and engineering, an S.M. in ceramics, and an Sc.D. degree in ceramics from the Massachusetts Institute of Technology (MIT). Following a year's postdoctoral research on electronic packaging at MIT, she joined NBS in 1984 as a postdoctoral research associate, working on the relationship between stress and diffusion in solids and on composition effects on sintering and grain growth. She became a permanent staff member at NBS in 1986, group leader of the Materials Structure and Characterization Group in 1994, and division chief of the Metallurgy Division in March 1996. She is a fellow of the ASM (American Society of Materials) International and of the American Ceramic Society (ACS), and is past chair of the ACerS Basic Science Division. She serves on the Technical Advisory Committee and the R&D Committee for iNEMI and the Visiting Committee for the MIT Department of Materials Science and Engineering, and has served on numerous other boards, including the board of trustees of the Gordon Research Conferences, the advisory committee of Carnegie Mellon University's Mesoscale Interface Mapping Project, and the editorial board for the *Annual Reviews of Materials Research*. She has written more than 90 scientific publications.

**John O'Brien** is the director of the Water and Wastewater Division for Genesee County, Michigan, providing utility service to more than 500,000 people. Mr. O'Brien is a certified operator in the state of Michigan. Previously he had worked at the city of Battle Creek, holding the position of utilities manager. During his 8 years with the city, Mr. O'Brien successfully completed the requirements for registration as a professional engineer in the state of Michigan. In 1994 Mr. O'Brien accepted a position with the consulting firm Consoer Townsend Envirodyne. While so employed, he was a lead engineer for water and wastewater facilities. During his years as a consultant, he earned his Indiana Engineering License and received his certification as a diplomat from the American Academy of Environmental Engineers. Mr. O'Brien graduated from Michigan Technological University with a bachelor's degree in civil engineering and a second degree in analytical chemistry.

**Matthew O'Keefe** is currently a professor of metallurgical engineering in the Department of Materials Science and Engineering and director of the Graduate Center for Materials Research at Missouri University of Science and Technology (MST). He received a B.S. degree from MST and a Ph.D. from the University of Illinois, both in metallurgical engineering. He previously worked for AT&T Microelectronics, AT&T Bell Laboratories, and the Air Force Research Laboratory. His research at MST focuses on specializing in the deposition, characterization, and industrial use of thin films, coatings, and environmentally friendly materials and processes for corrosion, wear, and microelectronic applications.

**John R. Plattsmier** serves as national director of pump stations and pipelines for HDR Engineering and has extensive experience in the field of engineering consulting. He has worked on various types of projects in management, technical, oversight, and reviewer roles. Mr. Plattsmier serves on national committees with the American Water Works Association and the American Society of Civil Engineers helping to set standards for pipeline planning and design. Prior to joining HDR, he was the director of design services for a consulting firm where he managed a staff of more than 200 engineers, architects, and designers to deliver designs for water facilities around the globe. He also served as a civil design discipline director (chief civil engineer), with responsibility for development and implementation of corporate standards, staff development, project delivery, and reviews. Mr. Plattsmier received a B.S. in civil engineering from Louisiana State University.

**Alberto A. Sagüés** is Distinguished University Professor at the Department of Civil and Environmental Engineering, University of South Florida. Previously he held positions at the University of Kentucky, Argonne National Laboratory, Juelich Nuclear Research Center, and Columbia University. He also was appointed by President Clinton to be a member of the Nuclear Waste Technical Review Board from 1997 to 2002. Dr. Sagüés received his Ph.D. in metallurgy from Case Western Reserve University and his licentiate in physics from National University of Rosario, Argentina, and is a registered professional engineer in Florida. His areas of expertise are corrosion of engineering materials, concrete, materials for infrastructure, materials for energy systems, durability forecasting, physical metallurgy, and nuclear waste disposal. He has authored 190 publications in the technical literature and 3 U.S. patents and has directed to completion the work of 30 M.S. and Ph.D. engineering students.

**William S. Spickelmire** is president and owner of RUSTNOT Corrosion Control Services, Inc., and has more than 31 years of experience as a project manager in all facets of corrosion control. He is a certified NACE cathodic protection specialist with expertise that encompasses rehabilitation, material selection, coating, and cathodic protection. He has conducted soil, water, and site corrosion investigations to evaluate and provide corrosion control recommendations for clients in diverse applications, conditions, and geographical locations. He has provided corrosion recommendations and designs for water and wastewater collection, transmission, storage, and treatment facilities; natural gas and petroleum facilities, tank farms, and high-pressure transmission and distribution systems; high-voltage power transmission lines; dams and diversion structures; bridges; mining facilities and solution mining projects; irrigation systems; pump stations; fish hatcheries; and mining, power, and industrial plants. National and small engineering firms, utilities, military organizations, industry, private companies, and public agencies throughout the United States have retained his services. He has provided corrosion control presentations and papers on an international basis. Mr. Spickelmire has extensive experience on corrosion considerations, comparisons, risk assessments and life-cycle analysis, and corrosion control requirements for different types of pipelines in a variety of soil conditions and project requirements. Recommendations for pipeline projects have included evaluation of replacement, slip lining, concrete linings, and inversion (in situ form) lining, material selection, cathodic protection, loose-bonded (polyethylene) and tight-bonded coatings, and corrosion control designs. He has provided corrosion recommendations for several thousand miles of water, irrigation, and sewer transmission pipelines with diameters up to 120 inches, as wells as over 2,000 miles of water distribution piping, and over 3,000 miles of oil and gas transmission pipelines. A former employee for more than 17 years with a major national engineering firm, CH2M HILL, he was a corrosion project manager for numerous projects throughout the United States. He has a B.S. from the College of Idaho and is a member of the American Water Works Association, NACE, and the Society of Protective Coatings. He is a member of the NACE TG 14 Committee for Corrosion and Corrosion Control for Cast and Ductile Iron Pipe and a member of the NACE Water Advisory Board. He has been an active member of NACE since 1978, serving in all offices of the Intermountain Section and receiving that section's Distinguished Service Award in 1996.

**David Trejo** is the Zachry Career Development Professor I in the Zachry Department of Civil Engineering at Texas A&M University. He received his bachelor's, master's, and Ph.D. degrees in civil engineering from the University of California at Berkeley with minors in electrochemistry and materials science. He has significant background in investigating, testing, assessing, and evaluating mechanisms of deterioration of various material and structural systems, including pipes, walls, foundations, bridges, water tanks, and other structures. He has participated in federal and state research investigating the physical, chemical, and electrochemical deterioration and repair of infrastructure systems. He has more than 10 years of experience in the construction and engineering industry, where he worked on many infrastructure projects, including testing and evaluating materials and structures for deterioration.

# Appendix B

# Dissenting Statement

This statement concerns the interpretation of the evidence of failures in ductile iron pipe (DIP) with polyethylene encasement (PE) and cathodic protection (CP), and of the interpretation of field data, for which the author, a member of the Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe, has different views from those stated in the body of the report. Relevant issues are noted below.

The first issue concerns the number of failures to merit consideration as evidence of the corrosion performance of DIP with PE and CP. That number was chosen to be three in the analysis presented in Chapter 4, "Failure Criteria," corresponding to the Southwest, Akron, and California City entries in Table 4-2. The author differs by noting that two of those failures have serious disqualifying factors. As detailed in Chapter 3, the California City event took place in an extremely aggressive environment (100 ohm-cm) where the pipeline had served half of its pre-failure life without any cathodic protection. Such a situation falls far short of that of a properly maintained and operated cathodic protection system, and the author deems it not relevant to the conditions of interest. Also as indicated in Chapter 3, the Akron, Ohio, failure occurred at a spot where the presence of inter-segment electrical bond, necessary for proper cathodic protection, could not be confirmed. As in the previous case, authentication of the failure as representative of regular operations cannot be supported by the author. It is also remarkable that both failures took place in very short segments of pipe (1.5 miles and 0.25 mile for the California City and Akron failures, respectively), which were also the two shortest pipe segments listed in Table 4-2, and each far shorter than the length-weighted average of all the entries. Those observations further suggest a singular character for those failures, possibly related to the level of maintenance, inspection, and control resources that may be available for large as opposed to small projects. The only remaining failure (Southwest) does not appear to have major potential disqualifying issues except for reported difficulties in consistently meeting CP goals as well as potential PE damage from aggregate during placement.[1] Consequently, the author estimates that only one failure merits serious consideration for analysis against the expectations from the benchmark stated by the Bureau of Reclamation.

The second issue concerns this author's disagreement with the analysis methodology used in Chapter 4 to compare evidence of field failures with the expectations from the benchmark of 0.000044 failures per mile per year stated by Reclamation, which will be considered as an agency-specified parameter in the following. The author contends that because of the very sparse DIP with PE and CP failure data set, interpretation of those data to calculate a nominal failure frequency for comparison to that of the benchmark is not appropriate, as it is akin to comparing over a short period of time the nominal death rate from a small community to that of a large city. Thus, comparison between this nominal rate and benchmark rates, as used in Chapter 4 and cited in Chapter 6, "Findings, Conclusions, and Recommendations," is not warranted in the view of the author. The corresponding sensitivity analysis in Chapter 4 of the report does not resolve this concern, as such analysis would be an extension of assigning undue significance to the nominal rate.

The author proposes instead to estimate, using the benchmark rate, the probability of having the number of failures observed in the DIP with PE and CP experience inventory for the given amount of pipe length-years in that inventory. If that probability is found to be appreciably large, then the DIP with PE and CP failure data set may not be indicative of diminished performance compared to that of the benchmark set. Conversely, if that probability is found to be very small, the DIP with PE and CP failure data may be seen as indicative of diminished performance relative to the benchmark. It is emphasized that this analysis is limited only to the implications of observed failure events. Other evidence of performance such as the presence of corrosion in the absence of failures was considered elsewhere in the report, as well as in discussions based on corrosion engineering principles.

In the following, the benchmark failure rate stated by Reclamation will be assumed to be numerically equal to the probability $P$ of one failure occurring per mile per year in a hypothetical large reference system (or "benchmark system"), so $P = 4.44 \times 10^{-5}$. That assumption is adopted considering that the arguments presented by Reclamation in developing the benchmark involved a considerable

[1] Graham E.C. Bell, Schiff Associates, "Measurements of Performance of Corrosion Control Mechanisms on DIP," presentation to the committee, Washington, D.C., July 29, 2008.

number of failures (on the order of 20) occurring over several years on a very large pipeline length, and that the corresponding number is <<1. The above considerations are comparable to those used in Chapter 4, in what pertains to treating the numeric Reclamation benchmark as a probability. The present analysis takes a different direction from here on. Assuming that the annual probability of failure per mile $P$ remains constant over time and that each mile of pipe and each year is statistically independent from the rest, the probability $P_0$ of having zero failures in the benchmark system in a given $T$ year period for a given length of pipe of $L$ miles can then be determined as follows:

$$P_0\ (\%) = 100\ (1 - P)^{TL} \sim 100\ \mathrm{e}^{-PTL}\ (TL >> 1). \qquad \text{(Eq. B-1)}$$

Thus the probability $P_{1+}$ of having at least one failure in the benchmark system over a given time and length interval is estimated by

$$P_{1+}\ (\%) = 100\ (1 - \mathrm{e}^{-PTL})\ (TL >> 1). \qquad \text{(Eq. B-2)}$$

Following a similar analysis the probability $P_{n+}$ of having at least $n$ failures in the benchmark system for a given length and time interval is estimated, when $TL$ is large, by

$$P_{n+}\ (\%) = P_{(n-1)+} - 100\ (PTL)^{n-1}\ \mathrm{e}^{-PTL}/(n-1)! \qquad \text{(Eq. B-3)}$$

which is a form of the Poisson distribution.[2]

Table 4-2 shows that the DIP with PE and CP documented experience concerns an integrated interval $TL \approx 7.94 \times 10^3$ mile per year. Consequently, by application of the above equations the probability of having at least one failure in that same $TL$ interval in the benchmark system would be approximately 29 percent. For at least two failures the probability drops to about 5 percent, while for at least three failures it is only about 0.5 percent.

The import of this finding together with the discussion on the first issue becomes apparent. With only one qualified failure, the probability of having at least one such failure in the benchmark system for the same integrated time-length is quite high, ~29 percent. Thus the single qualified failure could be easily dismissed as an event that would have been frequently observed in other surveys of comparable pipe length and duration in the benchmark system. On the other hand, if even two of the failures had merited qualification, the probability would have dropped to the much smaller ~5 percent value, while if all three of the failures considered

[2] J.H. Pollard, *A Handbook of Numerical and Statistical Techniques* (Cambridge: Cambridge University Press, 1977).

were pertinent, the probability of their having been observed in the length-time interval considered for the benchmark set would have been exceedingly small. The author proposes therefore that, absent solid evidence for more than one qualified failure in the $\approx 7.94 \times 10^3$ mile per year experience base, the failure data alone do not sufficiently support stating that DIP with PE and CP has clearly poorer corrosion performance than that of the Reclamation benchmark system.[3]

The third issue concerns the significance assigned in parts of the report to linearized corrosion rates values calculated from field and yard test measurements of corrosion penetration. Such values were largely considered outside the context of how frequently along the pipe and over what time period the sampling took place. In field samplings, localized penetration data are usually obtained at points where signs of severe corrosion distress had been observed, and often because a failure was noted. Therefore, it is not surprising that localized penetration rates there are high, since whichever protection system was present had clearly failed at that location. In the author's view, the main concern in these rarely occurring events should not be about what the rate of localized corrosion progression was, but instead about what the frequency of those events per pipe length-duration was, as in the focus of the previous two issues. Hence the meaning of those calculated values, at least as far as they concern field performance, is deemed by the author to be too limited to support or oppose the conclusions in the report derived from other considerations.

In summary, the author shares the committee view that the scientific understanding of corrosion mechanisms casts serious doubt that DIP with PE and CP can guarantee a long service life in highly corrosive soils. However, the author does not agree that the available failure data and calculations of linearized corrosion rates from field measurements provide conclusive enough supporting evidence for that view.

Alberto A. Sagüés, Member
Committee on the Review of the Bureau of Reclamation's Corrosion Prevention Standards for Ductile Iron Pipe

[3]The author notes that the committee considered two alternative benchmarks, one close to the Reclamation value and the other about 4 times smaller. The calculated probability of at least one failure for the latter is about 9 percent, which would suggest some concern if even one failure were qualified. However, potentially much less conservative alternative benchmarks (with consequently much greater probability of a single failure) are possible as well if correcting steel pipeline data for the fraction of soils that are highly corrosive. Such alternatives were recognized but not quantified by the committee in the absence of suitable data, but that absence if anything further emphasizes the inherent uncertainty in assigning undue significance to the presence or not of just one failure.

# Appendix C

# Definitions

The required criteria for corrosion control call for some terms that may not be familiar. Although these items are covered in more detail within the body of the report, brief descriptions are provided below for clarity of the general corrosion control discussion.

***anode:*** The positive electrode or metallic surface location where direct current is discharged into a surrounding electrolyte and corrosion (oxidation with a loss of electrons) occurs in a corrosion cell. The opposite of a cathode.

***appurtenance or fitting:*** Items including but not limited to valves, bends, tees, glands, restrained joints and joint restraints, couplings, spool pieces, miscellaneous piping, tapping saddles, blow-off valves, or hydrants, including metallic glands.

***bell-and-spigot pipe joint:*** The spigot end of a pipe, which is the same diameter as the pipe barrel, fits into a bell that is larger than the spigot, and a gasket is then used to contain pressurized material. Additional mechanical restraints, such as bolts or collars, may also be used to keep the joint intact. Bell-and-spigot joints may be push-on, mechanical, or restrained joints.

***bonded dielectric coating:*** An electrical insulating coating that is physically attached to the pipe surface.

***cathode:*** The negative electrode or metallic surface location where direct current is received or collected from a surrounding electrolyte and protection (reduction with a gain of electrons) occurs in a corrosion cell. The opposite of an anode.

***cathodic protection criteria:*** The National Association of Corrosion Engineers (NACE) criteria for cathodic protection levels in accordance with NACE Standard 169, "TG 169 Cathodic Protection of Pipelines in Seawater."

***cathodic protection station:*** An impressed-current cathodic protection installation location usually consisting of a rectifier and ground bed.

***cathodic protection system:*** Two common cathodic protection methods are galvanic anodes and impressed-current cathodic protection systems. A galvanic anode system consists of galvanic anode material (usually magnesium or zinc) that naturally corrodes or sacrifices itself and does not require an outside power source. An impressed-current-type system employs an outside power source, usually a rectifier (that converts alternating current to direct current) and forces (impresses) current from a number of anodes (or ground bed) through the environment to the structure to be protected.

***corrosion monitoring system:*** A system of test stations, joint bonds, and insulators that provides an electrically continuous pipeline that is electrically insulated from other structures and provided with test stations at specified locations to allow monitoring of various testing methods, including pipeline potential, galvanic anode outputs, electrical continuity, electrical isolation, and cathodic protection testing.

***coupons:*** Use of two small bare pieces (coupons) of the base type of pipe and an on/off switch that allows one coupon (protected) to be connected into the cathodic protection system and one coupon (unprotected) to freely corrode with no protection. The pair of coupons and on/off switch are used to allow various cathodic protection measurements (on, instant-off, and static [freely-corroding] potentials as well as current collection and direction measurements) to be used to ascertain protection levels provided to the structure.

***electrical isolation:*** The condition of being electrically isolated from other metallic structures (including, but not limited to, piping, reinforcement, and casings) and the environment as defined in NACE PR0286, "The Electrical Isolation of Cathodically Protected Pipelines."

***electrically continuous pipeline:*** A pipeline that has a linear electrical resistance equal to or less than the sum of the resistance of the pipe plus the maximum allowable bond resistance for each joint as specified or recommended by the pipe designer or pipe manufacturer.

***fastener:*** Items including but not limited to bolts, nuts, washers, tees, tie-rods, and restraining devices.

***ferrous metallic pipe:*** Any pipe or fitting made of steel or iron, or pipe containing steel or iron as a principal structural material (such as steel, ductile iron, and cast iron), except reinforced concrete pipe or stainless steel.

***holiday:*** A physical defect, damage, tear, or puncture in the loose polyethylene or a physical defect, disband, or damage in bonded dielectric coatings.

***joint bond:*** A method of making a pipeline electrically continuous by connecting insulated copper wire(s) or strap(s) across each side of the pipe joint or fitting.

***lead, lead wire, joint bond, pipe-connecting wire, cable:*** Insulated copper conductor; the same as wire.

***loose bonded coating:*** A dielectric coating that is not bonded or physically attached to the pipe surface (polyethylene encasement, polywrap, wrap, encasement, etc.).

***plastic reference pipe:*** Plastic conduit or pipe placed in soil next to the structure to allow a portable reference electrode to be inserted for structure-to-reference electrode potential measurements.

***potential, structure-to-reference electrode potential (also structure-to-reference electrode voltage):*** Common method to determine corrosion protection levels by measuring the difference in voltage (potential) between the subject metallic structure and the electrolyte in which it is buried or submerged, as measured to the standard specified reference electrode (usually a copper/copper sulfate reference electrode) placed in contact with the electrolyte.

***raceway:*** Conduit, sheath, plastic or metal pipe, or electrical metallic conduit (electrical metallic tubing) for casing of electrical or cathodic protection cables.

***resistance probe:*** Use of a probe with a known resistance to determine the amount of corrosion over a given period of time. As corrosion of the thin resistance probe occurs, the probe resistance increases. By measuring the resistance of the resistance probes over a period of time, the amount of corrosion activity that has occurred can be calculated in mils per year.

***test station:*** Insulated lead wire connections to the structure, which are brought to a test station terminal board or box in order to allow an electrical connection to be made to the structure for above-grade corrosion and cathodic protection testing.

# Appendix D

# Other Considerations for Corrosion Control

In this appendix, the committee presents some of the other considerations for corrosion control that they discussed in the development of the recommendations.

## CORROSION ALLOWANCE

The use of a *corrosion allowance* (manufacturing pipe with an excess wall thickness to extend the time to failure) in determining the thickness of the pipe by increasing the wall thickness of the ductile iron pipe (DIP) to allow for metal loss is generally not cost-effective or reliable, especially when pitting is the primary failure mode for DIP.[1] The method for providing corrosion allowance involves (1) determining the required thickness of pipe to maintain adequate strength based on operating pressure and depth of cover, (2) determining the rate of corrosion based on soil condition, (3) identifying the desired life of the pipe system, and (4) based on these factors, determining the thickness of the pipe system to be specified.

For example, a 30-inch-diameter pipe system with a working pressure of 300 pounds per square inch (psi) normally needs a wall thickness of 0.45 inch, assuming a soil environment that would cause a rate of corrosion of 20 mils per year (mpy). To design the pipe for a 50-year service life, the pipe thickness would be 0.45 inch

[1] Troy Stroud and James Voget, "Corrosion Control Measures for Ductile Iron Pipe," 46th Annual Appalachian Underground Corrosion Short Course (Morgantown, W.Va.: West Virginia University, 2001).

plus 0.020 inch per year over 50 years, giving a total design pipe wall thickness of 1.45 inches. This thickness would achieve the desired service life without loss of the required design thickness of the pipe system. However, as was noted in Chapter 2 of this report, such extremely thick pipe is not routinely manufactured.

## ENVIRONMENTAL CONTROLS (SOIL ENHANCEMENTS)

Specialized trench backfill in corrosive soils could be used to reduce the corrosivity at the pipe surface. This may provide only short-term protection to DIP due to leaching of the soil into the backfill. It has been observed, in many instances, that the less-corrosive backfilling material eventually takes on the characteristics of the surrounding soil.[2] This method can be as simple as using clean sand backfill, which will reduce the corrosion rate for a period. However, in areas with fluctuating water tables, the clean sand could become corrosive in a relatively short period of time.

An alternative method to consider in reducing corrosion rates is to change the environment in the trench with the use of controlled low-strength material (CLSM) that is placed in the pipeline trench after the pipe is installed.[3] The physical and chemical nature of this material tends to create a controlled environment of nonaggressive conditions and may inhibit the movement of chlorides and sulfates into the trench. The installer may also consider a chemical-enhanced backfill to counter the naturally occurring corrosive materials.

## ANTI-MIC POLYETHYLENE ENCASEMENT

In an attempt to minimize concerns about microbiologically influenced corrosion (MIC) under polyethylene encasement (PE), one manufacturer has developed a PE with anti-MIC additives. These anti-MIC polyethylene-encasement materials appear to hold some promise and are now available for commercial distribution.[4] The anti-MIC PE was used recently (2007-2008) on a project in Minnesota.[5] Additional independent testing and long-term evaluations still need to be completed to confirm the influence of MIC under PE on both water and wastewater lines.

---

[2] American Water Works Association, AWWA Manual M41, *Ductile-Iron Pipe and Fittings* (Denver, Colo., 1996), p. 173.

[3] Kevin Folliard, David Trejo, Scott Sabol, and Dov Leshchinsky, *Development of a Recommended Practice for Use of Controlled Low-Strength Material in Highway Construction*, NCHRP Report 597 (Washington, D.C.: Transportation Research Board, 2008).

[4] George Ash, Fulton Enterprises, Birmingham, Ala., communication with the committee, 2008.

[5] William Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective," *Materials Performance* 41(7):16 (2002).

## MICROPERFORATED POLYETHYLENE ENCASEMENT WITH CATHODIC PROTECTION

One PE manufacturer is experimenting with micro-perforated PE (similar to the perforated rock shield concept) on cathodically protected pipe samples in an effort to minimize cathodic protection (CP) shielding.[6] This concept will increase the current needed for CP but should prevent shielding of any area of the pipe from the protective current. Preliminary testing has been started in the Florida Everglades to determine electrical shielding, polarization, and current densities for microperforated PE pipe samples. Initial unpublished test data and field reports of the microperforated PE appear to be favorable, with calcareous deposits appearing on the pipe surface next to the perforations.[7] The initial current requirements for the microperforated polyethylene-encased pipe samples are reported to be less than for bare pipe but more than for polyethylene-encased pipe samples. Additional independent testing and long-term evaluations are needed to validate the effectiveness of microperforated PE in controlling corrosion and to determine whether it minimizes electrical shielding successfully.

## PIPELINE MONITORING AND REPAIR

### Passive Monitoring Systems

The committee reviewed several passive monitoring methods to determine more accurately the level of corrosion protection under PE. These include the use of resistance probes, reference electrodes, and perforated plastic monitoring pipes placed inside and outside the PE.[8] Although these passive monitoring techniques have only been used in a few locations, they show promise and are discussed in more detail below.

[6] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[7] Ash, communication with the committee, 2008.

[8] M. Schiff and B. McCollum, "Impressed Current Cathodic Protection of Polyethylene-Encased Ductile Iron Pipe," Paper 583 at Corrosion 93, New Orleans, La.; Graham Bell, Clifford Moore, and Scott Williams, "Development and Application of Ductile Iron Pipe Electrical Resistance Probes for Monitoring Underground External Pipeline Corrosion," NACE International Corrosion 2007 Paper 07335, Dallas, Tex.; Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective"; A.M. Horton, D. Lindemuth, and G. Ash, "Corrosion Control Performance Monitoring of Ductile Iron Pipe in a Severely Corrosive Tidal Muck," *Materials Performance* 45(5):50-54 (2006).

*Perforated Plastic Monitoring Pipes and Permanent Reference Electrodes*

Perforated plastic monitoring pipes allow potential measurements to be made inside (under) the polyethylene encasement and outside the polyethylene encasement for comparison purposes. This is done by inserting and pulling a portable reference electrode through the plastic monitoring pipes and recording potential measurements as the reference electrode is moved.[9] The theory is based on cathodic protection monitoring techniques first used for ground-level storage tanks, where perforated plastic monitoring pipes with portable reference electrodes were used to determine cathodic protection levels under the tank bottom. An example of this type of basic monitoring technique is shown in Figure D-1.

Other types of passive monitoring techniques include the placement of permanent reference electrodes inside and outside the polyethylene encasement.[10] The theory of the permanent reference electrodes is to compare the potentials made between similar types of reference electrodes (one on each side of the PE wrap). The resistance probes are described in more detail in the following subsection.

*Electrical Resistance Corrosion Probes*

An electrical resistance (ER) probe is a device that serves as a corrosion surrogate for the pipe wall; it monitors the accumulation of corrosion damage on a thin strip of metal by measuring the change in resistance of the thin strip as a function time. As the strip of metal thins due to corrosion, the resistance of the strip increases and the corrosion rate in mils per year can be calculated based on the length of time. The intent of the resistance probes is to measure the rate of corrosion in order to provide a snapshot of the protection levels being provided at that location on the pipeline with an above-grade type of measurement without having to excavate the pipeline. Typically probes are provided in pairs for cathodically protected pipelines; one probe is connected to the cathodically protected pipeline and one is not, as it is allowed to freely corrode to provide a reference for the normal corrosion rate in that soil. A pair of probes (four probes total) on DIP with PE are often placed both inside (under) and outside the encasement. One pair is placed inside and one pair is placed outside to compare the difference in corrosion rates under and outside the PE with and without CP. This monitoring

[9] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[10] Horton et al., "Corrosion Control Performance Monitoring of Ductile Iron Pipe in a Severely Corrosive Tidal Muck"; Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

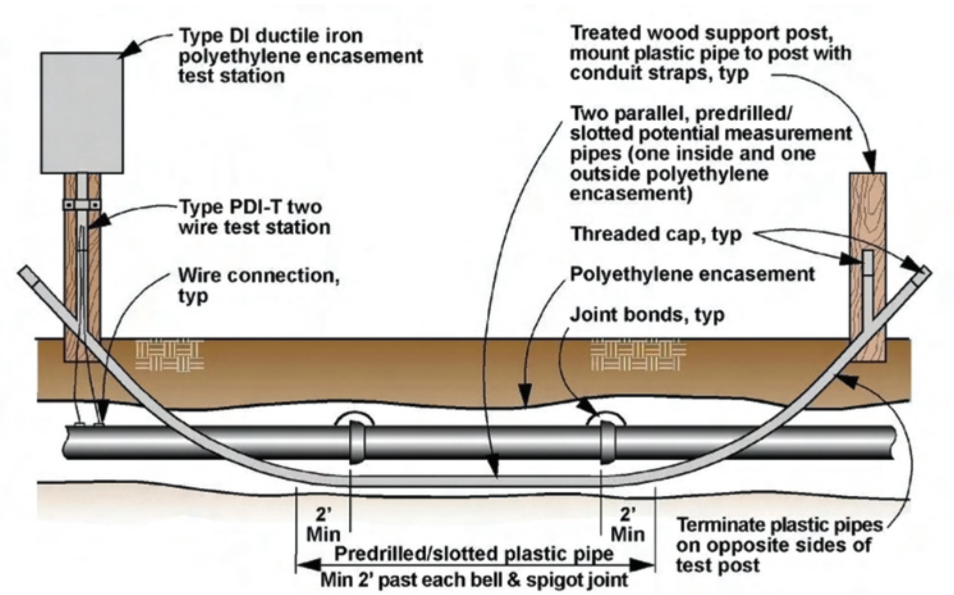


FIGURE D-1 Typical Type T Test Station with plastic monitoring pipe. SOURCE: Courtesy of William Spickelmire, RUSTNOT Corrosion Control Services, Inc.

technique has been tried on several different projects.[11] A few of the larger projects are discussed below in more detail.

**Southwest Pipeline Project** The Southwest Pipeline Project in North Dakota was installed in the 1980s with approximately 400,000 lineal feet (lf) of DIP with PE and CP. Commercially available steel probes (Figure D-2) were installed at eight locations along the pipeline. A total of 20 probes were installed at these eight separate locations.[12] Ten probes were placed under the PE wrap, 8 on the spigot next to the bell joint, and 2 at the midpoint of the pipe length. Eight were placed in the imported sand backfill and 2 in native-soil backfill next to the pipe trench. The probes have a lead wire to allow them to be bonded to the cathodically protected pipeline. The probes were measured at regular intervals from 1982 to 1992.

[11] Schiff and McCollum, "Impressed Current Cathodic Protection of Polyethylene-Encased Ductile Iron Pipe"; Horton et al., "Corrosion Control Performance Monitoring of Ductile Iron Pipe in a Severely Corrosive Tidal Muck"; Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective"; Graham E.C. Bell, Schiff Associates, "Measurements of Performance of Corrosion Control Mechanisms on DIP," presentation to the committee, Washington, D.C., July 29, 2008.

[12] Graham E.C. Bell, Schiff Associates, "Measurements of Performance of Corrosion Control Mechanisms on DIP," presentation to the committee, Washington, D.C., July 29, 2008.

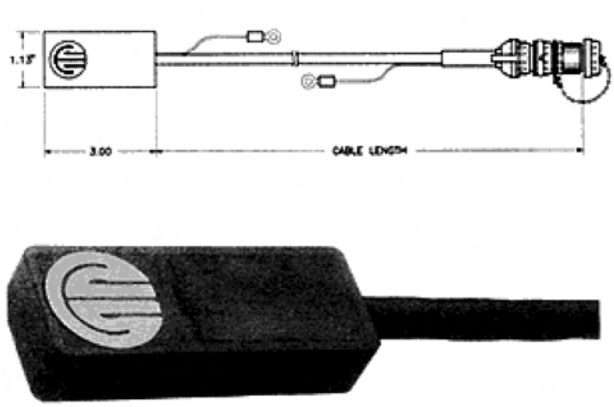


FIGURE D-2 Rohrback Cosasco Model 620 Corrosometer Probe. SOURCE: Courtesy of Rohrback Cosaco Systems.

In August 1989 some of the probes were grounded to the pipeline and protected with a galvanic anode. In July 1991 the pipeline was cathodically protected with an impressed-current CP system. An example of the type of steel resistance probes used on the Southwest Pipeline is shown in Figure D-2.

The results of the Southwest Pipeline's use of CP were as follows:

- After the application of CP, the corrosion rate of all probes bonded to the pipeline, both inside and outside the PE wrap, showed low corrosion rates, averaging 0.0189 mpy.
- The corrosion rates of DIP at undamaged encasement were low and governed by soil corrosivity, dissimilar metal, environmental corrosion cells, and so on.
- A clean sand backfill reduces corrosion rates below the rate in native-soil backfill.
- There is still an area of controversy regarding shielding of polyethylene-encased DIP from CP currents; it is recommended that probes be provided under encasement for other projects.
- To avoid technical issues, the probes should be made of the same material as the pipeline.
- According to Graham Bell in his presentation to the committee, the actual corrosion rates measured by the electrical resistance probes are most useful for comparison purposes only and "may not be an accurate measurement of the true pipe corrosion rate."

According to a presentation to the committee that was based on recent testing by the speaker, the probes that were placed on the DIP under the PE with CP have continued to show corrosion rates of less than 0.1 mpy.[13] The probe data are reported to show that the total accumulated corrosion damage for more than 20 years is less than 2.0 mils for DIP with PE and CP. Despite the fact that the small steel surface area of the steel-type resistance probes is anodic to the DIP, the testing indicated that CP has overcome the galvanic cell corrosion due to the difference between the steel (anode) and ductile iron (cathode) in addition to the influence of the soil corrosivity.

As mentioned in the presentation to the committee, on certain isolated portions of the Southwest Pipeline Project, cathodic protection current requirements were higher than for the majority of the pipeline sections. Potentials measured at the ground surface were also lower (below National Association of Corrosion Engineers [NACE] protection criteria) in these isolated sections. Schiff Associates[14] participated in an investigation to determine the reasons for these high current requirements and low potentials in one of these isolated portions of the pipeline. They concluded that the increased current requirements were due to the use of gravel backfill in those wet areas, which caused damage to the PE and exposed more pipe surface, increasing the CP current requirements. The rectifier was replaced with a larger sized rectifier to provide the additional current required. Schiff Associates reported that a field investigation of the DIP with PE and CP in that area did not show any corrosion on the pipe.

**Mid-Dakota Rural Water Service Project** The Mid-Dakota Pipeline Project in South Dakota was installed between 1996 and 2002 with approximately 262,000 lf of DIP with PE and CP. Commercially available ductile iron probes were installed along the pipeline. In an effort to ascertain the distance that cathodic protection may reach back under intact polyethylene encasement, a section of the polyethylene encasement was intentionally damaged and four resistance probes were placed at varying distances from the damaged PE location. Figure D-3 shows a schematic of this installation used to determine electrical shielding that was installed at Station 1529+04.

Figure D-4 shows that the probes were performing relatively well from installation in 1997 to May 2003 (2,100 days after installation), at which time Probe 3 failed and the readings on Probes 1, 2, and 4 increased rapidly. The site was excavated in June 2004 and the probes examined. One probe (Probe 3) was sent back to the original manufacturer, whose testing indicates that the probe was not manufactured correctly and not sealed properly; Probe 3 failed due to a manufacturing defect. Probe 3 was removed and two new probes were installed (Probes 5 and 6). A photo of the failed Probe 3 is shown in Figure D-5.

[13] Schiff and McCollum, "Impressed Current Cathodic Protection of Polyethylene-Encased Ductile Iron Pipe."

[14] Graham Bell, "Measurement of Performance of Corrosion Control Mechanisms on DIP."

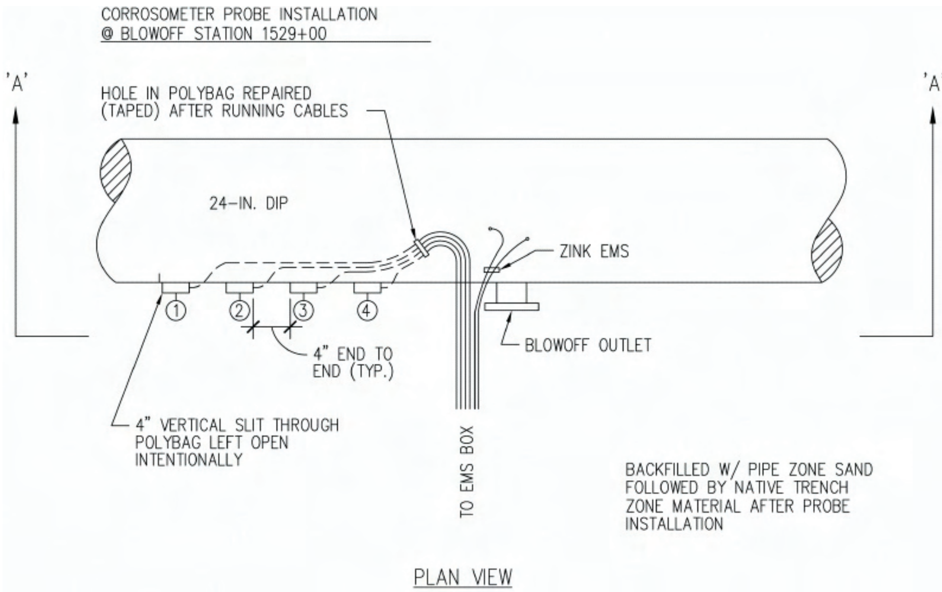


FIGURE D-3 Installation detail of probes at Station 1529+04 Mid-Dakota Rural Water Service Project, South Dakota. SOURCE: Schiff Associates, report to Bartlett & West Engineers, *Revised Summary and Conclusions; Excavation of MDRWS Station 1529+04*, June 30, 2004. Courtesy of Schiff Associates, Claremont, California.

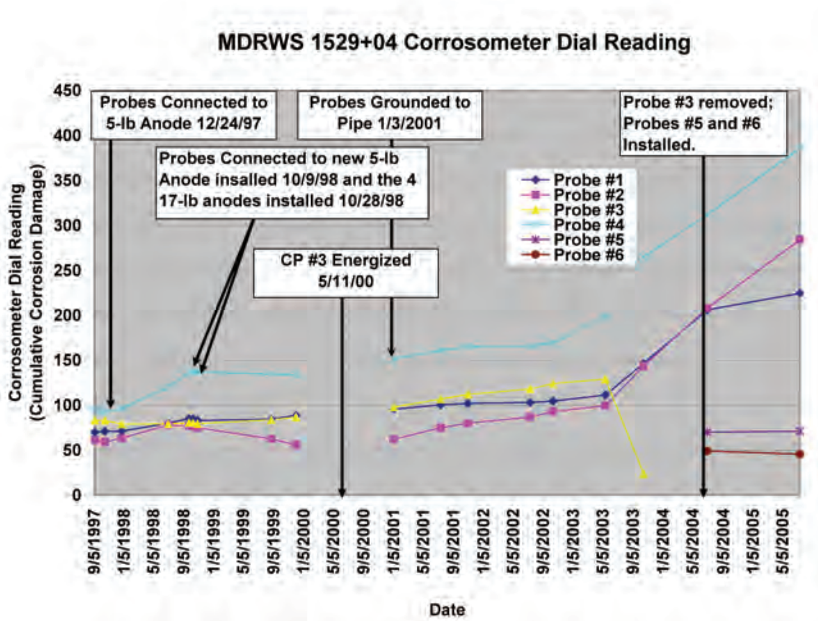


FIGURE D-4 Graph of probe readings at Station 1529+04 Mid-Dakota Rural Water Service (MDRWS) Project. SOURCE: Courtesy of Schiff Associates, Claremont, California.


FIGURE D-5 From Mid-Dakota Rural Water Service Project, South Dakota: failed Probe No. 3, following removal, showing manufacturing defect. SOURCE: Courtesy of Schiff Associates, Claremont, California.

During the excavation, the DIP surface was also inspected for corrosion. No significant corrosion damage was found on the pipe surface. But this probe reliability problem calls into question whether probes of this same type are providing accurate corrosion rates or are suffering from faulty manufacturing techniques.

In an effort to minimize some of the problems seen with high-profile (bulky) and steel-type probes, one manufacturer has worked recently to develop an improved DIP ER probe.[15] An example of this low-profile-type probe for DIP is shown in Figure D-6.

**Laboratory Evaluation of Electrical Resistance Probes** In a paper presented at NACE Corrosion 2007, Bell and colleagues[16] reported on their development and testing of various low-profile probe configurations, including these:

- Bare steel and coated steel,
- DIP with oxide removed (bare),
- DIP with oxide intact, and
- DIP with oxide and asphaltic material.

[15] Schiff Associates Report to Bartlett & West Engineers, *Investigation of High CP Current Requirements South West Pipeline Project near Taylor, ND* (Claremont, Calif., May 25, 2006).

[16] Bell et al., "Development and Application of Ductile Iron Electrical Resistance Probes for Monitoring Underground External Pipeline Corrosion."

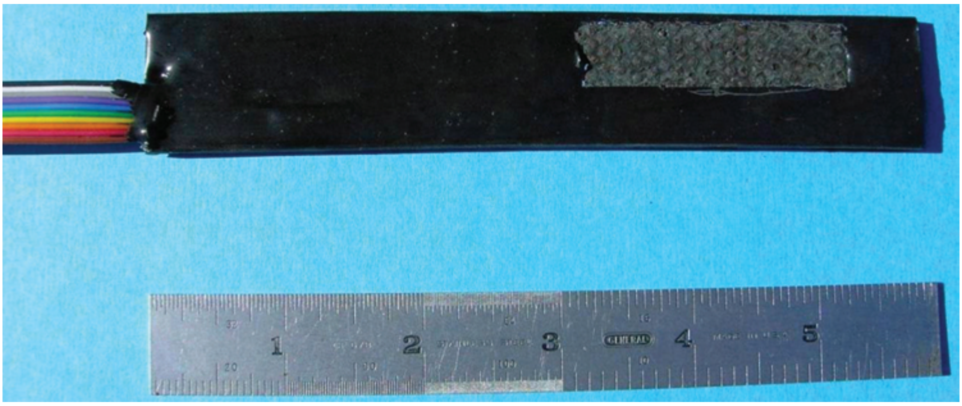

FIGURE D-6 Thin flat ductile iron pipe probe. SOURCE: Courtesy of Schiff Associates, Claremont, California.

Probes were tested under controlled conditions that included the following:

- Simulated sandy soil with 500 parts per million Cl-water,
- Room temperature, and
- Air bubbling.

The conclusions indicate that the low-profile ductile probes showed very good results and are a good surrogate for assessing the corrosion activity and rates on buried DIP.

Field evaluation of the low-profile probes was performed in November 2005. Although the data are limited and relatively short term, the indications are that the corrosion rates for steel in the native-soil backfill material are approximately 2.5 mpy, and the corrosion rates under the PE with and without CP are below the limit of detection for the instrument for the 98-day time period investigated.[17]

**WEB Water Project** Three DIP ER probes were installed on August 5, 2005, at one location on the WEB (Walworth, Edmunds, and Brown) Water Project in South Dakota. These were the new prototypical ductile-iron-type flat probes specifically designed to be used on polyethylene-encased ductile iron pipe. The thin flat profile (Figure D-6) of the probe is designed to help prevent "tenting" of the PE, which may lead to false indications of corrosion on the ER probes and not accurately reflect the actual pipeline condition.[18]

[17] Graham Bell et al., "Development and Application of Ductile Iron Pipe Electrical Resistance Probes for Monitoring Underground External Pipeline Corrosion."

[18] Schiff Associates, Report to WEB Development Association, *Electrical Resistance Probes Installed at Test Station 1459+35* (Claremont, Calif., May 11, 2006)

While all three of these passive monitoring techniques (plastic monitoring pipes, permanent reference electrodes, and resistance probes) show promise, there has been limited use of them in the industry. Additional installations, time, and comparisons to actual pipe corrosion rates need to be completed to verify their accuracy in determining actual corrosion rates and protection levels on buried pipelines. As they only show a snapshot of possible conditions at a specific location, they should be combined with other monitoring methods (above-grade potential surveys, excavations, smart pigging, and so on) to confirm that they accurately reflect the actual conditions for the entire pipeline.

### Active Monitoring and Repair

In addition to the passive monitoring alternatives recommended to avoid a failure in 50 years, several active pipeline monitoring and repair protection measures can be employed on DIP pipelines. These active-monitoring and repair-type measures are currently used or are being considered by the Pipeline and Hazardous Materials Safety Administration of the U.S. Department of Transportation to ensure the safe transportation of gas and oil products. Use of these measures has reduced the rate of transmission pipeline failures by alerting owners and operators of the presence of corrosion pitting, wall thinning, and other incipient failure mechanisms. Repairs can then be scheduled and made before a major rupture occurs.

An article in the *AWWA Journal* in 1999 pointed out that as more-sophisticated leak and pipe corrosion evaluation techniques become available, owners and utilities will be able to perform more evaluations of pipe condition and investigations of why failures are occurring.[19] These techniques include the following:

- *Close-interval surveys using the most-up-to-date techniques for assessing external corrosion and correct functioning of the CP systems.* These surveys should follow the *External Corrosion Direct Assessment* methodology developed by the Gas Technology Institute.[20] The guide rates existing technologies for assessing external corrosion in cased and noncased crossings, pipes shielded by coatings, and segments with stray currents or interference from other pipelines. There is also a phase-sensitive technology under development for pipelines with CP that may reliably detect coating disbondment from aboveground.
- *Providing access for intelligent internal in-line inspection devices.* This technique involves such modifications as including launching and receiving

[19] Jon Makar and Nathalie Chagnon, "Inspecting Systems for Leaks, Pits, and Corrosion," *AWWA Journal* 91(7):26-46 (1999).

[20] T.A. Bubenik and D.D. Mooney, *Development of External Corrosion Direct Assessment Methodology* (Columbus, Ohio: Battelle Memorial Institute, 2002).

arrangements, and valves that will permit the devices to pass. These new "smart pigs" can be used while a pipeline is in operation. They provide highly accurate location and severity information on external or internal corrosion as well as on other damage like dents or gouges. Some devices measure electrical currents traveling in pipelines, thus assessing the status of CP or stray currents from other sources. Magnetic-flux-leakage sensors can also detect coating disbondment.

- *Conducting potential measurements.* Corrosion occurring under loose-bonded intact PE or disbonded bonded dielectric coatings can electrically shield active corrosion from testing techniques for surface pipeline potential made along the ground surface. These techniques will locate areas of damaged polyethylene or coating defects where contact with the soil is imminent, but they have small likelihood of detecting corrosion that may be occurring under intact polyethylene or disbonded coatings. As the Colorado Springs, Colorado, initial in-line inspection data indicated, although only 2 percent of the tested sections had major corrosion damage (with 26 to 50 percent remaining wall life), the pipeline was suffering enough corrosion leaks and damage that it could not be counted on to provide reliable service and therefore was replaced.[21]
- *Use of remote field technology, as described in a 2002 paper by Calgary and Hydroscope.*[22] This type of technology was evaluated initially under American Water Works Association Research Foundation Project No. 90601 for Nondestructive Testing of Water Mains for Physical Integrity.[23] The use of these intelligent in-line inspections (smart pigging) methods, such as employed previously by Colorado Springs and Calgary in their pipeline condition assessments, are a more reliable method of determining actual pipe conditions than are just random digs.[24]

[21] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

[22] W. Hartman, K. Karlson, and R. Brander, "Waterline Restoration Based on Condition Assessment—A Case Study," Distribution and Operations Conference, Nashville, Tenn., September 2002.

[23] R. Jackson, C. Pitt, and R. Skabo, *Nondestructive Testing of Water Mains for Physical Integrity* (Denver, Colo.: AWWA Research Foundation, 1992).

[24] Spickelmire, "Corrosion Control Considerations for Ductile Iron Pipe—A Consultant's Perspective."

# Appendix E

# Acronyms

| | |
|---|---|
| ANSI | American National Standards Institute |
| ASCE | American Society of Civil Engineers |
| AWWA | American Water Works Association |
| | |
| CIP | cast iron pipe |
| CLSM | controlled low-strength material |
| CP | cathodic protection |
| | |
| dc | direct current |
| DDM | Design Decision Model |
| DIP | ductile iron pipe |
| DIPRA | Ductile Iron Pipe Research Association |
| DOT | U.S. Department of Transportation |
| | |
| ER | electrical resistance |
| | |
| IMP | Integrity Management Program |
| | |
| MIC | microbiologically influenced corrosion |
| | |
| NACE | National Association of Corrosion Engineers |
| NBS | National Bureau of Standards (now National Institute of Standards and Technology [NIST]) |

| | |
|---|---|
| OMR&E | operation, maintenance, replacement, and energy |
| OPS | Office of Pipeline Safety |
| PE | polyethylene encasement |
| PHMSA | Pipeline and Hazardous Materials Safety Administration |
| SRB | sulfate-reducing bacteria |
| TM | technical memorandum |
| WEB | Walworth, Edmunds, and Brown |
| WSSC | Washington Suburban Sanitary Commission |
| YDI | yellow-jacketed ductile iron |