A Literature Review of Soil-Side Corrosion Rates for Buried Metallic Piping

1025256

A Literature Review of Soil-Side Corrosion Rates for Buried Metallic Piping

1025256

Technical Update, September 2012

EPRI Project Manager

T. Eckert

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

REFERENCE HEREIN TO ANY SPECIFIC COMMERCIAL PRODUCT, PROCESS, OR SERVICE BY ITS TRADE NAME, TRADEMARK, MANUFACTURER, OR OTHERWISE, DOES NOT NECESSARILY CONSTITUTE OR IMPLY ITS ENDORSEMENT, RECOMMENDATION, OR FAVORING BY EPRI.

THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

Det Norske Veritas (U.S.A.), Inc.

THE TECHNICAL CONTENTS OF THIS DOCUMENT WERE **NOT** PREPARED IN ACCORDANCE WITH THE EPRI NUCLEAR QUALITY ASSURANCE PROGRAM MANUAL THAT FULFILLS THE REQUIREMENTS OF 10 CFR 50, APPENDIX B AND 10 CFR PART 21, ANSI N45.2-1977 AND/OR THE INTENT OF ISO-9001 (1994). USE OF THE CONTENTS OF THIS DOCUMENT IN NUCLEAR SAFETY OR NUCLEAR QUALITY APPLICATIONS REQUIRES ADDITIONAL ACTIONS BY USER PURSUANT TO THEIR INTERNAL PROCEDURES.

This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

Electric Power Research Institute, EPRI, and TOGETHER…SHAPING THE FUTURE OF ELECTRICITY are registered service marks of the Electric Power Research Institute, Inc.

Copyright © 2012 Electric Power Research Institute, Inc. All rights reserved.

ACKNOWLEDGMENTS

The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

Det Norske Veritas (U.S.A.), Inc.
Pipeline & Facility Risk Management
5777 Frantz Road
Dublin, OH 43017

Principal Investigator
S. Daily

This report describes research sponsored by EPRI.

This publication is a corporate document that should be cited in the literature in the following manner:

A Literature Review of Soil-Side Corrosion Rates for Buried Metallic Piping. EPRI, Palo Alto, CA: 2012. 1025256.

ABSTRACT

The external corrosion growth rate of a buried pipe is an essential variable needed in a fitness-for-service evaluation for calculation of the remaining life of the pipe. However, corrosion rates are difficult to estimate or measure, since the actual conditions are not known for all locations where corrosion is occurring. Furthermore, the process of determining appropriate rates of corrosion at nuclear power plants poses unique challenges because of the many variables including pipe embedment materials, dissimilar metals, coating quality, and level of cathodic protection. This technical update from the Electric Power Research Institute (EPRI) was developed to support members faced with these challenges, by providing relevant background information, technical perspectives, and guidance.

There is currently no industry consensus document that summarizes and recommends the usage of specific corrosion rates for the variety of materials and conditions that exist in conjunction with buried piping systems at nuclear power plants. To help fill this gap, EPRI initiated a project to review existing industry corrosion rate data, judge its credibility and applicability, and summarize the results with the intent of providing guidance regarding corrosion rates as a function of degradation types, materials, and the environment. The scope is limited to soil-side corrosion (degradation of the outside diameter of the pipe), and the primary focus is on carbon steel piping, although relevant information on other materials was considered. Researchers consulted more than 180 publications relating to corrosion of buried piping in soil environments, and the report compiles observations and insights drawn from this literature survey and review of the data. In addition, the report presents a discussion regarding the impact that electrical grounding has on the corrosion rate of buried metallic piping and tanks. Also contained in the report is a discussion regarding soil corrosivity and the effect that cathodic polarization has on corrosion rate.

Keywords

Buried pipe
Cathodic protection
Corrosion rate
Fitness-for-service
Linear polarization resistance
Soil side

CONTENTS

_1_ INTRODUCTION 1-1

Conversion Factors 1-1

_2_ BACKGROUND 2-1

_3_ OBJECTIVES 3-1

_4_ TECHNICAL APPROACH 4-1

_5_ RESULTS 5-1

National Bureau of Standards Study 5-1

NACE Default Corrosion Rate 5-6

LPR Results from DNV Direct Examination Projects 5-6

Direct Examination Laboratory Test Methods for Soil Samples 5-7

Statistical Analysis of DNV Direct Examination Data 5-8

Corrosion of Steel in Drilled Shafts 5-10

_6_ DISCUSSION 6-1

Impact of Electrical Grounding on Corrosion of Carbon Steel 6-1

General 6-1

Copper Grounding 6-1

Galvanic Corrosion of Carbon Steel Pipe 6-2

Soil 6-4

General 6-4

Soil Classification 6-5

Soil Parameters Affecting Corrosion Rate 6-6

Cathodic Polarization and Its Effect on Corrosion Rate 6-10

General 6-10

Anode and Cathode Control 6-11

External Coatings 6-13

Methodology for Determining External Corrosion Growth Rate 6-14

_7_ CONCLUSIONS 7-1

_8_ RECOMMENDATIONS 8-1

_9_ REFERENCES 9-1

_A_ CORROSION REFERENCES REVIEWED A-1

_B_ STATISTICAL ANALYSIS AND MODELING OF DET NORSKE VERITAS (DNV) DIRECT EXAMINATION DATA B-1

Introduction B-1

Clay Soil B-1

All Soil Data B-7

Sand Data B-10

_C_ CC TECHNOLOGIES GALVANIC CORROSION STUDY: CURRENT DENSITY PLOTS C-1

LIST OF FIGURES

Figure 5-1 Map Showing 44 Burial Sites and 8 Major Soil Groups Identified in the NBS Study 5-2
Figure 5-2 Maximum Pitting Rate as a Function of Soil Resistivity (All Data) 5-5
Figure 5-3 Histogram of LPR Corrosion Rate Frequency from DNV Direct Examination Soil Samples (2005 to Present) 5-9
Figure 5-4 Predicted LPR vs. Observed LPR for Sand Soil Type 5-10
Figure 6-1 Soil Texture Triangle Showing the USDA Classification System Based on Grain Size 6-6
Figure 6-2 Relationship of Variables Affecting the Rate of Corrosion in Soil 6-7
Figure 6-3 Evans Diagram (E vs. Log I) for Metal M 6-11
Figure 6-4 Polarization Schematic Illustrating the Effect of Corrosion Rate in a Mixed Metal Network 6-12
Figure B-1 Predicted LPR vs. Observed LPR for Clay Soil Type B-4
Figure B-2 Predicted Clay LPR vs. Observed LPR with Two Potential Outliers Dropped B-7
Figure B-3 Predicted LPR vs. Observed LPR for All Data B-10
Figure B-4 Predicted LPR vs. Observed LPR for Sand Soil Type B-12
Figure C-1 Galvanic Current Densities vs. Time (Hours) for Soil Sample 2-3 (Resistivity: 160 ohm-cm) C-1
Figure C-2 Galvanic Current Densities vs. Time (Hours) for Soil Sample 2-6 (Resistivity: 190 ohm-cm) C-2
Figure C-3 Galvanic Current Densities vs. Time (Hours) for Soil Sample 2-8 (Resistivity: 4,000 ohm-cm) C-2

LIST OF TABLES

Table 5-1 NBS Field Test Results on Open-Hearth Steel Tested for 12 Years at 44 Locations 5-3
Table 5-2 Corrosion Rates for Steel in Soil According to Soil Type 5-4
Table 5-3 Effects of Environmental Factors on Corrosion of Steel in Soils 5-4
Table 5-4 Soil Analysis Test Methods 5-7
Table 5-5 Statistical Summary of DNV Direct Examination Corrosion Rate Data (2005 to Present)... 5-8
Table 5-6 Free and Bonded Corrosion Rates for the Steel in Drilled Shafts Experimental Study 5-11
Table 6-1 Numerical Results of Galvanic Current Measurements 6-4
Table 6-2 Particle Sizes in Soil Texture 6-5
Table 6-3 Effect of Moisture Content on Soil Resistivity 6-8
Table 6-4 Soil pH Classification 6-8
Table 6-5 Soil and Water Resistivity Classification 6-9
Table 6-6 Effect of Chloride Concentration on Degree of Corrosivity 6-10
Table 6-7 Effect of Sulfate Concentration on Degree of Corrosivity 6-10
Table B-1 Direct Examination Data by Soil Type B-1
Table B-2 Clay LPR Correlation Coefficient Values B-2
Table B-3 Clay Soil Stepwise Regression Results B-2
Table B-4 Clay Soil General Regression Results B-3
Table B-5 Clay LPR_2 Correlation Coefficient Values B-4
Table B-6 Clay Soil LPR_2 Stepwise Regression Results B-5
Table B-7 Clay Soil LPR_2 General Regression Results..B-6
Table B-8 All Soil Data LPR Correlation Coefficient Values B-7
Table B-9 All Soil Data Stepwise Regression Results B-8
Table B-10 All Soil Data General Regression Results B-9
Table B-11 Sand Data LPR Correlation Coefficient Values B-10
Table B-12 Sand Soil Stepwise Regression Results B-11
Table B-13 Sand Soil General Regression Results B-11

1
INTRODUCTION

This technical update presents information gained from a literature review of soil-side corrosion rates for buried metallic piping, performed for the Electric Power Research Institute (EPRI) by Det Norske Veritas (U.S.A.), Inc. (DNV). The literature review was a primary element of an EPRI-initiated study that involved a survey of existing industry corrosion rate data, judgment regarding the credibility and applicability of these data, and a summary of the results with guidance regarding corrosion rates as a function of degradation types, materials, and the environment.

In addition, a meeting was held on June 23, 2011, at the DNV offices in Dublin, Ohio, with representatives from Atomic Energy Canada, Ltd. (AECL) and EPRI to review the scope of work for ongoing research that both AECL and DNV are performing on the subject, with the intent of filling identified gaps in the buried pipe corrosion rate database.

This report provides guidance for nuclear power plant owners and others performing fitness-for-service (FFS) evaluations of degraded buried and underground piping and tanks, with regard to the appropriate future corrosion rate in terms of mm/year and mils/year (mpy). The report also provides a discussion regarding the impact that electrical grounding has on the corrosion rate of the buried metallic piping and tanks. A discussion regarding soil corrosivity and the effect that cathodic polarization has on corrosion rate is also included.

This project considers corrosion rate data as they relate to the outer diameter (OD) of buried piping. Although many different materials are utilized for buried piping at nuclear power plants, the study focuses on corrosion rate data for carbon steel pipe.

A list of corrosion publications and reports that were reviewed in this study is included in Appendix A of this report. Appendix B provides a statistical analysis and modeling of DNV direct examination data, and Appendix C includes plots of galvanic corrosion current density from a previous corrosion study.

Conversion Factors

Several useful conversion factors for corrosion rate and current density are presented below.

For corrosion rate, the most commonly used expression in the United States is the mpy (mils per year) unit. One mil is equivalent to one thousandth of an inch.

To convert corrosion rate from mpy to the equivalent in metric units:

1 mpy = 0.0254 mm/yr = 25.4 microns/yr

1 mm/yr = 39.37 mpy = 1,000 microns/yr

To calculate the corrosion rate from metal loss:

$$\text{mpy} = 534 \times (W/DAT)$$

$$\text{mm/yr} = 87.6 \times (W/DAT)$$

where:

W = weight loss in milligrams

D = metal density in g/cm^3

A = area of sample in cm^2 (for mm/year) or in^2 (for mpy)

T = time of exposure of the metal sample in hours

To convert current density from mA/ft^2 to the equivalent in metric units:

$$1\ \text{mA/ft}^2 = 1.08\ \mu\text{A/cm}^2 = 10.8\ \text{mA/m}^2$$

For iron, corrosion rate may be expressed in current density (per Faraday's Law):

$$1\ \text{mpy} = 2.17\ \mu\text{A/cm}^2$$

2

BACKGROUND

Buried pipes at nuclear power plants present many challenges. The pipes are not readily accessible for inspection and leak detection and are subject to degradation mechanisms from the outside diameter (OD) or soil side, as well as the inside diameter (ID) or fluid side. The external environment of buried piping has chemical, geotechnical, and civil/structural considerations that can be unique to each installation and/or site. Pipe embedment materials can also vary in terms of their nature and the degree of corrosivity.

Fitness-for-service (FFS) evaluations of buried and underground piping and tanks that are found to be degraded require the use of future corrosion rate (rate of metal loss) in order to predict the remaining component lifetime and/or the time until the next inspection. Such a requirement is identified in EPRI report 1016456, *Recommendations for an Effective Program to Control the Degradation of Buried Pipe*. Other relevant publications that reference FFS evaluations include EPRI report 1021175, *Recommendations for an Effective Program to Control the Degradation of Buried and Underground Piping (1016456, Rev. 1),* and the upcoming ASME Code Case N-806, “Evaluation of Metal Loss in Class 2 and 3 Metallic Piping Buried in a Back-Filled Trench, Section XI, Division 1” (record No. 10-915). FFS assessment requires a baseline design analysis of the buried piping system, in accordance with the original design and construction code. The second step of the FFS assessment is to assemble the direct inspection results, and if needed, determine the degradation method (such as wall thinning, pitting, cracking, mechanical damage, occlusions, etc.) and estimate the future corrosion allowance (FCA), which is the projected degradation until the next inspection or until repair.

The external corrosion growth rate of a buried pipe is an essential variable needed for calculation of the remaining life of a pipeline. Actual corrosion rates are difficult to estimate or measure, since the actual conditions at all locations where corrosion is occurring are not known. Actual growth rates used in the remaining life calculation should be based on actual corrosion rate data applicable to the buried pipe under investigation. For example, if direct measurements of pipeline wall loss over a known time period are available from historical records for the pipeline being investigated, the actual growth rate can be calculated, although more than two data points are required due to the non-linearity of corrosion. Often, however, pipe wall loss data from historical records are not available or are incomplete. Therefore, when other data are not available, default corrosion rates based on statistically valid methods have been used. For instance, ANSI/NACE SP0502-2010, “Pipeline External Corrosion Direct Assessment Methodology” [1], provides a default pitting rate of 0.4 mm/year (16 mpy) for determining re-inspection intervals on pipelines when other data are not available. This rate represents the upper 80% confidence level of maximum pitting rates for long-term (up to 17 year duration) underground corrosion tests of bare steel pipe coupons without cathodic protection (CP) in a variety of soils, including native and non-native backfill.

There is currently no industry consensus document that summarizes and recommends the usage of specific corrosion rates for the variety of materials and OD conditions that exist in conjunction with buried piping systems at nuclear power plants. Furthermore, the nuclear industry presently does not follow NACE-recommended practice or standard practice for corrosion assessment or cathodic protection. Corrosion of buried piping at nuclear power plants is unique because of the many variables including pipe embedment materials, dissimilar metals, coating quality, and level of cathodic protection. For these reasons, a project has been initiated by EPRI to review existing industry corrosion rate data, judge its credibility and applicability, and summarize the results with the intent of providing guidance regarding corrosion rates as a function of degradation types, materials, and the environment.

3
OBJECTIVES

The objectives of this project are to:

- Provide to plant owners, and others performing fitness-for-service (FFS) evaluations of degraded buried and underground piping and tanks, guidance regarding the appropriate future corrosion rates in terms of mils/year and mm/year.
- Where appropriate, provide corrosion rates as a function of the type of degradation (e.g., pitting, crevice corrosion, under-deposit corrosion, general corrosion, cracking, galvanic corrosion, etc.) as could be determined during an inspection of the component.
- Where appropriate, provide corrosion rates for OD degradation (rate of wall loss) as a function of the material, degradation mechanism identified by the inspection, and local environment. (The work scope of the project is focused on OD corrosion and not ID corrosion.)
- As materials to be included, consider those metals most commonly used for buried and underground piping and tanks, including carbon steel, cast iron, 304 stainless steel, 316 stainless steel, copper, 90-10 copper nickel, 70-30 copper nickel, and super stainless alloys (e.g., AL6XN). However, the primary focus for this study is the assessment of corrosion rates for carbon steel pipe, although corrosion rates for other materials are also addressed. Where appropriate, base material and weldments are considered.
- Where appropriate, provide corrosion rates for piping and tanks that are cathodically protected as well as for those that are not cathodically protected.
- Where appropriate, provide OD rates as either a function of the soil type, or more preferably, as a function of key soil parameters (e.g., resistivity, chlorides, moisture content, etc.).
- Where appropriate, provide OD rates that reflect the presence of a coating and the condition of such coating.
- As a separate but related objective, identify high-priority areas where additional research is needed to develop missing data.
- Identify, through literature review, the effect that copper grounding and steel reinforcement in concrete have on the corrosion rate of the buried metallic piping and tanks.
- As an additional objective, collaborate with AECL, which is undertaking similar research, with the intent of filling gaps that are identified in the buried pipe corrosion rate database.

4

TECHNICAL APPROACH

The first step in the corrosion rate guidance study was to compile documents and references that relate to corrosion of buried piping in soil environments. Over 180 reports and publications were reviewed with regard to corrosion and corrosion rate data. A list of these references is included in Appendix A of this report.

The most comprehensive source of corrosion data can be found in the National Bureau of Standards (NBS) Circulars C401 (*Stray Current Electrolysis*) [2], C450 (*Underground Corrosion,* by T. J. Logan) [3], and C578 (*Underground Corrosion,* by Melvin Romanoff) [4]. Other publications of significance include Pipeline Research Council International (PRCI) Report PR-208-163 (*Field Testing the Criteria for Cathodic Protection of Buried Pipelines,* by Tom Barlo) [5] and *Uhlig's Corrosion Handbook*, 2nd Edition, by R. Winston Revie [6]. Each of these publications attempts to quantify the range and average corrosion rates of buried piping based on soil type and material exposed. However, the inherent problem with using such rates is that a degree of certainty is implied in an area of highly uncertain science.

Historical corrosion data can prove very beneficial in establishing specific corrosion growth rates for a given structure. The difficulty arises when data and the conditions under which they were obtained are misapplied; therefore, every attempt should be made to ensure reliability of data and to implement a conservative approach. Typical historical data include corrosion rates from buried coupons on a specific structure or a pipeline with similar characteristics (age, grade, coating, and cathodic protection) and environments.

Electric resistance (ER) probes allow direct measurement of the local general corrosion rate. ER probes that are commercially available typically use a thin strip or tube of steel (other materials may be selected) for the coupon that is electrically connected to the pipeline or structure. A bridge instrument is used to measure the resistance of the coupon over time. As the coupon corrodes, its thickness decreases and its resistance increases, allowing the corrosion rate to be calculated from the resistance change with time and the coupon parameters. These types of coupons, however, are not very sensitive to pitting corrosion. The linear polarization resistance (LPR) technique measures corrosion rate continuously in real time, from a probe permanently installed in an electrolyte. The LPR method is most commonly used to measure corrosion rate in corrosive fluids, although technology now exists that allows measurement of corrosion rate for metals in soils. This electrochemical measurement is based on applying a small potential shift to a corroding metal electrode, the resultant current being proportional to the corrosion rate. Correction for solution resistance is important. Linear polarization instrumentation converts the current measured to corrosion rate readings in mils per year (mpy).

Corrosion coupons provide information not only on metal loss and corrosion rate, but also on the distribution and forms of corrosion. Technical standards for corrosion testing include ASTM G1 for metal loss calculation, ASTM G46 for analysis of localized corrosion, and NACE RP-0775 for preparation, analysis, and interpretation of corrosion coupons. Data from corrosion coupons and other monitoring instruments seldom correlate exactly with the rate of corrosion observed in the field. Factors that can contribute to the lack of correlation include coupon location and flow characteristics when used for internal corrosion monitoring. Corrosion coupons still represent the most reliable method for determining corrosion rates as well as the forms of corrosion, such as pitting. Coupon test stations can be used to determine the effectiveness of cathodic protection and the corrosion rate under cathodic protection. Coupons provide corrosion rates only at the time of measurement, and therefore trending is required to establish meaningful corrosion rates as a function of time.

Det Norske Veritas (DNV) has considerable experience in External Corrosion Direct Assessment (ECDA) methodology. ECDA is an integrity assessment process applied to buried pipelines. In all of the ECDA projects DNV has undertaken (which include in excess of 1,000 miles of pipe, across North America), soil samples were collected at every site selected for direct examination. All of these soil samples were analyzed in terms of their physical and chemical properties and corrosion rate using LPR techniques. In the present study, DNV has tabulated the results of direct examination laboratory data from 2005 to present and performed statistical analyses to investigate correlations between chemistry, resistivity, physical properties, and corrosion rates. Over 350 data sets were analyzed, and linear regression was performed to produce corrosion rate models using variables such as soluble cations (Ca^{2+}, Mg^{2+}), soluble anions (NO_2^-, NO_3^-, Cl^-, SO_4^{2-}, S^{2-}, CO_3^{2-}, HCO_3^-), total acidity, total alkalinity, moisture content, resistivity, and pH.

5
RESULTS

National Bureau of Standards Study

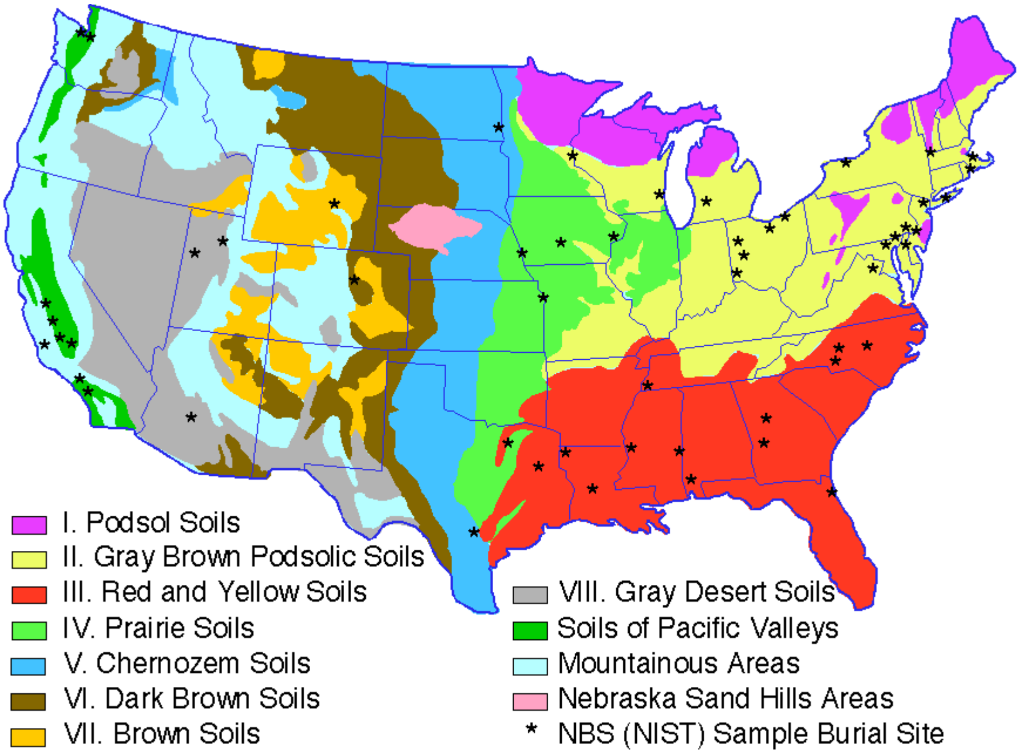
As mentioned in the preceding section, the most comprehensive source of corrosion rate data is found in the National Bureau of Standards (NBS) Circulars C401 (*Stray Current Electrolysis*, published in 1933) [2]; C450 (*Underground Corrosion* by K. H. Logan, published in 1945) [3]; and C579 (*Underground Corrosion* by Melvin Romanoff, published in 1957) [4]. The first two of these publications are now out of print. However, the third, by Romanoff, has been reprinted by the National Association of Corrosion Engineers (NACE International) in its entirety. The publication represents a summary of over 45 years of industrial investigations and field experiences related to the Bureau's underground corrosion studies.

More recently, a National Institute of Standards and Technology (NIST) study was initiated to re-examine NBS data using a variety of commercially available software packages for statistical analysis.[1] The results of this study are presented in NISTIR report 7415, *Analysis of Pipeline Steel Corrosion Data*, by R. Ricker, dated May 2, 2007 [7]. This study analyzed NBS corrosion rate data compiled between 1922 and 1940 and considered their relevance to pipeline management. The objectives of this study were to determine (1) if coatings would be required to prevent corrosion, and (2) if soil properties could be used to predict corrosion and determine when coatings should be used. While this study determined that coatings would be required for some soils, it found that the results of the NBS studies were so divergent that even generalities based on the data must be drawn with care. The investigators concluded that because there were so many diverse factors that influenced corrosion rates, interpretation of the results was extremely difficult and only approximations could be attempted.

For the NBS C579 study, eight different types of samples were buried with six sets of duplicates at 44 sites throughout the United States with various soil compositions as shown in Figure 5-1. The sample materials consisted of open-earth iron pipe, hand-puddled wrought iron pipe, Bessemer steel pipe, and copper-bearing steel pipe. The alloys and microstructures of these samples deviate significantly from those available today, primarily due to the dramatic improvements in the processing of steel that have reduced slag inclusions and mill scale. In addition, the NBS study made no special effort to clean the samples or remove the mill scale, which provided further inconsistency. Mill scale is typically more noble than the iron in the metal, and the presence of these phases will stimulate cathodic activity, enabling higher corrosion rates.

---

[1] In 1988 the National Bureau of Standards (NBS) became the National Institute of Standards and Technology (NIST).



(Source: NISTIR report 7415, R. Ricker, 2007)

Figure 5-1
Map Showing 44 Burial Sites and 8 Major Soil Groups Identified in the NBS Study

The results of the NBS tests on 6-inch-long, 3-inch-diameter open-hearth steel pipes over approximately 12 years (from 1922) at 44 locations are summarized in Table 5-1. Overall, corrosion rates ranged from 0.003 to 0.063 mm/year (0.1 to 2.5 mpy), with the average being 0.02 mm/year (0.8 mpy). The inherent problem with using such rates is that a degree of certainty is implied in an area of uncertainty. As an example, corrosion rates in well-aerated sandy soil may be reported as < 0.0254 mm/yr (1 mpy), but when 1,000 ppm chlorides are introduced in the same soil, corrosion rates may be an order of magnitude higher.

Table 5-1
NBS Field Test Results on Open-Hearth Steel Tested for 12 Years at 44 Locations

Overall Corrosion Rate			
	mm/yr	*mpy*	
Maximum	0.063	2.480	Merced silt loam, Button Willow, CA
Minimum	0.003	0.118	Everett gravelly sandy loam, Seattle, WA
Average	0.020	0.787	44 locations
Pitting Rate			
	mm/yr	*mpy*	
Maximum	>0.450*	>17.716*	Muck, New Orleans, LA
Minimum	0.033	1.299	Everett gravelly sandy loam, Seattle, WA
Average	0.143	5.630	44 locations
* Perforated			

(Source: Uhlig's Corrosion Handbook, R. Winston Revie, 2nd Edition, 2000)

The data contained in Tables 5-2 and 5-3 were based in large part on the referenced NBS studies, and they represent the inherent variability in "assigning" corrosion rates and the fact that no single factor controls the overall corrosion rate. Table 5-2 shows the variability of corrosion rate for steel based on soil type. On the basis of the data contained in Table 5-3, it can be concluded that general corrosion rates average between 0.013 and 0.064 mm/yr (0.5 and 2.5 mpy), while pitting rates average between 0.102 and 0.279 mm/yr (4 and 11 mpy). All of these data are based upon exposure conditions and linear extrapolations (measured depth and weight loss were divided by exposure time), which may also introduce errors. Furthermore, a linear extrapolation neglects the effects of seasonal variations and the kinetics of electrochemical corrosion reactions. It is generally accepted that corrosion rates decrease with time; therefore, one may expect a higher initial rate for an unspecified time followed by a decrease in corrosion rate. It should also be noted that the manner in which samples were retrieved for analysis in the NBS studies gives rise to concern that the retrieval of adjacent specimens may have introduced oxygen to the undisturbed specimen, a factor that could likely cause an increase in corrosion rates. It is also worthwhile to note, that upon examination and analysis, specimens were categorized into "general corrosion" and "pitting corrosion." Pitting corrosion was assigned to localized sites within a specimen where there was an obvious greater concentration of wall loss. Since carbon steel is not a material that is inherently susceptible to the classical definition of "pitting corrosion," the use of pitting rates from such studies is questionable.

Table 5-2
Corrosion Rates for Steel in Soil According to Soil Type

Soil Type	Overall Corrosion Rate (mm/yr)*	Overall Corrosion Rate (mpy)*	Number of Data Points
USDA “clay”	0.508	20	74
USCS “CH” or “OH”	0.762	30	30
USDA “silt loam”	0.229	9	39
USDA “sandy loam”	0.279	11	24
USDA “clay loam”	0.330	13	8
USDA “loam”	0.127	5	39
* Based on 80% confidence level of published corrosion test results.			

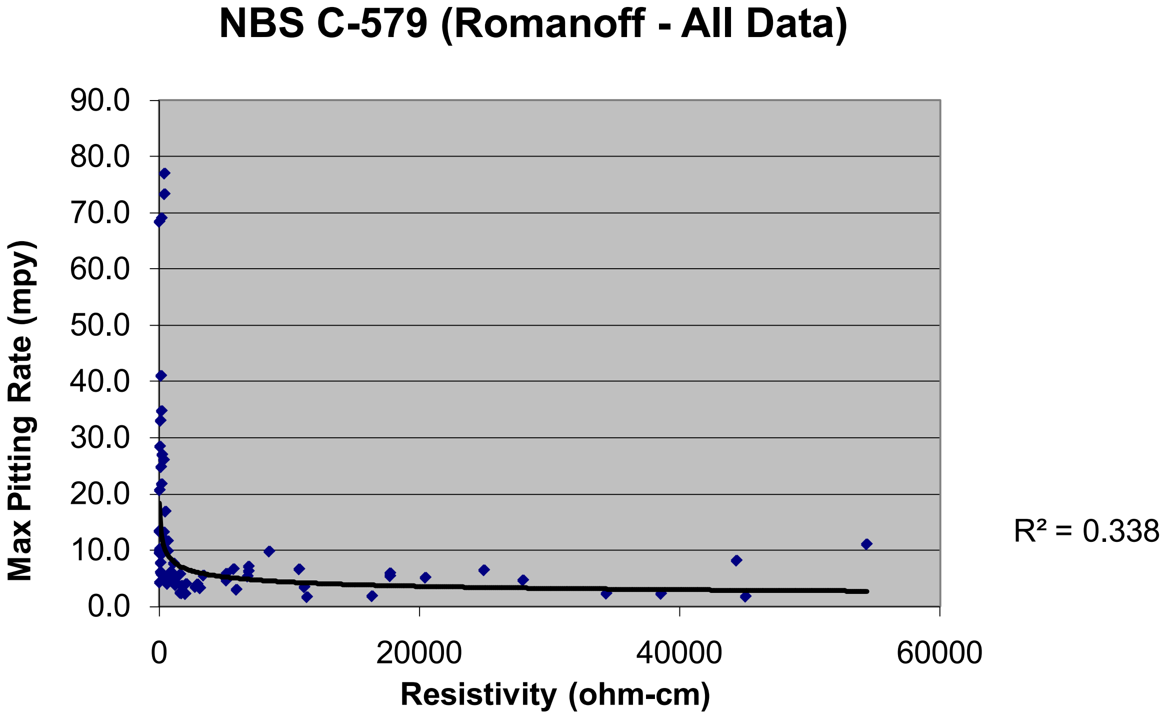
(Source: Uhlig’s Corrosion Handbook, R. Winston Revie, 2nd Edition, 2000)

Table 5-3
Effects of Environmental Factors on Corrosion of Steel in Soils

	Overall Corrosion Rate (mm/yr)			*Maximum Pitting Rate (mm/yr)*		
Environmental Factor	**Maximum**	**Minimum**	**Average**	**Maximum**	**Minimum**	**Average**
Resistivity (Ω-cm)						
<1000	0.063	0.018	0.033	0.310	0.110	0.200
1000-5000	0.058	0.006	0.017	>0.450*	0.050	0.140
5000-12000	0.033	0.005	0.018	0.230	0.060	0.140
>12000	0.036	0.003	0.014	0.026	0.030	0.110
Drainage						
Very Poor	0.058	0.038	0.046	>0.450*	0.160	0.280
Poor	0.037	0.010	0.024	0.230	0.050	0.140
Fair	0.063	0.018	0.022	0.310	0.080	0.160
Good	0.022	0.003	0.010	0.180	0.030	0.110
Porosity (air pore space %)						
<5	0.033	0.010	0.021	0.200	0.050	0.130
5-10	0.063	0.009	0.024	0.310	0.100	0.170
10-20	0.037	0.006	0.017	0.260	0.050	0.150
20-30	0.058	0.012	0.025	>0.450*	0.100	0.200
>30	0.038	0.004	0.013	0.230	0.030	0.090
* Perforated						

(Source: Uhlig’s Corrosion Handbook, R. Winston Revie, 2nd Edition, 2000)

Figure 5-2 provides a summary of all soil resistivity data as a function of corrosion rate from NBS Circular C-579 (Romanoff). As expected, the highest corrosion rates found are at sites with the lowest soil resistivity.



(Source: NBS C-579, Underground Corrosion, M. Romanoff)

Figure 5-2
Maximum Pitting Rate as a Function of Soil Resistivity (All Data)

The concept of "pitting factor" was introduced during the interpretation of the NBS data and was intended to establish the relative propensity of a material to experience localized corrosion. It is defined as the ratio of the average penetration rate to the average overall general corrosion rate. This concept is often misapplied when considering corrosion rates in soils. Romanoff concluded that the rate at which pits grow in soil under a given set of conditions tends to decrease with time [4]. The predominant mechanism for the development of localized corrosion is deferential aeration, a mechanism that would have been much more prevalent in the uncoated specimens used in the NBS studies than on coated pipelines (barring mechanisms associated with disbonded coating).

Establishing a reasonably conservative estimate of corrosion rate for buried piping in nuclear power plants requires consideration of unique circumstances. Such conditions may include evidence of microbiologically influenced corrosion (MIC) and corrosion caused by stray direct current. MIC in soils has been documented to occur at rates approaching 3.2 mm/yr (150 mpy) [8]. When active MIC has been confirmed during direct examination of a buried pipe and it has been determined to be the root cause of the investigated anomaly, the use of such rates will clearly demonstrate the need for alternative remedial measures, such as using a more conservative criterion for cathodic protection.[2]

The effects of stray direct current (DC) on established corrosion rates cannot be quantified easily because of the significance of the direct current and resulting dissolution of metal. To cause corrosion on pipelines, stray current must flow from an outside source onto the pipeline (the pick-up area) and then flow along the pipeline to some other area or areas where the current leaves the pipe (discharge area) to re-enter the earth, resulting in corrosion. Corrosion rates on piping from stray current sources can be extraordinarily large compared to corrosion rates from other forms of corrosion. One of the most significant and common sources of stray direct current on pipelines in urban areas is the DC-powered transit system. At nuclear power plants, sources of stray DC current may include foreign (isolated) impressed current cathodic protection systems and DC welding operations.

NACE Default Corrosion Rate

As stated previously, when pipe wall loss data from historical records are not available or are incomplete, default corrosion rates based on statistically valid methods have been used. ANSI/NACE SP0502-2010, “Pipeline External Corrosion Direct Assessment Methodology,” provides a default pitting rate of 0.4 mm/year (16 mpy) for determining re-inspection intervals on pipelines when other data are not available [1]. The default corrosion rate was derived from 348 sets of corrosion rate data taken from NBS Circulars C-450 (Logan) [3] and C-579 (Romanoff) [4]; PRCI Report PR-208-163 (Barlo) [5]; and ASTM documents authored by Palmer [9] and Camitz and Vinka [10]. The maximum rate that was included in the analysis was 2.0 mm/year (77 mpy) for steel pipe in cinders. The average rate was calculated to be 0.2 mm/year (7.9 mpy), and the standard deviation was 9.1 [11]. The 0.4 mm/year (16 mpy) default rate represents the upper 80% confidence level of maximum pitting rates for long-term (up to 17 year duration) underground corrosion tests of bare (electrically isolated) steel pipe coupons without cathodic protection (CP) in a variety of soils, including native and non-native backfill.

LPR Results from DNV Direct Examination Projects

As part of this study, Det Norske Veritas (DNV) summarized and analyzed the results of linear polarization resistance (LPR) corrosion rate measurements that were performed on soil samples obtained from pipeline excavation sites using a cleaned (corrosion-free) carbon steel coupon and the results compared with laboratory soil chemistry data obtained from the same soil sample. The direct examination work was typically performed in accordance with step 3 of the External Corrosion Direction Assessment (ECDA) process, which included measurement of wall loss where appropriate [1]. The chemical and physical properties of the soil were analyzed in the DNV laboratory for approximately 352 soil samples taken from various pipeline direct examination sites (dig sites) at various locations throughout the United States. The period of

---

[2] When MIC is confirmed to be the root cause of a corrosion anomaly, a polarized -950 mV (CSE) structure-to-soil potential is often used as the criterion for cathodic protection.

assessment ranged from 2005 to present. The laboratory data included measurement of soluble cations (Ca^{2+}, Mg^{2+}), soluble anions (NO_2^-, NO_3^-, Cl^-, SO_4^{2-}, S^{2-}, CO_3^{2-}, HCO_3^-), total acidity, total alkalinity, moisture content, pH, structure-to-soil potential, and corrosion rate using the LPR method. The lines that were analyzed consisted of oil and gas transmission pipelines. These lines typically had some level of cathodic protection and were coated with either coal tar enamel, coal tar epoxy, fusion bonded epoxy (FBE), or polyethylene tape wrap.

Although corrosion on coated pipelines at flaws in the coating has pit-like corrosion morphology, the mechanism is typically more of a general corrosion mechanism at concentrated flaws. Classical pitting corrosion (with its attendant unpredictability of pitting rates) is not the predominant mechanism for corrosion of carbon steel pipelines. It is thus reasonable to conclude that corrosion rates using LPR measurements obtained in the soil environment around the pipe or on laboratory specimens using soil from around the pipe can yield meaningful results from which to characterize corrosion growth rates. Based on these data, a statistical analysis was performed to compare the LPR corrosion rate from soil samples obtained at pipeline direct examination sites with variables such as soil type, resistivity, pH, moisture content, total alkalinity and total acidity, and various soluble ions such as NO_2^-, SO_4^{2-}, S^{2-}, and Ca^{2+}.

Direct Examination Laboratory Test Methods for Soil Samples

The test methods used for each parameter are given in Table 5-4.

Table 5-4
Soil Analysis Test Methods

Test Parameter	Methodology
Soluble Cations: Ca^{2+} and Mg^{2+}	ASTM D511, titration
Soluble Anions:	
NO_2^-	Standard Method 4500B, colorimetric
NO_3^-	EPA 353.2, colorimetric
Cl^-	EPA 325.1, colorimetric
SO_4^{2-}	ASTM D516, colorimetric
S^{2-}	EPA 376.2, colorimetric
CO_3^{2-}	Standard Method 2320 B, titration
HCO_3^-	Standard Method 2320 B, titration
pH	ASTM G51
Total Alkalinity	Standard Method 2320 B, titration
Total Acidity	EPA 305.1, titration
Moisture Content	AASHTO T265, weight loss technique
Resistivity	ASTM G57 (soil box method)
Corrosivity of Soil	LPR measurement (see explanation and procedure given below)

(Source: DNV Materials and Corrosion Technology Center)

The LPR technique involves the application of a small (± 10-20 mV versus Ecorr) DC polarization at a specified rate. The polarization resistance is defined as the slope at Ecorr of the resulting linear plot of voltage vs. current density:

$$R_p = (\Delta E/\Delta I)_{Ecorr}$$

The polarization resistance can be further related to the rate of corrosion of the sensing probe via the Stern-Geary equation:

$$i_{corr} = (1/R_p)\beta_a\beta_c \;/\; 2.303\ (\beta_a + \beta_c)$$

where i_{corr} is the corrosion current density, and β_a and β_c are Tafel constants (slopes of the linear portions of anodic and cathodic polarization curves, respectively, on an E versus *log* I plot). The corrosion rate can be calculated from i_{corr} via Faraday's Law, according to the following equation:

$$CR(mpy) = i_{corr} \times 129 \times WT / n \times d\,,$$

where WT is the equivalent weight of carbon steel, n = 2 (for carbon steel) and d = carbon steel density.

The standard DNV operating procedure for determining the corrosion rate of a steel specimen in a soil sample using the linear polarization resistance method requires the use of a Gamry PTC Paint Test Cell, graphite rod counter electrode, carbon steel plate working electrode (free of corrosion and at least 50 mm) and copper-copper sulfate reference electrode. The data collection system consists of a Princeton Applied Research VMP3 192.168.0.1 potentiostat and EC Lab V9.94 software. Polarization resistance measured by this DC electrochemical method is a composite number, which also contains the value of solution resistance (R_s). The error produced by the solution resistance can be substantial (especially in the low-conductivity environments) and is compensated for. The most accurate method for solution resistance compensation is the application of a high-frequency AC voltage (potentiostatic) signal and measuring the resultant current.

Statistical Analysis of DNV Direct Examination Data

As shown in Table 5-5, the corrosion rate for the 351 data sets ranged between essentially zero and 0.5 mm/year (21 mpy), which is considerably less than for the NBS or NACE data. The average was calculated to be 0.03 mm/year (1.3 mpy), and 95% of the values were less than 0.146 mm/year (5.76 mpy).

Table 5-5
Statistical Summary of DNV Direct Examination Corrosion Rate Data (2005 to Present)

	Corrosion Rate (mpy)	Corrosion Rate (mm/yr)
Minimum	0.0001	0.000003
Average	1.333	0.034
Maximum	20.750	0.527
5th Percentile	0.0118	0.0003
95th Percentile	5.760	0.146

Figure 5-3 provides a histogram of the frequency of the DNV corrosion rate data. Of the 351 data points that were analyzed, only two observations exceeded the NACE 0.4 mm/year (16 mpy) default corrosion rate.

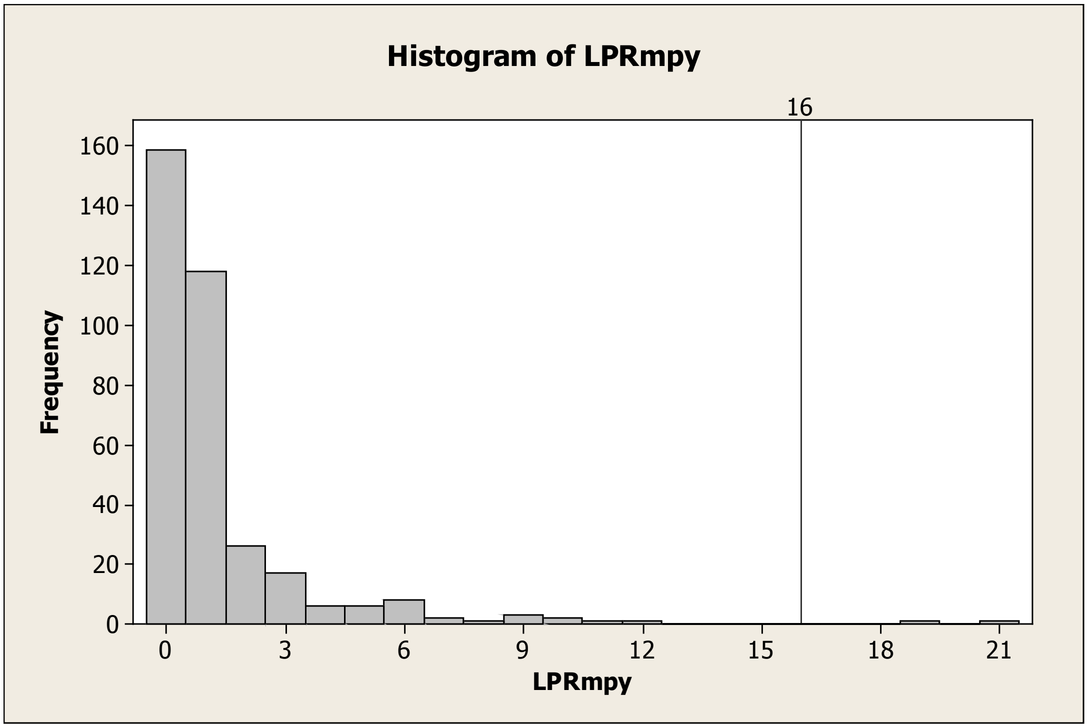


Figure 5-3
Histogram of LPR Corrosion Rate Frequency from DNV Direct Examination Soil Samples (2005 to Present)

The statistical modeling analysis of DNV direct examination data is included in Appendix B of this report. Statistical modeling was performed using three soil categories to determine if any correlation exists between the LPR corrosion rate data and variables such as moisture content, pH, resistivity, chloride ion content (Cl^-), sulfate content (SO_4^{2-}), nitrite (NO_2^-), and carbonate (CO_3^{2+}). Regression equations and predicted LPR versus observed LPR were prepared for each soil type. The statistical analysis examined 353 records in the data set. Due to the limitations in some of the data, the analysis was performed using three subsets of data: (1) Clay soil type only (n = 187), (2) All soil data (n = 353), and (3) Sand soil type only (n = 99).

It was thought that a correlation may exist between the LPR data with some or all of the soil types and key variables such as resistivity or pH, which could be used in a model to predict corrosion rate. However, from a multi-variable modeling perspective these variables are co-linear with chloride ions (Cl^-) and therefore do not enter into a statistical model with any significance. While a number of statistically significant findings are documented in the Appendix B report, the regression prediction capabilities are only valid for the Sand soil model. Figure 5-4 provides the regression model of predicted LPR versus observed LPR for sand soil, with good prediction capabilities. Unfortunately, due to missing data, only 49 cases could be used in this model.

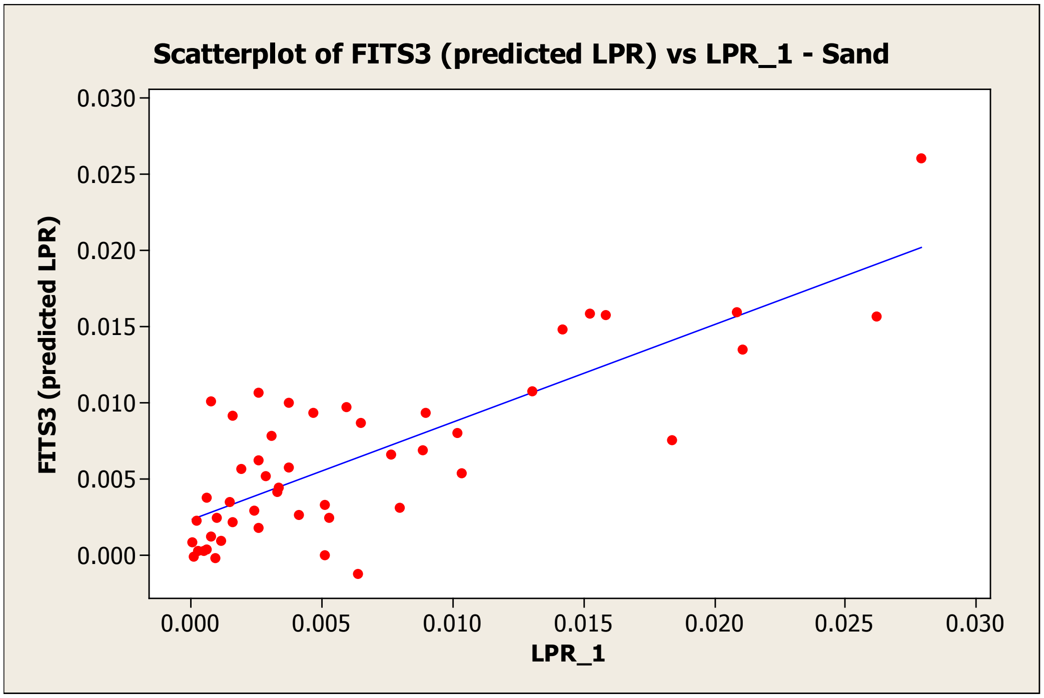


Figure 5-4
Predicted LPR vs. Observed LPR for Sand Soil Type

The regression equation for this analysis is:

$$LPR\_1 = -0.00163 + 0.000092\ Cl^{-} + 0.000513\ \text{Moisture Content}\ \%$$

Although soil chemistry data from soil samples would typically include percent moisture content, it is unlikely that chloride ions would play a significant role in corrosion of buried piping systems at nuclear power plants, unless the soil at the plant were subject to chloride ion ingress from coastal and/or brackish environments or from the use of de-icing chemicals.

Corrosion of Steel in Drilled Shafts

The specific case of steel passing through different media was investigated by Sarhan, O'Neill, and Simon in an experimental program [12]. The experimental study was designed to investigate the effect of two different media of substantially different pH values on the rate of corrosion of steel reinforcement in sand and clay soils and with different anode-to-cathode (a/c) ratios. The relative a/c area ratio is defined as the surface area of the exposed steel coupon (anode) to the surface area of the covered (embedded) steel coupon (cathode). Both 0.5 (1/20) and 0.1 (1/10) were chosen to represent typical ranges of ratios of longitudinal rebar exposed through a void to the remaining length of rebar embedded within a drilled shaft. The free and bonded corrosion rates are summarized in Table 5-6. The results suggest that the galvanic currents driven by the dissimilar metals could increase the corrosion rate of exposed steel by 3.3 to 5.6 times, particularly in environments with relatively non-corrosive soils, such as unsaturated shallow sand.

Table 5-6
Free and Bonded Corrosion Rates for the Steel in Drilled Shafts Experimental Study

Specimen	Conditions			Corr. Rate (mpy) 51 Days		Bonded	Corr. Rate (mpy) 136 Days		Bonded
	Soil	Depth (m)	a/c	Free Coupon (LPR)	Bonded Coupon (ZRA)	Free Ratio	Free Coupon (LPR)	Bonded Coupon (ZRA)	Free Ratio
S4Sa	Sand	1.22	0.05	0.18	1.27	7.1	0.22	2.06	-
S4Sb	Sand	1.22	0.05	0.25	1.96	7.8	0.14	0.24	1.69
S4Ha	Sand	1.22	0.1	0.21	0.33	1.6	0.13	0.41	3.12
S4Hb	Sand	1.22	0.1	0.11	0.45	4.1	0.08	0.28	3.45
S10Sa	Sand	3.05	0.05	5.48	1.28	0.2	1.93	0.72	0.37
S10Sb	Sand	3.05	0.05	1.16	1.41	1.2	1.61	0.26	0.16
S10Ha	Sand	3.05	0.1	0.9	0.85	0.9	2.16	0.59	0.27
S10Hb	Sand	3.05	0.1	0.83	na	na	3.17	0.37	0.12
C4Sa	Clay	1.22	0.05	0.7	0.78	1.1	0.35	0.44	1.26
C4Sb	Clay	1.22	0.05	1.72	0.6	0.3	0.91	na	na
C4Ha	Clay	1.22	0.1	2.35	na	na	2.74	na	na
C4Hb	Clay	1.22	0.1	3.66	na	na	2	na	na

Notes: 1. Specimens S4Sa through S4Hb represent non-corrosive soil (shallow sand).
2. Specimens S10Sa through C4Hb represent mildly corrosive soil (deep sand, shallow clay).

6

DISCUSSION

Impact of Electrical Grounding on Corrosion of Carbon Steel

General

Buried pipes at nuclear power plants are interconnected and grounded to reduce the effects of hazardous voltages associated with lightning and fault currents in the earth. Insulating devices that provide electrical isolation of buried piping systems for cathodic protection (CP) are typically not installed in nuclear power plants and if present are often shorted through external by-pass connections, making them ineffective. Because of the dissimilar metal couplings that exist through the common grounding, corrosion rates can significantly increase on some of the buried piping. When materials such as cast iron and carbon steel are interconnected in the soil, they are very close in the electromotive series of metals, and each suffers very little additional corrosion as a result of the coupling. However, creating a dissimilar metal couple by connecting carbon steel to copper, stainless steel, or reinforcing steel in concrete can form a very significant corrosion cell.

Copper Grounding

Electrical grounding at nuclear power plants has three important functions:

1. To provide personnel safety in the event of an electrical fault
2. To provide lightning protection
3. To provide a termination point for instrument shields

The above functions are accomplished through a grounding system that consists of a series of direct buried copper cables and vertical ground rods. The grid system at a nuclear power plant will usually extend over the entire station yard and may extend for some distance beyond the perimeter fencing. The grid normally consists of a network of copper conductors that are buried to a minimum depth of 0.15 m (0.5 ft) in the ground, forming a network of squares or rectangles. The spacing of the grid conductors will vary with the voltage class of the station. All cable crossings are securely bonded, and the system is connected to the normal grounding system as well as to all equipment, steel structures, security fencing, and directly or indirectly to the buried piping network. Primary conductors may consist of bare 500 MCM stranded copper cable, and secondary conductors may consist of bare # 2/0 AWG stranded copper cables.

When connected in a mixed metal network, copper will be cathodically protected by carbon steel. When copper is directly buried in the soil and completely isolated from other construction materials, it will corrode. In acidic soils, the corrosion rate of copper may be greater than that of iron or steel in the same environment. In addition, copper does not polarize as readily as ferrous metals when subjected to cathodic protection current. Kirkpatrick has stated that the "current density required to polarize the copper to an adequate potential necessary to protect a ferrous structure may be 10 to 20 times as high, on a per unit basis" [13]. Copper grounding can therefore have a significant effect on the polarization values for steel and the overall current requirement necessary to meet criteria for CP of buried pipes in nuclear power plants.

Galvanic Corrosion of Carbon Steel Pipe

The vast majority of carbon steel pipes at nuclear facilities are coated with coal tar enamel and/or coal tar epoxy. Because of the connection of the buried carbon steel pipe to the copper grounding, galvanic corrosion can produce high corrosion rates at defects in the coating if the cathode-to-anode area ratio is very high and the resistivity of the soil is low. In this kind of environment, copper and its alloys are usually very efficient cathodes, while stainless steel, if passive, is not. Hence, coupling coated carbon steel to copper generally results in more galvanic corrosion than coupling to a similar area of stainless steel [14].

There is not a significant amount of galvanic corrosion data for underground exposures, although Escalante and Gerhold investigated stainless steel coupled to copper [15] and other metals [16]. These authors did observe that the galvanic current between copper and stainless steel was constantly reversing in most soils; that is, they had similar potentials. Hence, copper and stainless steel may safely be coupled together underground in many cases [13].

The coupling of coated carbon steel pipe to the copper grounding can result in a small anode/large cathode area relationship, where the smaller anode (coated carbon steel pipe) is subject to a high density of current discharge per unit area at the coating flaw, with the total amount of current governed by the kinetics of the oxidation and reduction reactions and the resistivity of the electrolyte (soil). This situation is most severe in low-resistivity (high-conductivity) soils where copper grounding is in close proximity to the coated carbon steel pipe and small coating holidays are present in the coating on the steel piping. Dissimilar metals in a galvanic couple that are in close physical proximity usually suffer greater galvanic corrosion effects than those that are farther apart. The distance effect in the galvanic couple is therefore dependent on the electrolyte conductivity, because the propensity for current flow is the primary consideration.

The more noble metals and especially copper are electro-positive with respect to carbon steel. The native potential of clean mild steel in neutral soils and water can range between approximately -400 and -700 mV with reference to a copper-copper sulfate electrode (CSE), whereas the typical potential of copper is normally observed to be -200 mV (CSE). The galvanic series indicates that when copper is electrically coupled to mild steel in soil, the copper will become the cathode and the steel will become the anode, accelerating corrosion of the steel. Therefore, the driving voltage between the two metals (carbon steel and copper) can range between 0.2 and 0.5 Volts.

The National Electric Code (NEC) requirement to bond steel reinforcement in concrete to facility ground provides an additional impact to the corrosion rate of carbon steel piping at nuclear power plants. As a result of this requirement, the buried pipes are electrically continuous with the reinforcing steel in the concrete foundation walls and vaults. Reinforcing steel in concrete tends to be more noble (electro-positive) than carbon steel in soil because of the passive layer that develops on the rebar surface as a result of the high alkalinity of the portland cement. In new reinforced concrete structures, the structure-to-electrolyte potential of mild reinforcing steel can often range between 0 and -200 mV (CSE), resulting in a large galvanic couple when connected to carbon steel. The potential of the buried pipe will usually be depressed at the entry point through the wall as a result of the coupling to the rebar and buried copper grounding that exists around the perimeter of the building. These areas of pipe may have the highest corrosion rates and are often the most difficult to cathodically protect.

CC Technologies Galvanic Corrosion Study

In 2004 a galvanic corrosion study was conducted by CC Technologies, Inc. (now DNV) at a site where steel anchor rods had failed as a result of dissimilar metal corrosion. The structure is a concrete retaining wall in a coastal environment where steel anchor rods in soil were grounded to copper concentric neutral cables. To simulate the effect of the dissimilar metal corrosion activity, galvanic current densities were measured in the laboratory for dissimilar metal couplings between carbon steel and copper in soil.

Samples of AISI 1026 carbon steel rod and CD A110 copper alloy were chosen as the test materials for the laboratory study. A zero resistance ammeter (ZRA) was used to measure galvanic current flow between the two dissimilar materials. As part of the test, four different cathode/anode area ratios were evaluated (10/1, 5/1, 2.5/1, and 1/1). The tests were performed using three soil samples taken from the failure site (Samples 2-3, 2-6, and 2-8). The resistivity of the soil samples was measured to be 160, 190, and 4,000 ohm-cm, respectively. Although the resistivity of the soil in Samples 2-3 and 2-6 is relatively low (suggesting a brackish water influence), the study does show the importance of area ratios in the corrosion rate of dissimilar metal couplings. In certain areas of a nuclear power plant one could possibly expect a much higher ratio between the carbon steel anode and the copper cathode due to the extensive network of copper grounding and the relatively small area of exposed steel at the coating flaws in the pipes. Nevertheless, the laboratory study can be used to demonstrate the increased corrosion rate that can be expected for dissimilar metal couplings with much larger area ratios.

Figures C-1, C-2, and C-3 in Appendix C show the galvanic current densities for the galvanic couples as a function of time for the three soil samples. In all cases, the galvanic current density increased initially with time and then became more stable. The stabilized current densities for all cases are listed in Table 6-1, with corresponding corrosion rates for carbon steel. The corrosion rates were calculated using conversion factors based on Faraday's Law. For comparison purposes, the corrosion rate of the isolated steel specimen (without the copper coupling) is given. These rates were calculated using the linear polarization resistance (LPR) technique. The galvanic corrosion rates were typically greater as the area ratios increased, and the highest rate was calculated to be 6.78 mm/yr (267 mpy) with a copper/steel ratio of 10/1.

Table 6-1
Numerical Results of Galvanic Current Measurements

Soil ID	Cathode/ Anode Ratio	Galvanic Current Density (A/cm^2)	Calculated Galvanic Corrosion Rate (mm/yr)	Calculated Galvanic Corrosion Rate (mpy)	LPR Corrosion Rate of Steel (mm/yr)	LPR Corrosion Rate of Steel (mpy)
Sample 2-3 (160 ohm-cm)	10	2.4 x10^{-4}	2.86	112.5	0.65	25.6
	5	1.6 x10^{-4}	1.86	73.3		
	2.5	2.6 x10^{-4}	3.03	119.2		
	1	2.0 x10^{-4}	2.33	91.7		
Sample 2-6 (190 ohm-cm)	10	5.9 x10^{-4}	6.78	267.0	0.07	2.7
	5	3.5 x10^{-4}	4.17	164.0		
	2.5	2.4 x10^{-4}	2.86	112.5		
	1	2.2 x10^{-4}	2.56	100.8		
Sample 2-8 (4,000 ohm-cm)	10	5.7 x10^{-4}	6.78	267.0	0.34	13.4
	5	2.2 x10^{-4}	2.56	100.8		
	2.5	1.9 x10^{-4}	2.21	87.1		
	1	6.8 x10^{-5}	0.80	31.3		

Soil

General

Soil is composed of particles of broken-down rock that have been altered by chemical and environmental processes that include weathering and erosion. Soil is an aggregate of essentially four constituents: (1) mineral particulates, (2) organic matter from the surface and subsurface, (3) groundwater containing soluble salts, and (4) gases [17]. The proportions of the basic constituents vary greatly in different soil types. At nuclear power plants, the soil as a backfill for buried piping may be native material taken from the pipe excavation or plant site, imported (engineered) fill that was obtained from a local quarry, or a mixture of both. The particulate matter that is found in soils is usually small particles of the minerals from nearby rock formations, which consists mostly of insoluble minerals, as the soluble species have been removed by weathering over millions of years. The solubility of these minerals may vary with pH and will tend to buffer the pH of the groundwater.

The corrosivity of soils varies over a wide range because of the variety of compositions. Tests in one location are generally applicable only to that location, and tests of several years' duration are needed to obtain reliable data, as conditions can vary. Factors affecting the corrosiveness of soils include moisture, alkalinity, acidity, permeability of water and air (compactness or texture), and levels of oxygen, salts, and biological organisms. Many of these factors affect the electrical resistivity of soil, which is a good measure of corrosivity.

Soil Classification

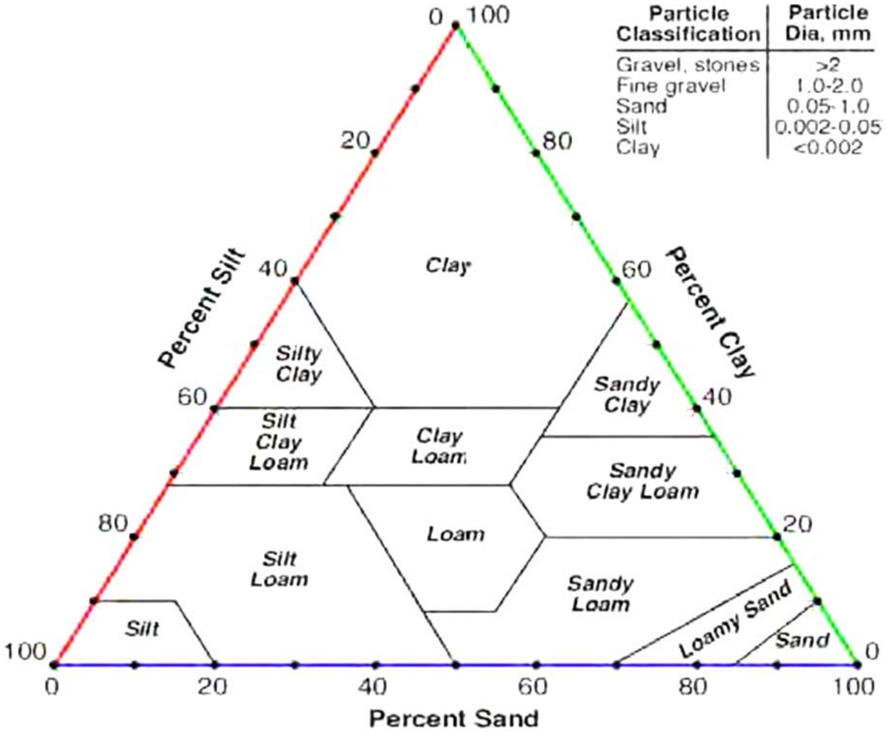
The distribution and size of mineral particles in a soil determine its texture. The United States Department of Agriculture (USDA) distribution of particle sizes is shown in Table 6-2. Soils with a high proportion of sand have a limited storage capacity for water, whereas clays with small grain size are excellent at retaining water.

Table 6-2
Particle Sizes in Soil Texture

Category	Diameter (mm)
Sand (very coarse)	1.00 - 2.00
Sand (coarse)	0.50 - 1.00
Sand (medium)	0.25 - 0.50
Sand (fine)	0.10 - 0.25
Sand (very fine)	0.05 - 0.10
Silt	0.002 - 0.05
Clay	<0.002

The USDA has placed soils into 11 categories on the basis of their size distribution of particles, as shown in Figure 6-1. These categories include sand, loamy sand, sandy loam, sandy clay loam, clay loam, loam, silty loam, silt, silty clay loam, silty clay, and clay soils.

Sand is a naturally occurring granular material composed of finely divided rock and mineral particles. The composition of sand is highly variable, depending on the local rock sources and conditions, but the most common constituent of sand in inland continental settings and non-tropical coastal settings is silica (silicon dioxide, or SiO_2), usually in the form of quartz. Clay is a general term covering many combinations of one or more clay minerals with traces of metal oxides and organic matter. Loam is soil composed of sand, silt, and clay in relatively even concentration (about 40-40-20% concentration, respectively). Loam soils generally contain more nutrients and humus than sandy soils and have better drainage and infiltration of water and air than silty soils. Silt is granular material of a size somewhere between sand and clay, whose mineral origin is quartz and feldspar.



Particle Classification	Particle Dia, mm
Gravel, stones	>2
Fine gravel	1.0-2.0
Sand	0.05-1.0
Silt	0.002-0.05
Clay	<0.002

Figure 6-1
Soil Texture Triangle Showing the USDA Classification System Based on Grain Size

The most common engineering classification for soils in North America is the Unified Soil Classification System (USCS). The USCS has three major classification groups: (1) coarse-grained soils (e.g., sands and gravel); (2) fine-grained soils (e.g., silts and clays); and (3) highly organic soils (referred to as "peat").

More recently, a universal soil classification system has evolved in the United States to classify soils. In this system, soils are considered as individual three-dimensional entities that may be grouped according to their physical, chemical, and mineralogical properties. The system uses a hierarchical approach, with the amount of information about a soil increasing down the classification ladder. The hierarchy approach is structured into five major categories: (1) order, (2) suborder, (3) great groups, (4) families, and (5) series.

Additional information on soil classification systems can be found at the NACE International Resource Center (http://www.nace.org/Corrosion-Central/).

Soil Parameters Affecting Corrosion Rate

As mentioned previously, a number of variables are known to have an influence on corrosion rates in soil. These include (1) water (moisture content), (2) degree of aeration, (3) pH, (4) redox potential, (5) resistivity, (6) soluble ionic species (salts), and (7) microbiological activity. The complex nature of selected variables that affect the rate of corrosion in soil is presented graphically in Figure 6-2 [16].

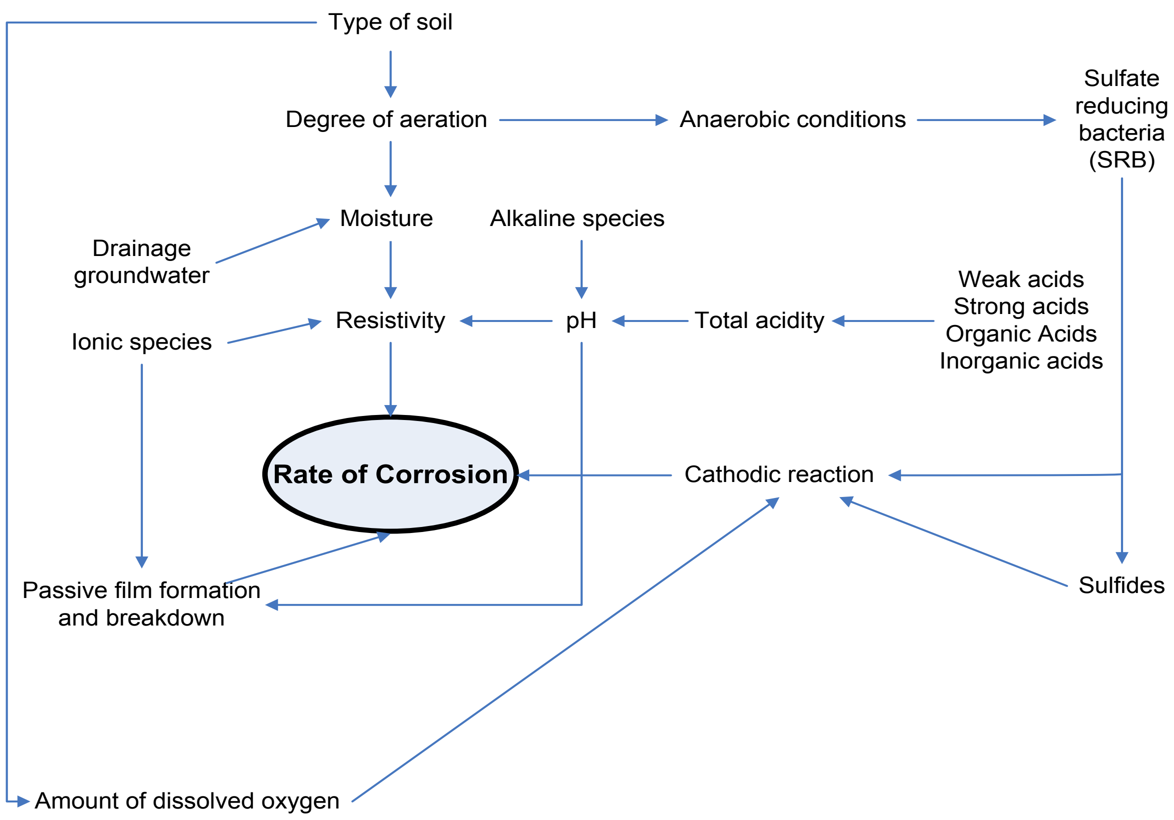


Figure 6-2
Relationship of Variables Affecting the Rate of Corrosion in Soil

Moisture Content

Water constitutes the essential electrolyte that supports the electrochemical process of corrosion in soil. Groundwater is important in this regard, as the elevation of groundwater fluctuates from area to area. The typical test method for determining moisture content in soil is based on removing soil moisture by oven-drying a soil sample until the weight remains constant. The moisture content is calculated from the sample weight before and after drying, and is expressed as a weight percent (%). Recent experience has shown that the percent of saturation may be more relevant in determining the corrosion characteristics of a particular soil. The water-holding capacity of a soil is strongly dependent on its texture. Coarse sands retain very little water, whereas fine clay soils store water to a high degree. Therefore, fully saturated sand may have a lower moisture content than partially saturated clay, based on weight percentage alone. Soils with high moisture content will typically have a lower resistivity and therefore are considered more corrosive to buried metallic structures. The data in Table 6-3 show the effect that moisture content has on soil resistivity [18].

Table 6-3
Effect of Moisture Content on Soil Resistivity

Moisture Content (% by weight)	Resistivity (ohm-cm)	
	Top Soil	Sandy Loam
0	>1000 x 10^6	>1000 x 10^6
2.5	250,000	150,000
5	165,000	43,000
10	53,000	18,500
15	19,000	10,500
20	12,000	6,300
30	6,400	4,200

pH

The term pH refers to the degree of alkalinity or acidity of an electrolyte, ranging from highly alkaline at 14 to highly acidic at zero, with neutrality at 7. A pH value represents the negative logarithm of the hydrogen ion concentration. Acidic soils (lower pH) are typically more aggressive with respect to buried metallic structures. As pH values increase to greater than 7 (the neutral value), they reflect conditions that are increasingly more alkaline and less corrosive. Alkaline conditions do not pose any serious threat to steel pipelines. Table 6-4 provides an outline showing the degree of corrosivity for buried steel pipelines with respect to soil pH [4].

Table 6-4
Soil pH Classification

Soil pH	Degree of Corrosivity
<5.5	Severe
5.5 - 6.5	Moderate
6.5 - 7.5	Neutral
>7.5	None (alkaline)

Differential Aeration

The differential aeration cell is probably most common corrosion cell found on pipelines or other underground structures [19]. In underground environments where the groundwater or soil is neutral or alkaline, the corrosion rate of buried metallic structures is primarily dependent on the oxygen concentration at the surface of the structure, and in turn depends largely upon the depth of the structure below grade and the diffusivity of air through the soil to the metal surfaces. Oxygen enables a corrosion reaction by maintaining the cathodic reaction. Oxygen concentration normally decreases with depth in soils and will typically be lower at the base of a pipe as compared to the top. Therefore, on large-diameter structures the base of the pipeline is more likely to be anodic relative to the top of the pipe, which is cathodic. A similar situation will also exist at a pipeline crossing beneath a paved access road, where the paved road lowers the oxygen concentration in the soil around the pipeline. The areas of lower oxygen concentration will become the anode in the differential aeration cell. In these regions, current leaves the metal surface, increasing the corrosion rate, and flows to the cathodic areas on the pipeline where the oxygen concentration is higher.

Soil Resistivity

Electrical resistivity is the measure of how strongly a material opposes the flow of electrical current. Resistivity has historically been used as an indicator of soil corrosivity. Since ionic current flow is related to soil corrosion, soils with low resistivity will usually increase corrosion reactions. However soil resistivity is by no means the only parameter affecting risk of corrosion, and soils with high resistivity will not guarantee the absence of corrosion. Macro corrosion cells may be formed along a pipeline where large variations in soil resistivity are encountered. (The SI unit of electrical resistivity is ohm-meter; to convert ohm-m to ohm-cm multiply by 100.) Soil resistivity is usually measured using the Wenner 4-Pin method in accordance with ASTM Standard G57-06. Another option is the soil box method, in which soil samples are taken from excavations or bore holes and measured for resistivity. Table 6-5 is a general guideline prepared by DNV for determining corrosivity of soils and water.

Table 6-5
Soil and Water Resistivity Classification

Soil Resistivity	Classification
<500 ohm-cm	Extremely Corrosive
500 to 1,000 ohm-cm	Very Corrosive
1,000 to 10,000 ohm-cm	Corrosive
10,000 to 20,000 ohm-cm	Moderately Corrosive
>20,000 ohm-cm	Progressively Less Corrosive

Redox Potential

Redox potential is a measure of a material’s tendency to acquire electrons and thereby be reduced. It is essentially the measure of the degree of aeration in a soil. A high redox potential indicates a high oxygen concentration. Low redox values indicate low oxygen concentration and provide an indication that conditions are conducive to anaerobic microbiological corrosion activity. Sampling of soils will lead to oxygen exposure; therefore, unstable redox potentials are likely to be measured in disturbed soil.

Chlorides

In general, chloride ions participate in the dissolution reactions of many metals, and furthermore their presence tends to decrease soil resistivity. Chloride ions may be found naturally in soils as a result of brackish groundwater or ancient sea beds, or they may be present as a result of de-icing salts being applied to roadways in northern climates. Table 6-6 correlates the effect that chlorides have on corrosion of buried steel pipelines [20].

Table 6-6
Effect of Chloride Concentration on Degree of Corrosivity

Chloride Concentration (ppm)	Degree of Corrosivity
>5,000	Severe
1,500 – 5,000	Considerable
500 – 1,500	Corrosive
<500	Threshold

Sulfates

Compared to chlorides, sulfate ions are generally considered to be more benign in terms of contributing to corrosion activity of steel pipelines in soil. However, concrete can be attacked as a result of high sulfate ion concentrations. The presence of sulfates in soils poses a direct risk to corrosion of buried steel pipelines since these ions are nutrients for sulfate-reducing bacteria (SRB), which convert these ions into highly corrosive sulfides. Table 6-13 correlates the effect that sulfates have on corrosion of buried steel pipelines [19].

Table 6-7
Effect of Sulfate Concentration on Degree of Corrosivity

Sulfate Concentration (ppm)	Degree of Corrosivity
>10,000	Severe
1,500 – 10,000	Considerable
150 – 1,500	Positive
0 - 150	Negligible

Cathodic Polarization and Its Effect on Corrosion Rate

General

Cathodic polarization (CP) can be defined as the change in electrode potential in the active (negative) direction caused by current across the electrode/electrolyte interface [21]. The 100-mV cathodic polarization criterion is one of three criteria stated in NACE Standard SP0169 for cathodic protection of underground or submerged metallic piping systems [21]. This criterion states that adequate protection is achieved with a minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. The formation or decay of polarization may be used to satisfy this criterion. When a structure is polarized in the negative direction from the native potential, the corrosion rate will decrease. The difference between the corrosion rate (expressed as current) and the rate of reduction is equal to the applied CP current. This process can be presented graphically in a plot of E vs. Log I (Evans diagram), as shown in Figure 6-3 [22].

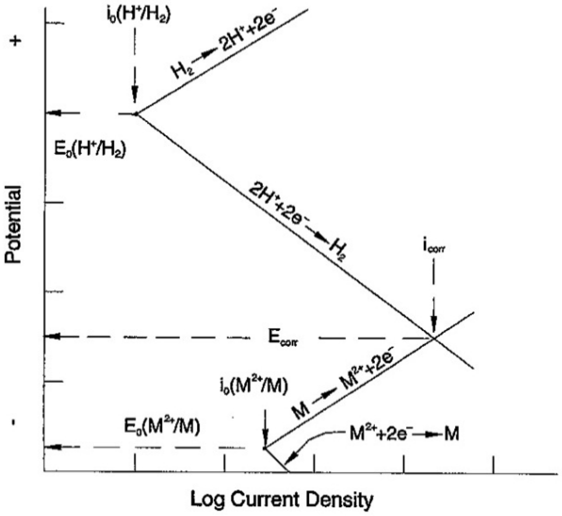


Figure 6-3
Evans Diagram (E vs. Log I) for Metal M

The slope of the anodic (corrosion) reaction in Figure 6-3 is the Tafel slope and typically has a value of ~100 mV per decade of current. With this Tafel slope, the corrosion rate of a structure decreases by a factor of 10 (one order of magnitude) for every 100 mV of cathodic polarization shift. Even if the cathodic polarization shift does not result in a polarized potential equal to or more negative than the open circuit potential of the anode, which would produce a zero corrosion rate, the corrosion current density (icorr) is nevertheless reduced logarithmically as the cathodic current density is increased. An order of magnitude decrease in corrosion rate will typically be sufficient to effectively mitigate corrosion of carbon steel in most soil environments.

NACE Standard SP0502-2010, “Pipeline External Corrosion Direct Assessment Methodology” [1], states that where other data are not available, a pitting rate of 0.4 mm/yr (16 mpy) may be used for determining re-inspection intervals. This default corrosion rate may be reduced by a maximum of 24%, provided it can be demonstrated that the CP levels of all pipelines or segments being evaluated have had at least 40 mV of polarization (considering IR drop) for a significant fraction of time since installation. This reduction in corrosion rate, as a result of cathodic polarization, is based on data presented by Barlo in the Pipeline Research Council International (PRCI) report PR-208-163 [5].

Anode and Cathode Control

Mears and Brown have indicated that for complete corrosion control, the cathodes of all existing corrosion cells on a structure must be polarized cathodically to the most electro-negative open circuit anode potential on the structure [23]. This statement is supported in NACE Standard SP0169. Typically, corrosion cells on steel structures exposed to soil environments operate under cathodic control, such that the corrosion potential (Ecorr) is relatively close to the open circuit potential of the anode. Hence, the negative shift in cathodic polarization required to achieve CP is relatively modest. An example of cathodic control, in which the cathode area is small relative to the anode area, would be a copper water service line that is connected to a large ductile iron water main.

However, if the cathode area is large compared to the anode area, the corrosion cell is likely under mixed or anodic control. Figure 6-4 provides a polarization schematic illustrating the effect of corrosion rate in a mixed metal network. The larger the cathode compared to the anode, the more oxygen reduction can occur, and hence, the greater the galvanic current and therefore corrosion. Structures operating under anodic control would include the buried carbon steel piping that is connected directly to a larger copper grounding, or to a more passive material such as stainless steel or reinforcing steel in concrete. Such cases commonly exist at a nuclear power plant.

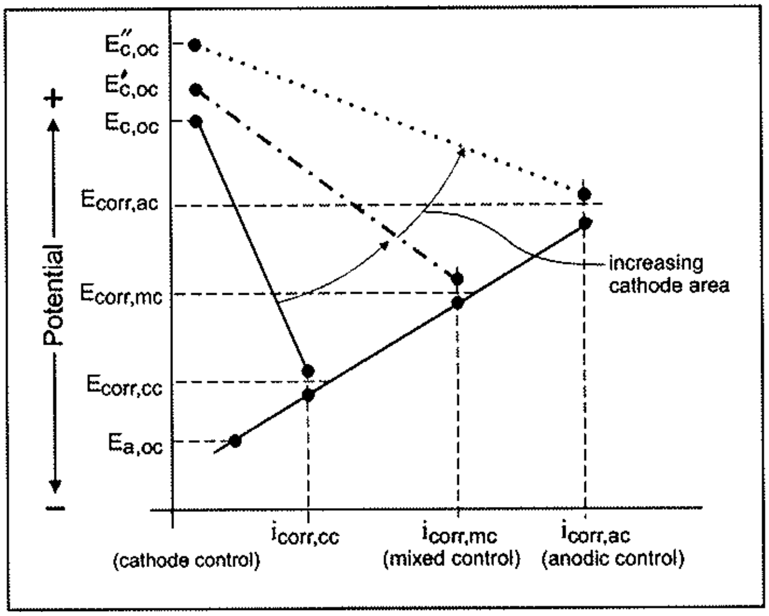


Figure 6-4
Polarization Schematic Illustrating the Effect of Corrosion Rate in a Mixed Metal Network

NACE International Publication 35108, "One Hundred Millivolt (mV) Cathodic Polarization Criterion" [22], states that the effectiveness of the 100-mV cathodic polarization criterion relies on corrosion cells operating under cathodic control. Although the 100-mV polarization criterion is useful in conditions where a pipe section is electrically isolated, it does not ensure that the structure is fully polarized in mixed metal networks. NACE SP0169 further stipulates that for dissimilar metal piping, a negative voltage between all pipe surfaces and a stable reference electrode contacting the electrolyte equal to that required for protection of the most anodic metal should be maintained. The major concern is that the difference in potential between the anode and cathode sites in a mixed metal network can be quite large (e.g., steel-copper, steel-stainless steel, etc.). Hence, to adequately polarize the steel piping that is to be protected in a mixed metal network, the potential of the galvanic coupling must first be overcome so that adequate current can be applied to the most anodic material in the couple (i.e., carbon steel).

External Coatings

Coatings, if properly applied to the surface of buried pipes, can provide an effective barrier to moisture and corrosion. In selecting a coating system for a given pipeline project, one of the most important characteristics to consider during the design is the stability of the coating, so that a high electrical resistance to earth is maintained over time. A good quality coating should resist the development of holidays (or flaws) from soil stress and contaminants, provide good adhesion to the pipe surface, resist disbanding, and have the ability to withstand damage from normal handling, storage, and installation.

A dielectric coating system for the buried pipelines serves as the first line of defense against corrosion. The coating provides a corrosion control barrier between the pipe surface and the local soil or water environment. Cathodic protection is used to supplement the coating and provides corrosion control to the piping at flaws or holidays in the coating. The pipelines receiving cathodic protection at nuclear plants are typically coated, and therefore only a small area of exposed steel will require protection. The combination of dielectric coatings and CP generally produces an effective corrosion control system with minimal current demands if the pipe is fitted with insulating devices. However, since the buried nuclear piping is not electrically isolated, much of the current that is produced from the CP systems will be received or “picked up” on the surrounding metallic structures that are not intended for CP. Many of these structures are bare or poorly coated. Therefore, the current requirement for adequate polarization of the buried pipes will be much larger compared to an electrically isolated piping system. It is not uncommon for CP systems at nuclear plants to have a design capacity in excess of 1,000 amperes of direct current to cathodically protect the extensive network of piping.

It has been reported that approximately 95% of the buried carbon steel pipes that were installed initially at nuclear power plants used coal tar enamel coatings on the external surface, and then later coal tar epoxy was used [24]. As the coal tar enamel coating ages, flaws and disbondment may develop, resulting in exposure of the steel surface to the soil or water environment. Mechanical damage to the coating may also have occurred as a result of the pipeline installation.

As stated above, cathodic protection is used to supplement the coating and provides corrosion control to the flaws or holidays in the coating. However, as also alluded to above, because of the electrical continuity between the low-resistance grounding system and high-resistance piping at nuclear power plants, the majority of CP current will flow to the bare copper grounding. Based on a power plant CP model that was developed by Garrity, 99.2% of the current from a CP system for buried piping will flow to the copper grounding, with balance of current (0.8%) being received on the exposed surfaces of the buried piping [25].

Copper does not polarize as readily as ferrous metals. Waters has reported that copper water piping required current densities ranging from $0.25\mu A/cm^2$ to $4.4\mu A/cm^2$ after a 9-month period [26]. Furthermore, Kirkpatrick has stated that the “current density required to polarize the copper to an adequate potential necessary to protect a ferrous structure may be 10 to 20 times as high, on a per unit basis” [13]. Gummow has reported that in non-aerated soils, copper-clad steel ground rods that would normally be cathodic to steel require the same or less current to adequately polarize steel. However in more aerated sandy soil, the current requirements for copper clad steel increased by 3 orders of magnitude when compared to steel [27]. The connected copper grounding system can therefore have a significant effect on the effects of cathodic polarization for effective CP of buried piping in nuclear power plants.

Methodology for Determining External Corrosion Growth Rate

The external corrosion growth rate is an essential variable needed for calculation of the remaining life of a buried pipeline that is subject to degradation. Actual corrosion rates are difficult to predict or measure, since the actual conditions at all locations where corrosion may be occurring are not known. The growth rate used in FFS evaluations should be based on corrosion rate data applicable to the pipeline under consideration. For example, if direct measurements over a known time period are available from maintenance records for the pipeline being assessed, or for a similar one, the actual corrosion growth rate for the specific location can be calculated. In the absence of specific data, four possible methods for determining corrosion rates are as follows:

1. *Historical Growth Rates:* Historical corrosion growth rates can be utilized for pipelines with similar characteristics (i.e., coating, CP, wall thickness, grade) installed in similar environments. Corrosion rate data from buried coupons, if available, can also be used to estimate corrosion rates.
2. *Linear Polarization Resistance Measurements:* LPR measurements can be used to establish corrosion growth rates. Both field and laboratory measurements have been found to be accurate.
3. *Linear Growth Rates:* Linear growth rates (or alternative modeling) can be used to establish the annual corrosion growth of external corrosion anomalies based on the peak metal loss depth divided by the years of exposure (years since installation).
4. *Default Corrosion Rates:* If no known corrosion growth rate information is available, and it cannot be approximated by any of the above three methods, industry-published default corrosion growth rate data can be relied upon.

When no other data are available, ANSI/NACE SP0502-2010, “Pipeline External Corrosion Direct Assessment Methodology,” provides a default pitting rate of 0.4 mm/yr (16 mpy) for determining re-inspection intervals of buried pipelines [1]. This number, however, is considered overly conservative for most transmission or distribution pipelines and is not representative of pipelines with anomalously high corrosion rates, such as pipelines that are influenced by MIC or stray DC currents, or piping that is subject to galvanic (dissimilar metal) corrosion.

7

CONCLUSIONS

1. The data reviewed in the study, which involved over 180 reports and publications, demonstrate the inherent variability in "assigning" corrosion rates and the fact that no single factor controls the overall corrosion rate. Although a thorough investigation was conducted, some of the objectives of the study, such as classification of corrosion rates according to weldments and coatings, could not be achieved due to insufficient availability of data.
2. The vast majority of carbon steel pipes at nuclear facilities are coated with coal tar enamel and/or coal tar epoxy. Because of the connection of the buried carbon steel pipe to the copper grounding, galvanic corrosion could produce high corrosion rates at defects in the coating if the cathode-to-anode area ratio is very high and the resistivity of the soil is low.
3. The data that were analyzed are mostly for electrically isolated pipelines, isolated specimens in test yards, and laboratory test specimens. The galvanic (dissimilar metal) coupling between the buried piping network and the copper grounding is considered one of the primary mechanisms for corrosion of carbon steel pipe at nuclear power plants. Unfortunately, based on the results of the study, there is not a significant amount of galvanic corrosion data that is published for underground exposures. Additional research and test data are needed in this area.
4. The statistical analysis of Det Norske Veritas (DNV) direct examination LPR data using regression equations found that it was difficult (or impractical) to extract any clear correlation between corrosion rate and variables in soil chemistry and composition. The best model for corrosion rate that could be developed is based on using chloride ion concentration and moisture content as the variables in the soil. However, even under the best case conditions, using all DNV supplied data, taken and measured in controlled conditions, there is still a wide variation in the data, with difficulty correlating many of the variables. This makes it even more difficult to see a reasonable correlation from the literature data search, as oftentimes the testing conditions are varied, and not always stated.
5. The external corrosion growth rate of a buried pipe is an essential variable needed for calculation of the remaining life of a pipeline. Actual corrosion rates are difficult to estimate or measure, since the actual conditions at all locations where corrosion is occurring are not known. Actual growth rates used in the remaining life calculation should be based on actual corrosion rate data applicable to the buried pipe under investigation. Often, however, pipe wall loss data from historical records are not available or are incomplete. Therefore, when other data are not available, default corrosion rates based on statistically valid methods should be used.

8

RECOMMENDATIONS

1. ANSI/NACE SP0502-2010, “Pipeline External Corrosion Direct Assessment Methodology,” provides a default pitting rate of 0.4 mm/year (16 mpy) for determining re-inspection intervals on pipelines when other data are not available. This number, however, is considered overly conservative for most transmission or distribution pipelines and is not representative of pipelines with anomalously high corrosion rates, such as pipelines that are influenced by MIC or stray DC currents, or piping that is subject to galvanic (dissimilar metal) corrosion. The 0.4 mm/year (16 mpy) default rate represents the upper 80% confidence level of maximum pitting rates for long-term (up to 17 year duration) underground corrosion tests of bare (electrically isolated) steel pipe coupons without cathodic protection (CP) in a variety of soils, including native and non-native backfill. Consideration should be given to increasing this rate (default corrosion rate) to 0.5 mm/year (20 mpy) for carbon steel piping in nuclear power plants to account for the dissimilar metal coupling with the copper grounding. This default corrosion rate may be reduced by a maximum of 24%, provided that it can be demonstrated that the CP level of the piping being evaluated has at least 40 mV of polarization (considering IR drop) for a significant fraction of time since installation.
2. Further research and testing are needed to assess the corrosion rate and polarization characteristics of dissimilar metal couplings using various carbon steel/copper area ratios and other variables, such as the soil environment. This can be accomplished by setting up a series of tests in the laboratory and field using coupon test stations that are fitted with a third copper ground rod. Electrical resistance probes may also be employed to provide additional corrosion rate data. Such research and testing will hopefully enable better judgment regarding the use of a default corrosion rate for carbon steel piping systems in nuclear power plants. This testing can also be used to support more sound decision making regarding use and selection of CP criteria for mixed metal piping systems in nuclear power plants.

9

REFERENCES

1. ANSI/NACE Standard SP0502-2010, “Pipeline External Corrosion Direct Assessment Methodology” (Houston, TX: NACE).
2. National Bureau of Standards Circular C401, *Abstracts and Summaries of Bureau of Standards Publications on Stray Current Electrolysis,* 1933.
3. National Bureau of Standards Circular C450, *Underground Corrosion,* K.H. Logan, 1945.
4. National Bureau of Standards Circular C579, *Underground Corrosion,* M. Romanoff, 1957.
5. Barlo, T. J., *Field Testing the Criteria for Cathodic Protection of Buried Pipelines,* PRCI report PR-208-163, 1994.
6. *Uhlig’s Corrosion Handbook, 2nd Edition,* R. Winston Revie, 2000.
7. Ricker, R. E., *Analysis of Pipeline Steel Corrosion Data From NBS (NIST) Studies Conducted Between 1922-1940 and Relevance to Pipeline Management,* NISTIR 7415, 2007.
8. Garrity, K. C., Lopez-Garrity, A., and Lawson, K. M., “Application of Corrosion Growth and Analysis in Support of Direct Assessment Reassessment Intervals,” Paper No. 06182, NACE Corrosion/2006 (Houston, TX: NACE).
9. Palmer, J. D., “Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping,” ASTM STP 1013, 1989.
10. Camitz, G., and Vinka, T. G., ”Corrosion of Steel and Metal-Coated Steel in Swedish Soils,” ASTM STP 1013, 1989.
11. Correspondence with Bill Amend, Det Norske Veritas (U.S.A.), Inc.
12. Sarhan, H. A., O’Neill, M. W., and Simon, P. D., “Corrosion of Reinforcing Steel in Drilled Shafts with Construction Flaws,” Transportation Research Record 1786, Paper No. 02-2812.
13. Kirkpatrick, E. L., “Electrical Grounding and Cathodic Protection Issues in Large Generating Stations,” Materials Performance, November, 2001.
14. Francis, R., “Galvanic Corrosion: A Practical Guide for Engineers” (Houston, TX: NACE International), 2001.
15. Escalante, E., and Gerhold, W. F., “Galvanic Coupling of Some Stainless Steels to Copper Underground,” *Materials Performance* 10 (1976), (Houston, TX: NACE International).
16. Escalante, E., and Gerhold, W. F., “Galvanic and Pitting Corrosion – Field and Laboratory Studies,” in *Galvanic Corrosion*, ed. R. Baboian, ASTM STP 576 (W. Conshohocken, PA: ASTM, 1976).
17. Roberge, P. R., *Corrosion Engineering Principles and Practice,* McGraw Hill, 2008.
18. “IEEE Recommended Practice for Grounding of Industrial and Commercial Power Systems,” Green Book, IEEE, 1982.

19. Peabody, A.W., “Control of Pipeline Corrosion,” 2nd Edition (Houston, TX, NACE International).
20. ACI-318, “Building Code Requirements for Reinforced Concrete,” American Concrete Institute, 1999.
21. NACE Standard Practice SP0169-2007, “Control of External Corrosion on Underground or Submerged Metallic Piping Systems” (Houston, TX: NACE).
22. NACE Publication 35108, “One Hundred Millivolt (mV) Cathodic Polarization Criterion” (Houston, TX: NACE).
23. Mears, R. B., and Brown, R. H., “A Theory of Cathodic Protection,” *Transactions of the Electrochemical Society,* 74th General Meeting, 1938.
24. Eckert, T., meeting minutes for EPRI project Guidance for Buried Pipe Corrosion Rates, Item 3, June 23, 2011.
25. Garrity, K. C., “The Impact of Grounding Practices on Corrosion, CP, and ECDA for Piping in Nuclear Power Plants,” presentation given at EPRI BPIG Meeting, February 16, 2010.
26. Waters, D. M., “Cathodic Protection to Protect Copper Pipelines from External Corrosion,” NACE Corrosion/82, 1982, Paper No. 41, p. 15.
27. Gummow, R.A., “Cathodic Protection Current Requirements for Electrical Grounding Materials,” NACE Corrosion/2004, Paper No. 04045, pp. 1 and 7.

A

CORROSION REFERENCES REVIEWED

This appendix lists references consulted in the course of the literature review. Note that the numbering system used in the following table is self-contained—that is, the numbers do not correspond to the numbers used for source documentation in the body of this report.

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
1	A New Technique for Correlation of Underground Corrosion	G. L. Song, C. Cao, and H. C. Lin	NACE 95070491	1995	Yes
2	A Structural Reliability Based Assessment of Non-Piggable Pipelines	M. Van Os, P. Mastrigt, et al.	NACE Corrosion 2005 Paper 05151	2005	No
3	An Approach to Determining Reassessment Intervals Through Corrosion	F. Song and N. Sridhar	SWRI	2006	No
4	Application of Corrosion Growth and Analysis in Support of Direct Assessment Reassessment Intervals	A. Lopez-Garrity, K. Garrity, and K Lawson	NACE Corrosion 2006 Paper 06182	2006	Yes
5	Cathodic Protection Criteria of Thermally Insulated Pipeline Buried in Soil	J.-G. Kim and Y.-W. Kim	Corrosion Science	2001	Yes
6	Cathodic Protection of Pipelines in High Resistivity Soils and the Effect of Seasonal Changes	F. King, G. Boven, K. Lawson, and N. Thompson	NACE Corrosion 2006 Paper 06163	2006	Yes
7	Corrosion and Corrosion Control	H. H. Uhlig and R. W. Revie		1984	No
8	Corrosion Guide	Hubbell, Inc.		2003	No
9	Corrosion of Galvanized Steel in Soils	I. A. Denison and M. Romanoff	National Bureau of Standards	1952	Yes
10	Corrosion of Low-Alloy Irons and Steels in Soils	I. A. Denison and M. Romanoff	National Bureau of Standards	1952	Yes
11	Corrosion of Reinforcing Steel In Drilled Shafts with Construction Flaws	H. Sarhan, M. O'Neill, and P. Simon	Transportation Research Record 1786		Yes
12	Corrosion of Steel Pilings in Soils	M. Romanoff	National Bureau of Standards	1962	No
13	Corrosion of Steel Structures in Sea-Bed Sediment	X. Wang, J. Duan, Y. Li, J. Zhang, et al.	Bulletin of Material Science	2005	Yes
14	Corrosiveness of Soils with Respect to Iron and Steel	H. Holler	Ind. Eng. Chem.	1929	Yes
15	Determining Corrosion Growth Accurately and Reliably	L. Fenyvesi and S. Dumalski			No
16	Determining Pipeline Corrosion				No
17	Direct Assessment of Localized Corrosion Using Localized Corrosion Monitoring Technique	W. Y. Mok, J. A. M. de Reus, and V. Jovancicevic	NACE Corrosion 2005 Paper 05341	2005	No
18	Ductile Iron Corrosion Factors to Consider and Why	W. Spickelmire			No

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
19	Effect Of Boundary Conditions of Failure Pressure Models on Reliability Estimation of Buried Pipelines	O. Lee, J. Pyun, and D. Kim	Journal of Korean Society of Precision Engineering	2003	No
20	Effective Corrosion Mitigation	G. Bell	NACE Corrosion 2010	2010	No
21	Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping	J. D. Palmer			No
22	Exploring the Relationship Between Soil Properties and Deterioration of Metallic Pipes Using Predictive Data Mining Methods	Z. Liu, R. Sadiq, B. Rajani, and H. Najjaran	National Research Council	2010	No
23	First Energy Davis Besse Indirect Inspections	A. Kowalski and K. Lawson	CC Technologies Report 83284602	2009	No
24	Fresh Water Corrosion in the Duluth - Superior Harbor	C. Marsh, J. Bushman, A. Beitelman, R. Buchheit, and B. Little		2004	No
25	Gas Pipelines Corrosion Data Analysis and Related Topics	D. Lewandowski		2002	Yes
26	Prediction of Corrosion Defect Growth on Operating Pipelines	L. Fenyvesi, H. Lu, and T. Jack	IPC2004-000268	2004	No
27	A New Probabilistic Methodology For Undertaking External Corrosion Direct Assessment	A. Francis, M. McCallum, M. Van Os, et al.	IPC2006-10092	2006	No
28	Determination Of The Corrosion Rate of a MIC Influenced Pipeline Using 4 Consecutive Pig Runs	G. Achterbosch and L. Grzelak	IPC2006-10142	2006	Yes
29	Effect of Transitions In The Water Table and Soil Moisture Content on the Cathodic Protection of Buried Pipelines	F. King, R. Given, R. Worthington, and G. Van Boven	IPC2006-10171	2006	Yes
30	Life Prediction Estimation of an Underground Pipeline Using Alternate Current Impedance and Reliability Analysis	H. Castaneda, J. Alamilla, and R. Perez	NACE 04050429	2004	Yes
31	Modeling Pipe Deterioration using Soil Properties - An Application of Fuzzy Logic Expert System	H. Najjaran and B. Rajani	NRCC - 47014	2004	No
32	Monitoring the Corrosion Susceptibility of Mild Steel in Varied Soil Textures by Corrosion Product Count Technique	E. E. Ogizie, I. B. Agochukwu, and A. I. Onuchukwu	Science Direct	2003	Yes
33	Analysis of Pipeline Steel Corrosion Data From NBS (NIST) Studies Conducted Between 1922-1940 and Relevance to Pipeline Management	R. Ricker	NISTIR 7415	2007	Yes

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
34	On the Probabilistic Distribution of External Pitting Corrosion Rate in Buried Pipelines	F. Caleyo, J. Velazquez, J. Hallen, and J. Araujo	IPC 2008	2008	No
35	Predicting Corrosion Rates for Onshore Oil and Gas Pipelines	J. Race, J. Dawson, L. Stanley, et al.	PPIMC 2007	2007	Yes
36	Predictive Model for Pitting Corrosion in Buried Oil and Gas Pipelines	F. Caleyo, J. Velazquez, A. Valor, et al.	NACE Corrosion 2009	2009	No
37	Probability Distribution of Pitting Corrosion Depth and Rate in Underground Pipelines: A Monte Carlo Study	F. Caleyo, J. Velazquez, A. Valor, et al.	Science Direct / Corrosion Science	2009	No
38	Progress Report on the Corrosion Behavior of Selected Stainless Steels in Soil Environments	W. Gerhold, E. Escalante, and B. Sanderson	NBSIR 76-1081	1976	No
39	Projecting Pipeline Pitting Rates And Cathodic-Protection Requirements Using Corrosion Coupons	T. J. Barlo	NACE Corrosion 1996 Paper 96203	1996	Yes
40	Rapid Underground Corrosion Measurements for Buried Pipelines	P. Kempe, A. Denzine, and E. Tiefnig	NACE Corrosion 2000 Paper 00092	2000	Yes
41	Real Time Monitoring of Corrosion in Soil Utilizing Coupled Multielectrode Array Sensors	X. Sun	NACE Corrosion 2005 Paper 05381	2005	Yes
42	Risk Informed Assessment of Degraded Buried Piping System in Nuclear Power Plants	J. Braverman, G. DeGrassi, et al.	NUREG/CR-6876 BNL-NUREG-74000-2005	2005	No
43	Preparation, Installation, Analysis, and Interpretation of Corrosion Coupons in Oilfield Operations		NACE RP077505	2005	Yes
44	Soil Analysis and Corrosiveness Calculations Webinar	B. Ammend	Structural Integrity	2009	Yes
45	Soil Chemistry Analysis and Effects on Corrosion Rate	D. Ersoy	GTI	2005	Yes
46	Soil Corrosion Monitoring Near Pipeline Under CP	S. J. Bullard	DOE/ARC	2005	Yes
47	Soil Corrosivity Analysis				Yes
48	Soil Properties Affecting Corrosion and CP of Steel in Texas Soils	T. J. Moore		1985	Yes
49	Standard Guide for Applying Statistics to Analysis of Corrosion Data		ASTM G16-95	1995	Yes
50	Statistical Modeling of Pitting Corrosion and Pipeline Reliability	A. K. Sheikh and D. A. Hansen	NACE Corrosion: March 1990, Vol. 46	1990	Yes

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
51	Techniques for Assessment of Soil Corrosivity	C. L. Durr and J. Beavers	NACE Corrosion 1998 Paper 98667	2006	Yes
52	Tests on the Corrosion of Buried Ferrous Metals	J. C. Hudson, T. A. Bandfield,, and H. A. Holden		1942	Yes
53	The Effects of Soil Characteristics on Corrosion	V. Chaker and J. D. Palmer	ASTM STP1013	1989	Yes
54	Time Dependence of the Minimum Requirements for CP Against Pitting Corrosion in Natural Soils	T. Barlo			Yes
55	Underground Corrosion, Escalante	E. Escalante	NBS STP741-EB-DL	1979	Yes
56	Using Soil Analysis and Corrosion Rate Modeling to Support ECDA and Integrity Management of Pipelines and Buried Plant Piping	S. Biagiotti, S. Biles, and C. Chaney	NACE Corrosion 2010 Paper 10059	2010	Yes
57	Water and Soil-Side Corrosion of Copper Water Service Lines	A. Cohen and A. Brock	NACE MP 1995	1995	Yes
58	Chemical & Physical Properties of Soils from DNV Pipeline Direct Examination Projects - Sand Soil		DNV	Various	Yes
59	Chemical & Physical Properties of Soils from DNV Pipeline Direct Examination Projects - Clay Soil		DNV	Various	Yes
60	Chemical & Physical Properties of Soils from DNV Pipeline Direct Examination Projects - Gravel Soil		DNV	Various	Yes
61	Chemical & Physical Properties of Soils from DNV Pipeline Direct Examination Projects - Organic Soil		DNV	Various	Yes
62	Chemical & Physical Properties of Soils from DNV Pipeline Direct Examination Projects - Loam Soil		DNV	Various	Yes
63	Chemical & Physical Properties of Soils from DNV Pipeline Direct Examination Projects - Sandy Loam Soil		DNV	Various	Yes
64	Chemical & Physical Properties of Soils from DNV Pipeline Direct Examination Projects - Other Soil		DNV	Various	Yes
65	Chemical & Physical Properties of Soils from DNV Pipeline Direct Examination Projects - Combined (All) Soils		DNV	Various	Yes
66	A Numerical Model for Cathodic Protection of Buried Pipes	F. Brichau and J. Deconinck	NACE Corrosion 1994 Paper 10039	1994	No

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
67	American National Standard for Polyethylene Encasement for Effective, Economical Protection for Ductile Iron Pipe In Corrosive Environments		American National Standard	2000	No
68	Application of the Stochastic Process to Pitting Corrosion	H. P. Hong	NACE Doc ID 00010010	1994	No
69	Bayesian Estimates Of Measurement Error For In-Line Inspection and Field Tools	R. Worthingham and T. Morrison	IPC 27263	2002	No
70	Buried and Underground Piping and Tanks				No
71	Cathodic Protection Parameters Measured on Corrosion Coupons and Pipes Buried in the Field	T. J. Barlo	NACE Corrosion 1998 Paper 98661	1998	No
72	Changes in Soil Properties and Crop Production due to Pipeline Construction	S. D. Zellmer	TRB 00493986		No
73	Comparison of the Soil Corrosion Resistance of Ductile Iron Pipe and Gray Cast Iron Pipe				No
74	Comprehensive Review of Structural Deterioration of Water Mains: Physically Based Models	B. B. Rajani and Y. Kleiner	NRC	2011	No
75	Copper Corrosion In Moderate and High Resistivity Soils				No
76	Corrosion Basics		NACE	1984	No
77	Corrosion Control Procedure for Gray Iron and Ductile Iron Pipe				No
78	Corrosion Protection of Ductile Iron Pipe	D. Kroon, D. Lindemuth, S. Sampson, et al.	NACE Corrosion 2004 Paper 04046		No
79	Corrosion Resistance of Stainless Steels in Soils And Concrete	C. Biarritz		2001	No
80	Corrugated Pipe Corrosion in Soils				No
81	Design Decision Model for Corrosion Control of Ductile Iron Pipelines	L. G. Horn	DIPRA	2006	No
82	Development of Ph Sensor for Indirect Evaluation of Pipeline Corrosion	A. Triques, D. Gonzalez, J. Celnik, et al.			No
83	Effect Of Aeration On Hydrogen-Ion Concentration of Soils in Relation to Identification of Corrosive Soils	M. Romanoff	NBS RP1639	1945	No
84	Electrical Resistivity Survey in Soil Science: A Review	A. Samouelian, I. Cousin, A. Tabbagh, A. Bruand, et al.			No

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
85	Engineering Behavior of Soil Materials on the Corrosion of Mild Steel	A. I. M. Ismail and A. M. El-Shamy	Science Direct / Applied Clay Science	2008	No
86	Evaluation of Corrosion Failure by Extreme Value Statistics	T. Shibata	ISIJ International 1991	1990	No
87	Evaluation of the Corrosivity of the Soil Through Its Chemical Composition	C. A. M. Ferreria, J. A. C. Ponciano, D. S. Vaitsman, and D. V. Perez		2007	No
88	External Corrosion and Protection of Ductile Iron Pipe				No
89	External Corrosion of Buried Iron Pipes	H. Collins		1986	No
90	First Energy Davis Besse Direct Examination and Post Assessment		CC Technologies Report 83284603		No
91	Fundamental Issues in the Application of Electrochemical Impedance Spectroscopy	D. Macdonald	NACE Corrosion 2005 Paper 05343	2005	No
92	Geotechnical Investigations for Corrosive Soils	G. Davenport, E. Rinne, and A. Zamora			No
93	Guideline for the Management of Underground Piping and Tank Integrity		Nuclear Energy Institute	2010	No
94	Historical and Recent Approaches to Corrosion Rate Distributions				No
95	IBP1143 - The Use of Weibull Statistics in the Analysis of Hydrotest Data	C. Scott	Rio Pipeline 2007		No
96	Identifying Trends In Cast Iron Pipe Failure with GIS Maps of Soil Environments	P. Davis, I. Allan, et al.			No
97	Identifying Trends in Cast iron Pipe Failure with GIS Maps	P. Davis, I. Allan, and S. Burn			No
98	Impact of Soil Properties on Pipe Corrosion: Re-examination of Traditional Conventions	B. B. Rajani and Y. Kleiner	NRC	2010	No
99	Improved Method for Measuring Pipe-to-Soil Potential	K. Kasahara, T. Sato, and H. Adachi	Tokyo Gas		No
100	Industry Initiative on Underground Piping and Tanks Integrity	A. Pietrangelo	Nuclear Energy Institute	2010	No
101	Investigation of Soil Corrosivity in the Corrosion of Low Carbon Steel Pipe in Soil Environment	A. Rim-rukeh and J. K. Awatefe	Journal of Applied Sciences Research	2006	No
102	Investigation of Soil Corrosivity of Low Carbon Steel Pipe in Soil Environment	A. Rim-rukeh and J. K. Awatefe		2006	No

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
103	Investigation of the Inhibitive Effect of Benzylidene-benzene on Corrosion of Carbon Steel Pipelines in Acidic Medium		Science Direct		No
104	Quantitative Evaluation Of Indirect Inspection Reliability and Pipeline Reliability Based on Statistical Methods	J. Mihell, D. Coleman, and R. Sporns	IPC 2004-000057	2004	No
105	Reliability-Based Evaluation of Pipelines Using Above Ground Inspection Methods for External Corrosion	M. Fuglem and M. Stephens	IPC 2004-000247	2004	No
106	Assessment of Corrosion Defects in Old, Low Toughness Pipelines	M. Martin and B. Andrews	IPC 2006-10140	2006	No
107	An External Corrosion Direct Assessment Module for a Pipeline Integrity Management System	M. Van Os and P. Van Mastrigt	IPC 2006-10159	2006	No
108	Method for Establishing Hydrostatic Re-Test Intervals for Pipelines with Stress-Corrosion Cracking	R. Fessler and S. Rapp	IPC 2006-10163	2006	No
109	A Statistical Predictive Model to Prioritize Site Selection for Stress Corrosion Cracking Direct Assessment	A. Merle and P. F. Ehlers	IPC 2006-10573 -	2006	No
110	Laboratory Electrochemical Testing of Pipe Surfaces in Soil	J. Scully and K. Bundy		1984	No
111	Localized Corrosion of Carbon Steel in a CO2 - Saturated Oil Field Formation Water	G. Zhang and Y. Cheng	Electrochimica Acta	2009	No
112	Long Term Underground Corrosion of Stainless Steel	M. Flitton and T. Yoder	NACE 2007	2007	No
113	Managing Subsurface Property Hazards Reactive Soils and Underground Storage Tanks	P. Hudak, D. Wachal, and B. Hunter		1999	No
114	Mapping Soil Resistivity	R. Jurick and R. McHattie	The Northern Engineer	1981	No
115	Methods for Accessing Pitting Damage in Carbon Steel Exposed to Alkaline Chloride Waste Environments	M. A. Hill and R. Lilliard	NACE	2006	No
116	New Techniques for Studying Soil Corrosion of Underground Pipeline	N. Yahaya, N. Noor, S. Othman, et al.	Journal of Applied Science	2011	No
117	Observations on the Behavior of Steel Corroding under Cathodic Control in Soils	A. Denison and R. B. Darnielle		1939	No

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
118	Physiochemical Characteristics of Controlled Low Strength Materials Influencing the Electrochemical Performance and Service Life of Metallic Materials	C. Halmien		2005	No
119	Pipe Line Corrosion in Soil	W. Schwerdtfeger and O. N. McDorman	NBS	1951	No
120	Pipeline Corrosion in Soil	Dr. Maher A. Alodan and Dr. Faraj Abdulaleem		2007	No
121	Pitting Likelihood Ranking for Stainless Steels in Soil	F. Gui, R. Thodla, and S. Brossia	EPRI Report	2008	No
122	Potential and Current Requirements for CP Protection of Steel in Soils	Schwerdfeger			No
123	Prediction of Soil Corrosivity Using Linear Polarization	E. Kalantzis		1997	No
124	Predictive Model for Pit Growth on Underground Pipes	Y. Katano, K. Miyata, and H. Shimizu	NACE	2003	No
125	Predictive Model for Pitting Corrosion in Buried Oil and Gas Pipelines	J. Valazques, F. Caleyo, A. Valor, et al.	NACE 2009	2009	No
126	Probabilistic Assessment for Failure probability of Pipe Lines by Extreme Value Distribution	S. H. Lee, B. Choe, Y. Kim, et al.		2005	No
127	Probabilistic Modeling Of Corroded Pipeline Structures	D. P. Brennan and U. O. Akpan	IPC 27233	2002	No
128	Recommended Practice for ECDA Exhibits Some Confusion				No
129	Reliable Inference for the Maximum Pit Depth within Pitting Colonies on Long Pipelines	A. T. Martinsek	NACE	2003	No
130	Review comments on Corrosion Protection of Ductile Iron Pipe	D. Kroon, D. Lindemuth, S. Sampson, et al.			No
131	Soil Corrosivity Determination by Electrochemical Methods	M. Arpaia, A. Frignani, P. Pernice, et al.			No
132	Soil Properties and Qualities				No
133	Soil Survey Laboratory Information Manual	National Soil Survey Center Soil Survey Laboratory			No
134	Some Pipe-to-Soil Potential Readings Mislead Operators	J. M. Leeds	Pipeline and Gas Industry	1997	No
135	Statistical Analyses of Field Corrosion Data for Ductile Cast Iron Pipes Buried in Sandy Marine Sediments	F. Kajiyama and Y. Koyama	NACE 97020156	1997	No

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
136	Statistical Analysis of Soil Characteristics to Predict Mean Time to Corrosion Failure of Underground Metallic Structures	J. B. Bushman and T. E. Mehalick	ASTM STP 1013	1989	No
137	Statistical and Stochastic Approaches to Localized Corrosion	T. Shibata	NACE 96110813	1996	No
138	Statistical Characterization of Pitting Corrosion - Part 1: Data Analysis	R. E. Melchers	NACE	2005	No
139	Statistical Characterization of Pitting Corrosion - Part 2: Probabilistic Modeling for Maximum Pit Depth	R. E. Melchers	NACE	2005	No
140	Steel Corrosion Rate in Soils by A.C and D.C. Electrochemical Methods	P. Pernice, M. Arpaia, and A. Costantini		1990	No
141	Step 7 Corrosion Guide		CHANCE	2003	No
142	Stray Current Effects on Ductile Iron Pipe	R. W. Bonds	DIPRA		No
143	Stress Analysis Methods for Underground Pipelines	L. C. Peng			No
144	Supplemental Report to the Comprehensive Reliability Assessment by Nuclear Safety Associates			2010	No
145	Testing Soil for Corrosiveness	W. Robinson	MP 1993	1993	No
146	The Critical Soil Moisture Content in the Underground Corrosion of Mild Steel	S. K. Gupta and B. K. Gupta		1979	No
147	The Effect of Soil Resistivity And Soil Temperature on the Corrosion of Galvanically Coupled Metals in Soil	E. Escalante	ASTM-STP-978		No
148	The Influence of Reynolds Number on the Galvanic Corrosion of the Copper/AISI 304 Pair in Lithium Bromide using a Zero-Resistance Ammeter	M. T. Montanes, R. Sanchez-Tovar, et al.	Corrosion Science 2009	2009	No
149	The Use of Coupons for Monitoring the Cathodic Protection of Buried Structures	K. Lawson and N. Thompson	NACE Corrosion 1998 Paper 98672	1998	No
150	The Use of IR Drop Coupons as a Practical & Effective Test Method	J. Didas	NACE Corrosion 1998 Paper 98666	1998	No
151	Underground Petroleum Piping System				No
152	Using Cast Iron Pipe in Highly Corrosive Environments	D. Hoffman		1966	No

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
153	Application of Extreme Value Statistics to the Prediction of Maximum Pit Depth in Non-Piggable Buried Pipelines	F. Cayelo, J. M. Hallen, L. Alfonso, and J. J. Escamilla-Davish		2008	Yes
154	Changes in Soil Properties and Crop Production Due to Pipeline Construction	S. Zellemer, J. Taylor, and D. Johnson		1989	Yes
155	Corrosion by Soils	K. H. Logan			Yes
156	Determining Pipeline Corrosion Growth Rates				Yes
157	Effect of Aeration on Hydrogen-Ion Concentration of Soil in Relation to Identification of Corrosion Soils	M. Romanoff		1945	Yes
158	Laboratory Electrochemical Testing of Pipe Surface in Soils	J. R. Scully and K. J. Bundy		1984	Yes
159	Low-Field Electrical Characteristics of Soil	C. Mallon and R. Denson		1981	Yes
160	Natural Resources Conservation Service	United States Department of Agriculture			Yes
161	On the Probabilistic Distribution of External Pitting Corrosion Rate in Buried Pipelines	F. Cayelo, J. C. Velasquez, J. M. Hallen, and J. E. Araujo		2008	Yes
162	Pipeline Corrosion R&D at NIST	R. Ricker	NIST		Yes
163	Pitting Corrosion of Pipeline Steel In Dilute Bicarbonate Solution with Chloride Ions	X. Mao, X. Liu, and R. W. Revie		1994	Yes
164	Predictive Model for Pit Growth on Underground Pipes	K. Katano, K. Miyata, H. Shimizu, and T. Isogai		2003	Yes
165	Predictive Model for Pitting Corrosion in Buried Oil and Gas Pipelines	F. Cayelo, J. C. Velasquez, J. M. Hallen, and J. E. Araujo		2009	Yes
166	Probability distribution of pitting corrosion depth and rate in underground pipelines: A Monte Carlo Study	F. Cayelo, J. C. Velasquez, J. M. Hallen, and A. Valor		2009	Yes
167	Protection Potential of ST3 Steel in Liquid Cultures of Soil Micro-organisms	V. Pritula, G. Sapozhikova, and G. Mogil'nitskii		1987	Yes
168	Soil Corrosivity Determination by Electrochemical Methods	M. Arpaia, A. Frignani, P. Pernice, and G. Trabanelli		1981	Yes
169	Soil Properties Affecting Corrosion and Cathodic Protection of Steel in Texas Soils.	T. J. Moore		1985	Yes
170	Some New Views on Soil Corrosion	E. Schaschl and G. A. Marsh			Yes
171	Some new views on Soil Corrosion	E. Schaschl and G. A. Marsh	MP 1963	1963	Yes

No.	Title	Author(s)	Source	Date	Corrosion Rate Data
172	Sulfide Determination in Submerged Soils with an Ion-Selective Electrode	A. Allam, G. Pitts, and J. P. Hollis		1971	Yes
173	Sulphate-Reducing Bacteria - Their Contribution to the Corrosion Process	J. A. Hardy and J. L. Brown			Yes
174	Test on the Corrosion of Buried Ferrous Metals	J. Hudson and T. Banfield		1942	Yes
175	Testing Soil for Corrosiveness	W. C. Robinson			Yes
176	Testing Soil for Corrosiveness	W. C. Robinson		1993	Yes
177	The Effects of Chloride Concentration on the Corrosion Rate of Galvanized Steel Specimen	CC Technologies		1988	Yes
178	The Useful Life of Steel Piles in Soil				Yes
179	Underground Corrosion	M. Romanoff	NACE Reprint	1957	Yes
180	Field Testing the Criteria for Cathodic Protection of Buried Pipelines	T. J. Barlo	PRCI Report PR-208-163	1994	Yes
181	Corrosion of Steel and Metal-Coated Steel in Swedish Soils	G. Camitz and T. G. Vinka	ASTM STP 1013		Yes
182	Galvanic Corrosion, A Practical Guide for Engineers	R. Francis	NACE Press	2001	No

B

STATISTICAL ANALYSIS AND MODELING OF DET NORSKE VERITAS (DNV) DIRECT EXAMINATION DATA

Introduction

This statistical summary provides an overview of the Det Norske Veritas (DNV) direct examination linear polarization resistance (LPR) corrosion rate data. Statistical modeling was performed using three soil categories to see if any correlation exists between the LPR data and variables such as moisture content, pH, resistivity, chloride ion content (Cl^-), sulfate content (SO_4^{2-}), nitrite (NO_2^-), and carbonate (CO_3^{2+}). Regression equations and predicted LPR versus observed LPR were prepared for each soil type. As seen in Table B-1, there are 353 records in the data set for the statistical analysis, with the count and percentage broken down by soil type. Due to the limitations in some of the data, the analysis was performed using three subsets: (1) Clay soil type only (n = 187), (2) All soil data (n = 353), and (3) Sand soil type only (n = 99).

Table B-1
Direct Examination Data by Soil Type

Soil Type	Count (n)	Percent (%)
Clay	187	52.97
Clay Loam	5	1.42
Gravel	4	1.13
Industrial Fill	9	2.55
Loam	16	4.53
Organic Material	17	4.82
Sand	99	28.05
Sandy Loam	10	2.83
Other	5	1.42
Wet Backfill Sand	1	0.28
N =	353	

Clay Soil

Pearson correlation coefficients were computed between LPR and all other quantitative variables in the data. Only selected results are shown below. The variables shown were either found to be statistically significant at the 95% confidence level or were variables found to be of interest in other subsets of the data. To be statistically significant at the 95% confidence level, the p-value associated with the correlation coefficient must be 0.05 or less. Statistically significant implies that with 95% confidence there is evidence of a non-zero correlation between the two variables. This relationship may be positive or negative. Having a statistically significant correlation also implies that there is sufficient evidence of a non-zero linear trend between the two variables. The sign of the corresponding regression slope term will be the same as the sign of the correlation coefficient and is reported in Table B-2.

Table B-2
Clay LPR Correlation Coefficient Values

LPR	r, correlation coefficient	p-value	Statistically significant at 95% confidence level?
Ca^{2+}	0.214	0.029	Yes
NO_2^-	0.165	0.095	No
Cl^-	0.095	0.338	No
SO_4^{2-}	0.299	0.003	Yes
pH	0.261	0.000	Yes
Moisture Content	-0.199	0.007	Yes
Resistivity	-0.123	0.094	No

Correlation analysis examines only bivariate relationships—that is, it only considers two variables at a time. From the above, a stepwise regression was run to aid in the development of a multi-variable regression. From the stepwise procedure, a more general regression procedure was used to allow more in-depth assessment. For clay soil type, the stepwise regression results for LPR are shown in Table B-3, with the more general regression results immediately following in Table B-4. In accordance with the methodology, if any variable in the regression analysis is missing, then that entire record is dropped from the regression. Because of much missing data, the number of records used in a given regression is often quite less than the number of records (rows) in the corresponding data set.

Table B-3
Clay Soil Stepwise Regression Results

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15			
Response is LPR on 5 predictors, with N = 97			
N(cases with missing observations) = 90 N(all cases) = 187			
Step	1	2	3
Constant	0.09281	0.08306	0.09041
Moisture Content % -	0.00154	-0.00139	-0.00155
T-Value	3.16	-2.94	-3.31
P-Value	0.002	0.004	0.001
SO_4^{2-}	0.00002	0.00002	
T-Value	2.83	2.95	
P-Value	0.006	0.004	
Resistivity	-0.00000		
T-Value	-2.25		
P-Value	0.027		
S	0.0696	0.0671	0.0657
R-Sq	9.50	16.63	20.94
R-Sq(adj)	8.55	14.86	18.39
Mallows Cp	12.6	6.3	3.2

Table B-4
Clay Soil General Regression Results

The regression equation is	
LPR = 0.0904 - 0.00155 Moisture Content % + 0.000025 SO_4^{2-} - 0.000001 Resistivity	
97 cases used, 90 cases contain missing values	
Predictor	Coroef SE Coef T P
Constant	0.09041 0.01208 7.49 0.000
Moisture Content %	-0.0015513 0.0004686 -3.31 0.001
SO_4^{2-}	0.00002488 0.00000844 2.95 0.004
Resistivity	-0.00000135 0.00000060 -2.25 0.027
S	0.0657219 R-Sq = 20.9% R-Sq(adj) = 18.4%
Analysis of Variance	
Source	DF SS MS F P
Regression	3 0.106373 0.035458 8.21 0.000
Residual Error	93 0.401701 0.004319
Total	96 0.508074

The predictive equation is the one seen above: LPR = 0.0904 - 0.00155 Moisture Content % + 0.000025 SO_4^{2-} - 0.000001 Resistivity. In Figure B-1, it can be seen that although all variables in the above regression model are indeed statistically significant at the 95% confidence level (their p-value is less than $\alpha = 0.05$), the resulting prediction is obviously poor.

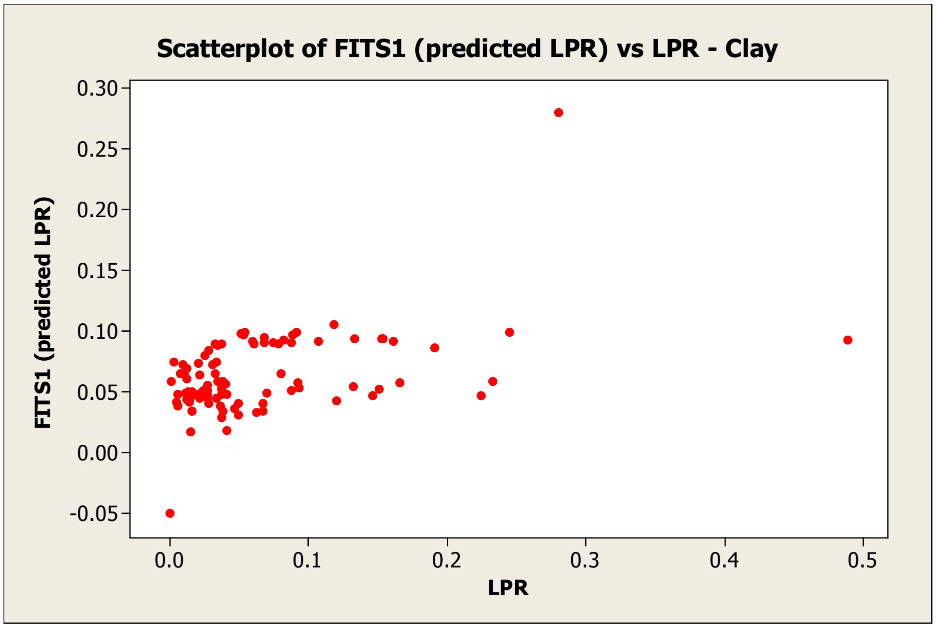


Figure B-1
Predicted LPR vs. Observed LPR for Clay Soil Type

The examination of such visual aids is key in not reporting a model that is of little practical use. This led to additional analyses on the clay data with the hope of developing a better predictive model. In essence, two potential LPR outliers were dropped from the data, and subsequent results for clay use the new variable name LPR_2 to indicate the dropping of two LPR values. Dropping selected data values should not be done lightly, because the deleted values may be providing key insights. For the regression modeling purposes in this report, the intent is to develop the best possible predictive model. Further results in Tables B-5, B-6, and B-7 continue this modeling process for clay with LPR_2.

Table B-5
Clay LPR_2 Correlation Coefficient Values

LPR_2	r, correlation coefficient	p-value	Statistically significant at 95% confidence level?
Ca^{2+}	0.288	0.003	Yes
NO_2^-	0.218	0.028	Yes
Cl^-	0.128	0.197	No
SO_4^{2-}	0.382	0.000	Yes
pH	0.325	0.000	Yes
Moisture Content	-0.201	0.006	Yes
Resistivity	-0.146	0.048	Yes

Table B-6
Clay Soil LPR_2 Stepwise Regression Results

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15					
Response is LPR on 6 predictors, with N = 96					
N(cases with missing observations) = 91 N(all cases) = 187					
Step	1	2	3	4	5
Constant	0.05078	0.07071	0.07752	-0.01547	-0.02462
SO_4^{2-}	0.00003	0.00003	0.00003	0.00003	0.00003
T-Value	4.00	3.80	3.98	4.13	4.20
P-Value	0.000	0.000	0.000	0.000	0.000
Moisture Content %		-0.00099	-0.00114	-0.00092	-0.00077
T-Value		2.64	-3.10	-2.47	-2.06
P-Value		0.010	0.003	0.016	0.042
Resistivity			-0.00000	-0.00000	-0.00000
T-Value			-2.63	-2.90	-2.87
P-Value			0.010	0.005	0.005
pH				0.0114	0.0116
T-Value				2.24	2.33
P-Value				0.027	0.022
NO_2^-					0.0115
T-Value					2.17
P-Value					0.032
S	0.0544	0.0527	0.0511	0.0500	0.0490
R-Sq	14.56	20.52	26.07	29.94	33.43
R-Sq(adj)	13.65	18.81	23.66	26.86	29.73
Mallows Cp	22.6	16.6	11.1	7.9	5.3

Table B-7
Clay Soil LPR_2 General Regression Results

The regression equation is	
LPR_2 = - 0.0246 + 0.000026 SO_4^{2-} - 0.000769 Moisture Content %	
96 cases used, 91 cases contain missing values	
Predictor	Coef SE Coef T P
Constant	0.02462 0.04188 -0.59 0.558
SO_4^{2-}	0.00002647 0.00000630 4.20 0.000
Moisture Content %	-0.0007693 0.0003727 -2.06 0.042
Resistivity	-0.00000130 0.00000045 -2.87 0.005
pH	0.011610 0.004983 2.33 0.022
NO_2^-	0.011515 0.005301 2.17 0.032
S	0.0490310 R-Sq = 33.4% R-Sq(adj) = 29.7%
Analysis of Variance	
Source	DF SS MS F P
Regression	5 0.108641 0.021728 9.04 0.000
Residual Error	90 0.216364 0.002404
Total	95 0.325005

Figure B-2 shows an improved model but one that is still far from perfect. Note how flat the blue regression line is. Therefore the predicted values are significantly less than the observed LPR values.

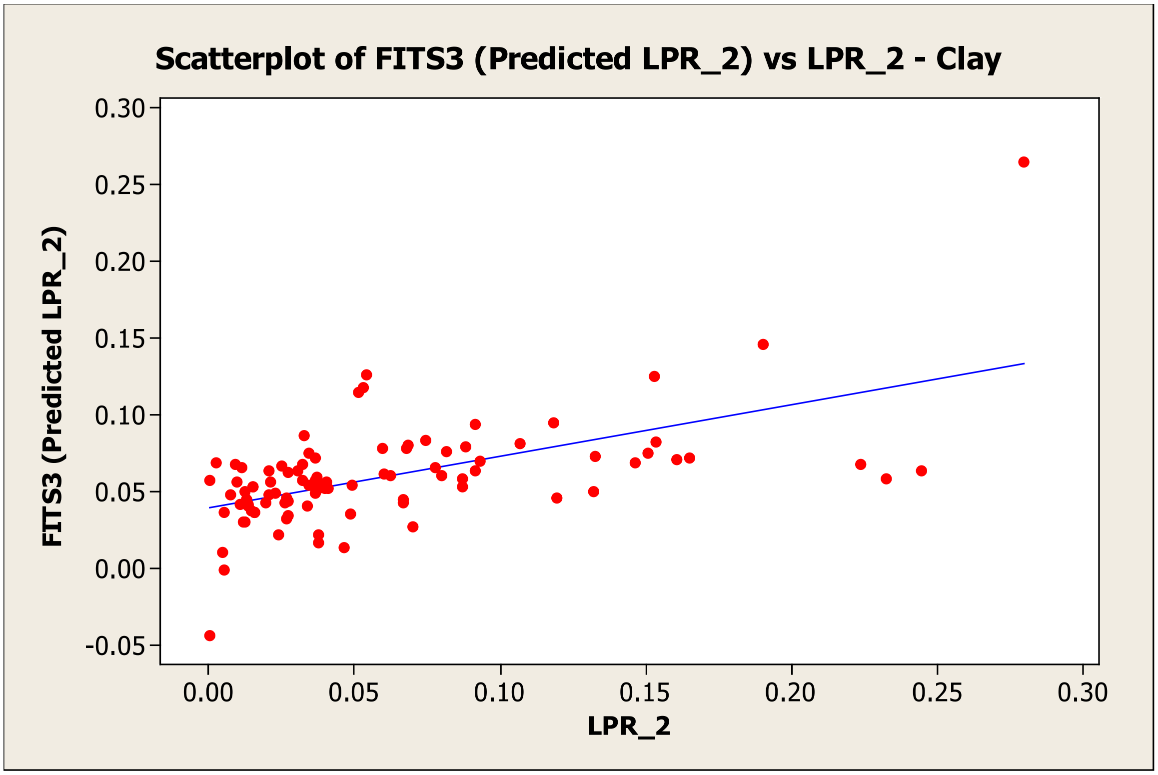


Figure B-2
Predicted Clay LPR vs. Observed LPR with Two Potential Outliers Dropped

All Soil Data

In this section the final model for all soil data is directly shown. The results are shown in Tables B-8, B-9, and B-10 and in Figure B-3.

Table B-8
All Soil Data LPR Correlation Coefficient Values

LPR_2	r, correlation coefficient	p-value	Statistically significant at 95% confidence level?
Ca^{2+}	0.218	0.003	Yes
NO_2^-	0.214	0.028	Yes
Cl^-	0.229	0.197	Yes
SO_4^{2-}	0.279	0.000	Yes
pH	0.241	0.000	Yes
Total Acidity	-0.093	0.281	No
Moisture Content	-0.05	0.351	No
Resistivity	-0.152	0.004	Yes

Table B-9
All Soil Data Stepwise Regression Results

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15				
Response is LPR on 7 predictors, with N = 160				
N(cases with missing observations) = 193 N(all cases) = 353				
Step	1	2	3	4
Constant	0.03620	0.03150	0.03550	0.05018
SO_4^{2-}	0.00003	0.00003	0.00003	0.00003
T-Value	3.84	3.83	3.85	3.67
P-Value	0.000	0.000	0.000	0.000
NO_2^-	0.0170	0.0162	0.0146	
T-Value	2.83	2.73	2.46	
P-Value	0.005	0.007	0.015	
Resistivity	-0.00000	-0.00000		
T-Value	-2.38	-2.82		
P-Value	0.019	0.006		
Moisture Content % -	-0.00075			
T-Value	-2.06			
P-Value	0.041			
S	0.0600	0.0588	0.0579	0.0573
R-Sq	8.53	12.98	16.02	18.27
R-Sq(adj)	7.95	11.87	14.41	16.16
Mallows Cp	16.5	10.1	6.3	4.1

Table B-10
All Soil Data General Regression Results

The regression equation is	
LPR = 0.0503 + 0.000026 SO_4^{2-} - 0.000781 Moisture Content %	
- 0.000000 Resistivity + 0.0146 NO_2^-	
166 cases used, 187 cases contain missing values	
Predictor	Coef SE Coef T P
Constant	0.050350 0.008726 5.77 0.000
SO_4^{2-}	0.00002611 0.00000695 3.76 0.000
Moisture Content %	-0.0007809 0.0003507 -2.23 0.027
Resistivity	-0.00000047 0.00000016 -2.88 0.005
NO_2^-	0.014594 0.005803 2.51 0.013
S	0.0562661 R-Sq = 18.7% R-Sq(adj) = 16.7%
Analysis of Variance	
Source	DF SS MS F P
Regression	4 0.117192 0.029298 9.25 0.000
Residual Error	161 0.509706 0.003166
Total	165 0.626899

Figure B-3 shows how flat the blue regression line is and thus the predicted values are often quite a bit less than the observed LPR values.

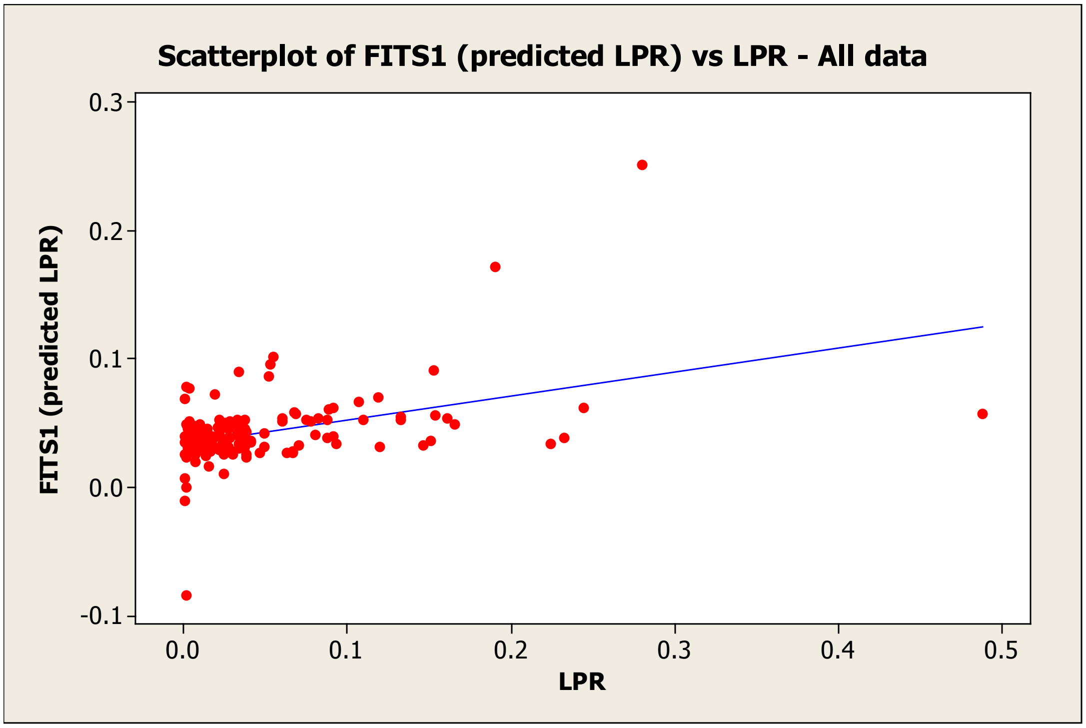


Figure B-3
Predicted LPR vs. Observed LPR for All Data

Sand Data

In this section, the final model for sand is shown directly without some of the intermediary results. To develop a good model one potential outlier was dropped.

Table B-11
Sand Data LPR Correlation Coefficient Values

LPR_2	r, correlation coefficient	p-value	Statistically significant at 95% confidence level?
Ca^{2+}	0.257	0.075	No
NO_2^-	0.267	0.092	No
Cl^-	0.64	0.000	Yes
SO_4^{2-}	-0.2	0.230	No
pH	0.045	0.658	No
Moisture Content	0.336	0.010	Yes
Resistivity	-0.415	0.000	Yes

Table B-12
Sand Soil Stepwise Regression Results

Alpha-to-Enter: 0.15 Alpha-to-Remove: 0.15	
Response is LPR_1 on 3 predictors, with N = 49	
N(cases with missing observations) = 50 N(all cases) = 99	
Step	1 2
Constant	0.002387 -0.001626
Cl^-	0.00011 0.00009
T-Value	5.71 6.23
P-Value	0.000 0.000
Moisture Content % -	0.00051
T-Value	5.47
P-Value	0.000
S	0.00546 0.00430
R-Sq	40.94 64.21
R-Sq(adj)	39.69 62.65
Mallows Cp	30.1 2.5

Table B-13
Sand Soil General Regression Results

The regression equation is	
LPR_1 = - 0.00163 + 0.000092 Cl^- + 0.000513 Moisture Content %	
49 cases used, 50 cases contain missing values	
Predictor	Coef SE Coef T P
Constant	-0.001626 0.001104 -1.47 0.148
Cl^-	0.00009204 0.00001476 6.23 0.000
Moisture Content %	0.00051318 0.00009386 5.47 0.000
S	0.00429679 R-Sq = 64.2% R-Sq(adj) = 62.6%
Analysis of Variance	
Source	DF SS MS F P
Regression	2 0.00152334 0.00076167 41.26 0.000
Residual Error	46 0.00084927 0.00001846
Total	48 0.00237261

Figure B-4 shows the best regression model developed in this full analysis. Note how much better the predicted and actual match.

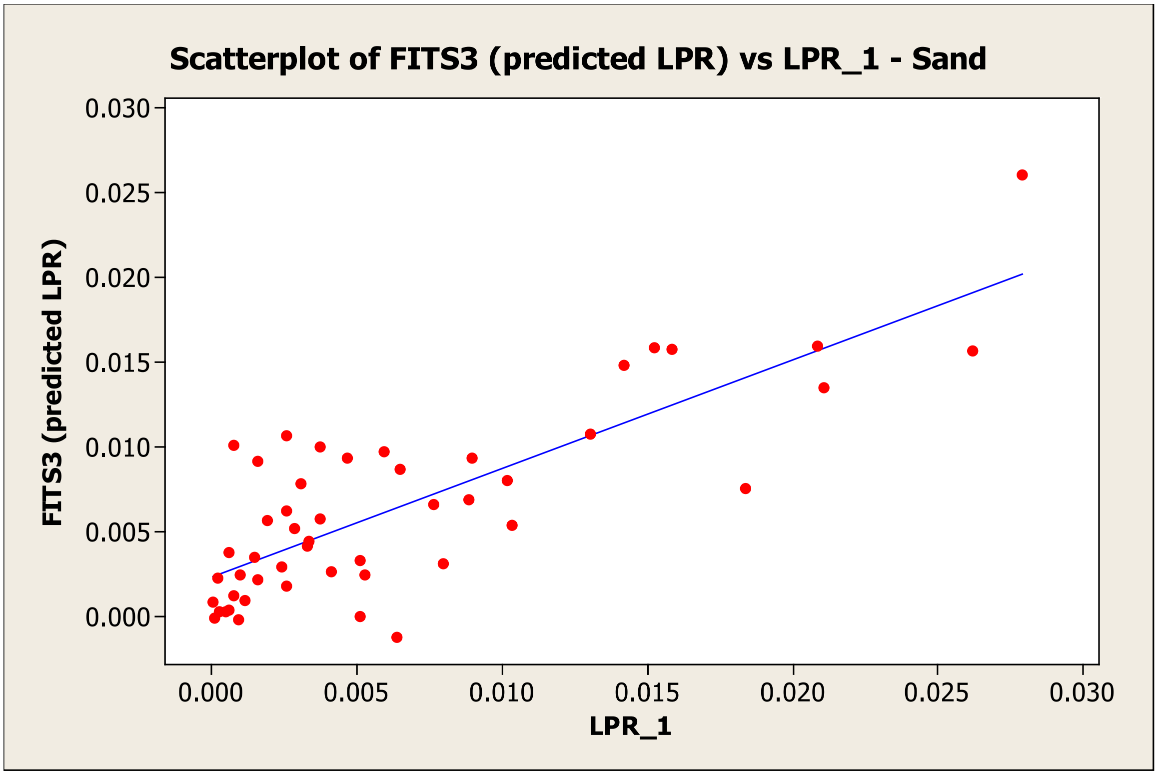


Figure B-4
Predicted LPR vs. Observed LPR for Sand Soil Type

C

CC TECHNOLOGIES GALVANIC CORROSION STUDY: CURRENT DENSITY PLOTS

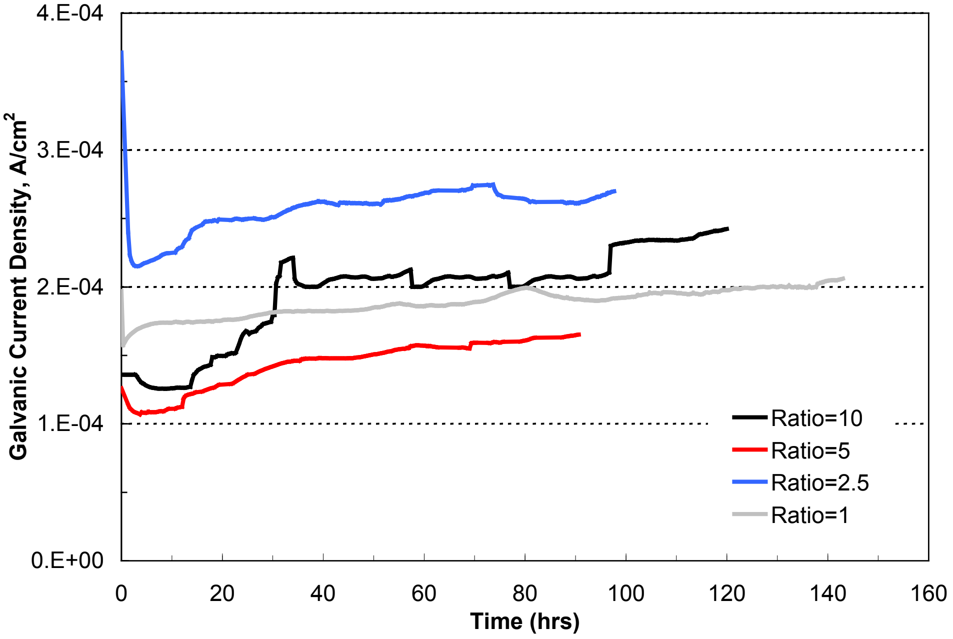


Figure C-1
Galvanic Current Densities vs. Time (Hours) for Soil Sample 2-3 (Resistivity: 160 ohm-cm)

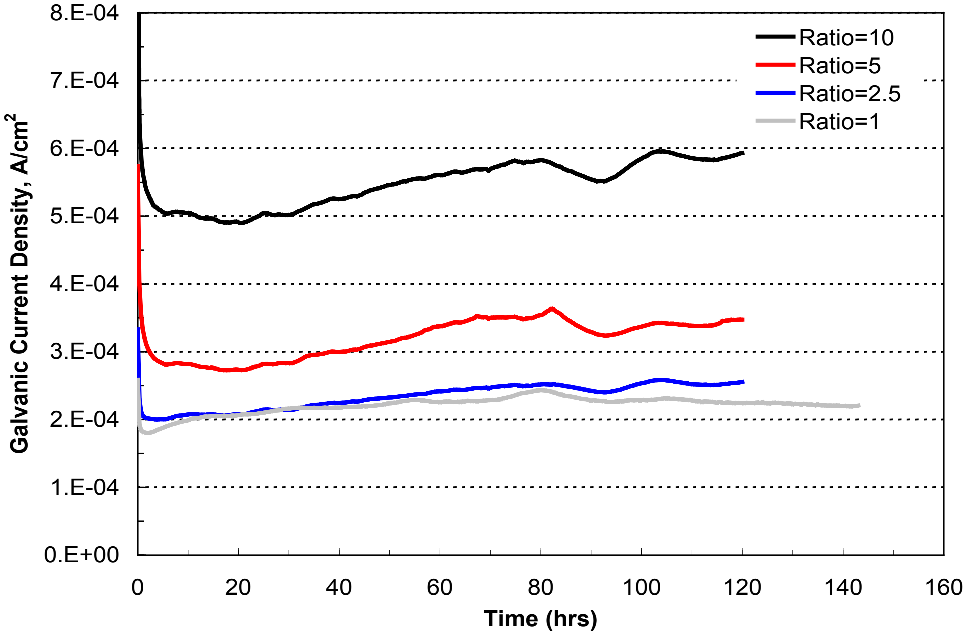


Figure C-2
Galvanic Current Densities vs. Time (Hours) for Soil Sample 2-6 (Resistivity: 190 ohm-cm)

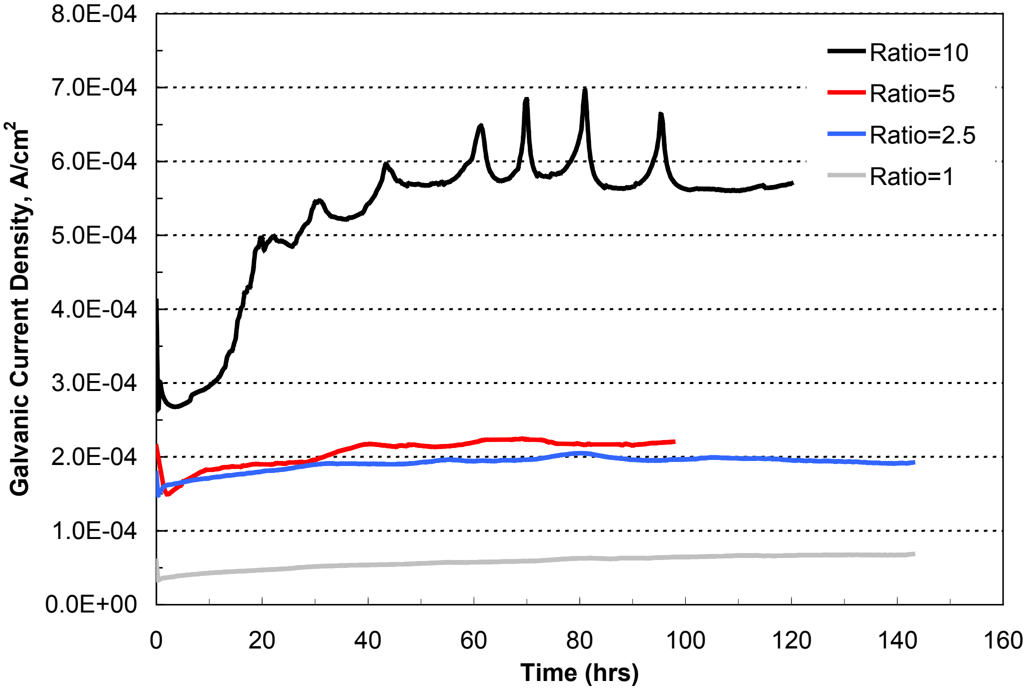


Figure C-3
Galvanic Current Densities vs. Time (Hours) for Soil Sample 2-8 (Resistivity: 4,000 ohm-cm)

Export Control Restrictions

Access to and use of EPRI Intellectual Property is granted with the specific understanding and requirement that responsibility for ensuring full compliance with all applicable U.S. and foreign export laws and regulations is being undertaken by you and your company. This includes an obligation to ensure that any individual receiving access hereunder who is not a U.S. citizen or permanent U.S. resident is permitted access under applicable U.S. and foreign export laws and regulations. In the event you are uncertain whether you or your company may lawfully obtain access to this EPRI Intellectual Property, you acknowledge that it is your obligation to consult with your company's legal counsel to determine whether this access is lawful. Although EPRI may make available on a case-by-case basis an informal assessment of the applicable U.S. export classification for specific EPRI Intellectual Property, you and your company acknowledge that this assessment is solely for informational purposes and not for reliance purposes. You and your company acknowledge that it is still the obligation of you and your company to make your own assessment of the applicable U.S. export classification and ensure compliance accordingly. You and your company understand and acknowledge your obligations to make a prompt report to EPRI and the appropriate authorities regarding any access to or use of EPRI Intellectual Property hereunder that may be in violation of applicable U.S. or foreign export laws or regulations.

The Electric Power Research Institute, Inc. (EPRI, www.epri.com) conducts research and development relating to the generation, delivery and use of electricity for the benefit of the public. An independent, nonprofit organization, EPRI brings together its scientists and engineers as well as experts from academia and industry to help address challenges in electricity, including reliability, efficiency, health, safety and the environment. EPRI also provides technology, policy and economic analyses to drive long-range research and development planning, and supports research in emerging technologies. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries. EPRI's principal offices and laboratories are located in Palo Alto, Calif.; Charlotte, N.C.; Knoxville, Tenn.; and Lenox, Mass.

Together…Shaping the Future of Electricity

1025256

Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com