Final Report

Improvement of External Corrosion Direct Assessment Methodology by Incorporating Soils Data

To

U.S. Department Of Transportation

Research and Special Projects Agency

Contract DTRS56-03-T-0003

November 2005

Final Report

on

Improvement of External Corrosion Direct Assessment Methodology by Incorporating Soils Data

To

U. S. Department of Transportation
Research and Special Projects Agency
Contract No. DTRS56-03-T-0003

November 2005

by

B. N. Leis, E. B. Clark, M. Lamontagne, and J. A. Colwell

BATTELLE
505 King Avenue
Columbus, Ohio 43201-2693

Marr & Associates
711 Main St. East
Milton, Ontario LT9 3Z3

Acknowledgements

This project was completed under contract to the Research and Special Projects Agency U. S Department of Transportation, under Contract No. DTRS56-03-T-0003, with Mr. James Merritt serving as the contracting officer's technical representative. Cost-share for this project came through funding from the Pipeline Research Council International (PRCI), associated with their project on 2002 Data Collection for Direct Assessment and Interstate Natural Gas Association of America (INGAA), associated with their project on Aging Pipeline Analysis.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 01-10-2005	2. REPORT TYPE Final	3. DATES COVERED *(From - To)* 2/3/2003 – 10/1/2005

4. TITLE AND SUBTITLE:
Improvements to the External Corrosion Direct Assessment Methodology by Incorporating Soils Data

5a. CONTRACT NUMBER
DTRS56-03-T-0003

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
B. N. Leis, E. B. Clark, and J. A. Colwell (Battelle)
M. Lamontagne (Marr & Associates)

5d. PROJECT NUMBER
118

5e. TASK NUMBER
7

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) AND ADDRESS(ES)
Battelle
505 King Avenue
Columbus, OH 43201

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
US Department of Transportation
Research and Special Programs Administration
Office of Contracts and Procurement, DMA-30
400 7th Street, SW, Room 7104
Washington, DC 20590

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Unlimited

13. SUPPLEMENTARY NOTES
None

14. ABSTRACT

To enhance the ECDA process, this project evaluated whether soils data could be used in a model to predict locations where external corrosion would be an issue. If by adding soils data to the previously collected ECDA datasets it could be shown that areas suffering corrosion could be predicted consistently, then operators would have an additional tool at their disposal to help maintain the country's natural gas pipeline infrastructure safely and reliably. The approach targeted soils-corrosivity, because if corrosivity dominated a very simple model would be viable as a screening tool – with such a model then viable when other data is not available, unreliable, or difficult to obtain.

Soil corrosivity was characterized in terms of a model that couples soils type with topography and drainage, with consideration also given to a simpler approach based on pH and resistivity. The results indicated that there is essentially no correlation between corrosion susceptibility based on soils-corrosivity expressed in terms of these two models. While an attempt was made to calibrate these measures of susceptibility using ILI data for corrosion incidence and severity, the frequency of corrosion for the sites evaluated was limited, which confounded this process.

Important conclusions include: 1) little correlation existed between external corrosion and soils corrosivity for six sites. It follows that corrosivity cannot be viewed as a dominant factor controlling corrosion susceptibility; 2) the lack of correlation is not surprising given the effectiveness of CP and coating integrity at the six sites evaluated; 3) soils models to guide ECDA must consider CP and coating integrity; 4) the observation that local corrosivity is not important if the coating and/or CP system is working well indicates sites for ECDA should first be chosen in regard to CP history to identify areas where CP is effective and/or the coating functional in contrast to areas susceptible to corrosion; and 5) where the ECDA process identifies deficiencies in either coating or CP, then higher level measurements of corrosivity (e.g., resistivity) will likely suffice to decide locations for further examination as part of the ECDA process.

15. SUBJECT TERMS
ECDA, corrosion susceptibility, soil corrosivity, soils model, soil type, topography, drainage, pH, resistivity

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Brian Leis
a. REPORT Unclassified	b. ABSTRACT Unclassified	c. THIS PAGE Unclassified			19b. TELEPHONE NUMBER *(include area code)* 614-424-4421 or -614-424-3976

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

Page

List of Figures

List of Tables

Executive Summary

Maintenance to keep external corrosion from degrading the nation's pipeline infrastructure, much of which was constructed decades ago, has always been an industry focus. Technologies that mitigate degradation caused by external corrosion began with the use of a protective coating system prior to burying the system and application of cathodic protection (CP). To broaden the effectiveness of the technologies used for corrosion control, the industry recently has codified techniques that have been used for many decades by formulating a comprehensive best practice known as external corrosion direct assessment (ECDA).

This project was conducted to evaluate whether soils data could be used in a model to predict locations where external corrosion could become a factor in pipeline degradation. If a soils model developed to interpret soils data collected as part of the ECDA datasets could be used to predict consistently which areas are prone to corrosion, then operators would have an additional tool to help maintain the country's natural gas pipeline infrastructure and keep it operating safely and reliably. Soils corrosivity was selected for closer examination for the simple reason that if it were a dominant factor in degradation in certain situations, a very simple model could be developed as a screening tool. Such a model could be useful even when other pipeline data are unavailable, unreliable, or difficult to obtain.

After considering a simple modeling approach based on pH and resistivity, a model to characterize soil corrosivity was developed by coupling soils type with topography and drainage. The results indicated that there is essentially no correlation between soil characteristics and corrosion susceptibility based on soils corrosivity as expressed in terms of these two metrics.

The more important conclusions drawn from this work include:

1. Little correlation was observed between external corrosion and soils corrosivity for data gathered at excavations along pipelines of the six operators who participated in this project. It follows that corrosivity by itself cannot be considered the dominant factor controlling corrosion susceptibility – even for aging pipeline systems – unless CP is ineffective and the coating condition is degraded. This lack of correlation is not surprising given the potentially significant role of both CP and coating integrity at the sites evaluated. This leads logically to the second conclusion.
2. Soils models that are developed to guide ECDA must consider CP and coating integrity. The fact that a local condition is more corrosive at one site versus another does not control the incidence of corrosion if the coating and/or CP system is working well. Consequently, site selection for ECDA should consider CP history to differentiate between areas where CP is effective and/or the coating functional versus areas where CP is not effective and the coating is not intact resulting in locations susceptible to corrosion.
3. If the ECDA process identifies deficiencies in either coating or CP, then higher level measurements of corrosivity (e.g., resistivity) will probably suffice to identify locations for further examination.

Improvement of External Corrosion Direct Assessment Methodology by Incorporating Soils Data Introduction

Introduction

The nation's pipeline infrastructure is a critical domestic asset that supports delivery of energy products to many parts of the country where demand is much higher than the supply that is locally available. Much of this infrastructure was constructed decades ago, and is continually maintained and improved to minimize disruption in service. As this infrastructure continues to age, pipeline operators are challenged to improve service safely while competitively delivering natural gas. Given the seriousness of any line rupture, and the significance of the pipeline system to the nation's energy supply and commerce, industry and government have worked over the years to ensure that processes and procedures are continuously improved. This has been accomplished by implementation of industry-wide regulations and by improved operations resulting from a better understanding of the technical issues that impact the integrity of pipelines.

One important technical issue that has received considerable attention over the years involves external corrosion of buried pipelines. This form of degradation occurs when unprotected line-pipe steel comes in contact with moist or wet soil. External corrosion is mitigated by application of a coating system prior to burying the system and by application of a cathodic protection (CP) system. Parameters that define whether corrosion will occur are (1) effectiveness of the coating system, (2) effectiveness of the cathodic protection system when the coating system is not, and (3) capacity of the corrosivity of the environment at the pipe surface to promote unacceptably high corrosion rates in the event that both the coating system and the CP system fail.

Over the years, the pipeline industry has developed various techniques to deal with the threat of external corrosion. To broaden the effectiveness of this corrosion control, a comprehensive structured process called External Corrosion Direct Assessment (ECDA) was developed. It combined the application of the long-used industry techniques with more recently developed technologies to improve effectiveness and provide for continuous feedback that can potentially reduce the incidence of external corrosion in the future.

The ECDA process was developed recently in a joint government-industry program[(e.g.,1-4)*] under funding from the Office of Pipeline Safety (OPS) of the US Department of Transportation (DOT), the Interstate Natural Gas Association of America (INGAA), the Pipeline Research Council International (PRCI), and the American Gas Association (AGA). One project in this industry-government partnership involved an evaluation of data from aboveground measurements, in-line inspections, and excavations by several pipeline operators. The data were used to test assumptions about the effectiveness of different but complementary aboveground inspection methods and of the overall ECDA process to locate active corrosion and coating faults, and infer metal-loss defect populations. Results of this first program to evaluate the developing ECDA standard showed that without a common codified process, operators had adopted different views for how an ECDA should be performed even though they had decades of experience conducting integrity assessments using similar methodologies. As that program concluded, emphasis shifted to providing draft language for the National Association of

---

[*] Numbers in superscript parenthesis refer to citations grouped at the end of this text.

Corrosion Engineers (NACE) ECDA recommended practice[5] (RP) and the ASME integrity management (IM) supplement[6]. Similar consideration was given to the IM practices developed by the American Petroleum Institute[7] (API). These standards now form the basis for consistent application of ECDA by pipeline operators.

The cost-share companion project to this project (Reference 3) was the first to formally evaluate the efficacy of ECDA implementation using data from companies and contractors. Because the work reported in Reference 3 began before the NACE ECDA standard was completed, it was not a "clean sheet" use of the structured ECDA process. Even so, several lessons were learned that will allow the industry to improve subsequent ECDA processes. Since soils data had proven useful in field studies of SCC susceptibility[e.g.,8] there was interest in conducting a companion project to determine the potential usefulness of soils data in identifying sites where corrosion might be problematic. The work to determine whether this is a possible improvement to the ECDA process is described in this report.

Objective and Potential Benefit

The objective of this project was to evaluate whether a soils model could be used to help predict locations where pipeline degradation could be caused by external corrosion.

Soils characteristics are one of the recommended ECDA data elements. If by using a soils model to interpret soils data collected as part of the ECDA process it could be shown that areas suffering corrosion could be predicted more consistently, then operators would have an improved ECDA capability at their disposal to help maintain the country's natural gas pipeline infrastructure safely and reliably.

If a soils model provided entrée to sites more prone to corrosion, inspection and maintenance could be targeted to those areas. Successful application of the model would parallel the use of soils data and modeling in application to SCC[8], and the ECDA process could more accurately target the most significant external corrosion threat locations – with the benefit of increased public safety at reduced net cost.

Approach and Scope

An empirical approach was adopted to assess if the usual aboveground electrical measurements currently embedded in ECDA when augmented with measurements of standardized soil parameters such as resistivity, pH, moisture content, soluble ions, soil and terrain classification, and drainage could better identify corrosion hot spots. Since the measurement methods and field practices associated with these and other soils parameters have been developed in parallel applications for SCC, this approach is not new. Using data and insights gained through similar modeling in applications to stress corrosion cracking, the scope of the work was to evaluate the efficacy of soils models in applications to ECDA. If the results were found to improve the current ECDA process, then development could proceed with soils models and a structure and practices specific to ECDA, leading to an updated ECDA standard.

The approach capitalizes on the observation that the extent of external corrosion on a buried pipeline depends on the corrosivity of the soil in balance with the quality and condition of the pipeline's coating and the effectiveness of the CP. Theoretically, corrosion is not a problem where either the CP or the coating is effectively protecting the pipeline. In contrast, where soils data and models have been effective in predicting SCC susceptibility, the coating is disbonded or otherwise ineffective, and/or the CP is not a factor. It follows that in applications to external corrosion, soils models can improve the ECDA process only where corrosion is active because the protective schemes are ineffective. Because identification or prediction of a failed coating is an essential element of successful ECDA, soils models have some plausible utility.

Tasks and Report Structure

The project was divided into three technical tasks, and a reporting task. The first technical task covered data development (collection, quality review, interactions with pipeline companies). The second technical task involved data analysis (data alignment and developing confidence measures), while the third covered modeling efforts (data inputs, model predictions, and process evaluation).

The results are presented in the task sequence above, following a brief review of the ECDA process and soils modeling as it pertains to ECDA. Thereafter, the results are presented and discussed in summary format, sequentially by site, based on data collected along the pipeline segments that were excavated by the six operators who participated in the program. Finally, conclusions are drawn regarding soils-modeling as a potential tool within the ECDA process.

The ECDA Process

This brief review of the ECDA process below is intended to illustrate where in this process soils modeling is expected to play a role. Readers are referred to NACE RP0502(5) for a more detailed description.

The ECDA process combines aboveground inspection techniques including some that have been used for decades, along with data analyses, results from excavations, and other assessments to develop a better understanding of the external corrosion situation along a pipeline. It has four steps:

- **Pre-Assessment:** This step includes activities to collect and integrate historic data to determine if ECDA is feasible, define ECDA regions, and select complementary indirect inspection tools. The types of data that are collected include but are not limited to information on design, materials, construction, environment, corrosion protection, prior surveys, prior inspections, prior integrity evaluations, and maintenance actions. *Soils characteristics are a data element in NACE PR502 that should be collected in the this step to estimate soil corrosivity – to assess the possibility of corrosion should coating holidays be present, and should the CP system not be functioning properly in this location. A soils model that interprets these soils data could enhance this assessment and improve selection of ECDA regions.* The section following this brief review of ECDA describes the elements that should be considered when evaluating the corrosivity of soils.
- **Indirect Inspection:** This step includes activities required to conduct aboveground inspections to identify locations where corrosion activity may be occurring, may have occurred, or may occur in the future, at coating faults and/or other corrosion protection anomalies. Two or more complementary indirect inspections are required over the entire pipeline segment to improve the reliability of detection of corrosion protection anomalies under the wide variety of conditions that may be encountered along a pipeline right-of-

way. Consistent rules are required for defining potential corrosion protection anomalies based on the inspection data.

- **Direct Examination:** This step includes analyses of the indirect inspection data to prioritize sites for excavations. The data from the indirect measurements are combined with existing data to prioritize corrosion protection indications as immediate, scheduled, or monitored (similar to the categories used in ASME B31.8S Integrity Management Plan Supplement[(6)]). *A soils model could increase the accuracy of the prioritization process in this step.* These analyses are followed by pipe surface examinations, measurements, remaining strength analyses, "like-similar" evaluations, and mitigation of corrosion protection problems. Minimum requirements are included for determining how many excavations are required and for assessing the impact of external corrosion on the structural integrity of the pipeline.
- **Post-Assessment:** This step includes integrated analyses of the data collected from the previous three steps to assess the effectiveness of the ECDA process and determine re-evaluation intervals. This step also includes validation dig requirements and metrics required for monitoring the long-term effectiveness of ECDA.

As is evident from the above summary, the ECDA process is formalized at a high level. However, its implementation is necessarily variable because of the nature of the specific line segments, including topography, location, and other operational considerations.

Soil Parameters as Plausible Measures of Corrosivity

While the use of a single soils parameter such as resistivity would be ideal as an engineering estimate of soils corrosivity, experience indicates that corrosivity cannot be accurately described by one parameter or even a simple equation involving a number of parameters. The relationships among the different parameters that influence corrosivity are complex. Another consideration is the fact that a pipeline can traverse through several different soil types and characteristics in both the horizontal and vertical directions, sometimes across a very short length (i.e., less than a meter). Yet another complicating factor in the estimation of soils corrosivity is the use of backfills[1] that can differ to varying degrees from native soils. These environments must be properly identified and characterized before an accurate assessment of the overall soil environment can be made and applied to a pipeline integrity threat.

The parameters of most interest for modeling soils are soil type and oxygen availability, soil resistivity and moisture, pH, total acidity and cation exchange capacity, redox potential, chlorides and sulfides, carbonates, and bacteria. Each of these is discussed below to provide the reader with an overview and to provide some background prior to discussing the soil surveys completed during this project.

Soil Type and Oxygen Availability

The first soil parameters that are usually reviewed during corrosion surveys are soil type and texture. Soil type is defined by the mode of deposition at the depth of the parent material (C horizon) and recognizable morphological features within the soil profile. Soil texture is a

---

[1] Migration of chemical elements and minerals from the native soils over time tends to reduce such differences.

descriptive parameter by which the percentage of sand, silt, and clay content is organized into 14 different classes based on primary particles (size < 2mm) and coarse fragments (size > 2mm).

The mode of deposition and dominant texture can influence many soil properties such as the drainage (vertical and lateral movement of moisture), retention of moisture, and movement of gases, which can also be dependent on position within a landscape and both regional and localized hydrological characteristics of the area. For example, clay soils have the ability to store relatively more water within their pores than other textures under simplified conditions. Based on these characteristics, clay soils would be expected to support cathodic protection (CP) levels more easily, and also would be expected to exhibit lower resistivities. Bedrock or soils with a high rock or coarse fragment content have higher resistivities, and can also block cathodic protection from reaching the pipe and/or create conduits for groundwater to flow along the pipeline.

According to Escalante(9,10), the most important factor affecting the corrosion rate of steel is the rate of oxygen transport within the soil. Seasonal precipitation, fluctuating water tables, or areas where a pipeline traverses across soils with different drainage regimes can create oxygen concentration cells. The area of the pipe within the water zone becomes anodic to the pipe above the waterline, with the area just below the waterline having the highest corrosion rate.

Escalante(10) also found that as the resistivity of the environment increases, the corrosion changes from a general, uniform pattern to a more localized pattern. This illustrates the need for cathodic protection even in high resistivity soils because of the greater chance of developing a deep pit on the pipeline than developing a larger area of general corrosion.(11)

A different type of backfill (potential change in characteristics from the native soil) around the pipeline can also have an effect on the corrosion rate of the steel. Camitz and Vinka(12) observed that carbon steel panels that were embedded in a sand backfill had higher corrosion rates than panels that were buried in the original soil unless the original soil had a much lower resistivity than the sand. They postulated that the greater permeability of the sand to oxygen transport through both air and water led to the increased corrosion rates.

Differences between the disturbed soil surrounding the pipeline and the undisturbed soil on the pipeline right-of-way (ROW) also affect oxygen availability. As Camitz and Vinka have shown, undisturbed soil tends to be less corrosive than disturbed soil because oxygen is more easily transported through the disturbed soil.

Areas where soil moisture is very low throughout the year or where the pipeline lies below the waterline throughout the year would not be expected to develop oxygen concentration cells. However, there are few areas that receive almost no precipitation, and/or groundwater flow along the pipeline, and under these diverse conditions, microbiologically influenced corrosion (MIC) can pose a potential threat to the pipeline. Active MIC can be very aggressive, resulting in high corrosion rates.

Soil Resistivity and Moisture

Soil resistivity, which is relatively easy to measure accurately, has been an important parameter historically in pipeline construction. Resistivity of the soil is a function of soil matrix and the interstitial fluid (moisture) that can conduct electric current. Since interstitial fluids have orders of magnitude higher conductivity than the mineral phase by itself, their presence and the degree of mineralization can significantly reduce resistivity of a soil. Thus, typical soil resistivity measurements represent a composite measure of the moisture content of a soil and dissolved electrolytes in the soil water. Clay minerals, due to the particularities of their crystal structure, have a relatively high conductivity; so their presence will reduce the resistivity of a sample.

Table 1, reproduced from Peabody(13), describes the relationship between soil resistivity and degree of corrosivity defined on a relative scale. Although several variations of this table have been published by various researchers, this one describes the situation quite accurately with respect to field observations when the soil is homogeneous.

Table 1. Resistivity Ranges for Levels of Soil Corrosivity

Resistivity (ohm-cm)	Degree of Corrosivity
< 500	Very Corrosive
500 - 1,000	Corrosive
1,000 - 2,000	Moderately Corrosive
2,000 - 10,000	Mildly Corrosive
> 10,000	Progressively Less Corrosive

Soil moisture and dissolved ion content determine the resistivity of the soil. A liquid electrolyte must be present in the soil to complete the circuit for the anodic and cathodic reactions. Without it, corrosion of the pipeline would not occur.

Despite the general validity of the relationships shown in Table 1, soil resistivity does not always provide a good estimate of soil corrosivity, especially when there are variations within the ROW. Escalante(9) found that above 2,000 ohm-cm, soil resistivity became unreliable as an indicator of soil corrosivity. Robinson(14) also stated that soils that have a large variation in resistivity will often be more corrosive than soils that have a small variation in resistivity, even if this resistivity would be more corrosive according to the information in Table 1. Van Eck(15) has shown that varying soil conditions result in more corrosion than a homogeneous soil environment.

pH, Total Acidity, and Cation Exchange Capacity

The pH of a soil is a measure of the concentration of free hydrogen ions within the soil solution. Any protective oxide film on pipeline steel becomes thermodynamically unstable in acid solutions and thus deteriorates in an acidic environment.

The total acidity of the soil is a measurement of both the soluble and exchangeable aluminum and hydrogen ions present in the soil. Research done by the NBS(16) and others has shown that the total acidity of a soil is a better indicator of the soil's corrosiveness than the pH of the soil alone. The pH of the soil is still important; however, as it affects the redox potential of the soil and can be measured in the field, whereas the total acidity can only be determined from laboratory tests.

Table 2, reproduced from Peabody(13), relates soil pH to the degree of soil corrosivity. Table 3, reproduced from Romanoff(17), relates the total acidity of a soil to the soil's corrosivity. The cation exchange capacity (CEC) is calculated similarly to the total acidity, but measures both the basic and acidic cations. The CEC of a soil refers to the soil's ability to hold or attract positively charged cations. Clay soils are on the more corrosive side of the range because they usually have a higher CEC than silt or sand textured soils.

Table 2. Effect of pH on Soil Corrosivity

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

Table 3. Effect of Total Acidity on Soil Corrosivity

Total Acidity (Meq/100g)	Degree of Soil Corrosivity
< 4	Very Low
4.1 - 8.1	Low
8.1 - 12.0	Moderate
12.1 - 16	High
> 16	Very High

Redox Potential

Redox potential is a measurement of the relative reduced (anaerobic) or oxidized (aerobic) condition of a soil. In most soil environments, the redox potential reflects the balance between the rate of oxygen entry and the rate of its consumption by biological or chemical processes.

In an underlying soil zone saturated with water, oxygen arrival is limited by its solubility in water and the rate of diffusion. Where the rate of oxygen uptake exceeds the rate of its arrival, redox potential readings drop to less positive values corresponding to a reducing (anaerobic) environment.

A correlation between redox potential and corrosivity was published by Starkey and Wight(18). The pH of a soil can also affect the value of the redox potential. Bohn(19) mentions in this context that the commonly used correction factor (-59 mV/pH) does not have a sound theoretical or empirical basis, but can be useful when trying to compare redox values between soils of different pH. Bohn(19) also states that redox values obtained in aerated soil are not as easily reproducible as those in anaerobic soils because oxidized ions are not present at a high enough concentration.

Table 4. RedoxPotential Ranges for Levels of Soil Corrosivity

Redox Potential (mV)	Degree of Corrosivity
< 100	Severe
100 - 200	Moderate
200 - 400	Slight
> 400	Non corrosive

Chlorides and Sulfates

Chloride ion concentration is important for two different reasons. First, the presence of dissolved chloride salts, such as sodium chloride, in groundwater helps lower the soil resistivity. Second, chlorides also can prevent the formation of passive films so any disruption may not reform easily leading to localized corrosion. Table 5, also taken from Peabody(13), correlates chloride ion concentration with soil corrosivity.

Sulfates are generally not considered directly corrosive to pipeline steel; instead these ions provide an energy source for sulfate reducing bacteria (SRB). These bacteria convert the sulfate into various sulfide products (sulfide, bisulfite, thiosulfate) based on the species, oxygen levels, and availability of other nutrients such as nitrate/nitrite, formate, and acetate. Sulfates can also promote the breakdown of concrete coatings or weights. Table 6, taken from Spickelmire(20), shows the relationship between sulfate concentration and soil corrosivity.

Table 5. Effect of Chloride Concentration on Soil Corrosivity

Chloride Concentration (ppm)	Degree of Soil Corrosivity
> 10,000	Severe
1,500 - 10,000	Considerable
150 - 1,500	Positive
< 150	Negligible

Table 6. Effect of Sulfate Concentration on Soil Corrosivity

Sulfate Concentration (ppm)	Degree of Soil Corrosivity
> 200	Very Severe
150 - 200	Severe
100 - 150	Minimal
50 - 100	Little
< 50	None

Chloride and sulfate concentrations are typically determined from laboratory analysis of soil pore water.

Carbonates

Carbonates can be an important factor in external corrosion, but are probably more important when considering a pipeline's susceptibility to SCC (both low and high pH cracking).

Dissolved carbonate will buffer the water in the neutral to alkaline pH range. In the presence of calcium and/or magnesium ions, saturated carbonate solutions will precipitate on the pipe surface forming an impermeable barrier. The scales formed either on the pipe's surface or the exterior side of the pipeline's coating are hard and tightly adherent. Presence of calcium carbonate scale, dolomite, or hydromagnesite on the pipe surface indicates a low potential for corrosion and normally indicates a protective CP system, because the elevated pH indicates hydroxyl ion formation.

The presence of carbonates can be observed in the field with a hydrochloric acid test on the soil, but a laboratory analysis of the soil is required for a quantitative concentration measurement.

Bacteria

The potential for corrosion due to the presence of aerobic and anaerobic microbes in the soil has not been typically included in soils corrosivity models. Soil type and the position of the pipe in the soil profile have an impact on microbiological activity. Aerobic degradation of organic material occurs in the top surface layer. The metabolic by-products would include organic acids, thereby, lowering soil pH. As the soil depth increases and become more anoxic, anaerobic pathways are used. These would include the use of sulfate, nitrate, carbon dioxide, and various metal ions.

There is a direct relationship between the amount of organic material in the backfill and the level of microbiological activity. As the organic content of the soil increases, so does the biological activity. In soil conditions where organic nutrients are low, microbial counts decrease with organic content and depth.

Not only can microbes influence the natural galvanic corrosion, they can also produce corrosive acids and by-products that are cathodic to the pipeline, increase CP requirements, deteriorate coating, or block any CP from reaching the pipeline. Care must be taken to identify environments where bacteria will significantly increase the risk of the pipeline to external corrosion. It should be noted that the presence of microbial activity in soils does not necessarily indicate that MIC is an active corrosion mechanism.

Soils Surveys to Develop Inputs to Soils Models

The purpose of a soil survey is to gather information from a limited number of points within a homogeneous soil unit area (i.e., polygon) under the assumption that the information can be extrapolated to all points over the area of interest. Central to this assumption is the observation that the species transported in groundwater comprises native soils along and around the RoW, as well as what might be in select backfill imported for bedding or padding as required.

Because the geology of soils is very complex, it is very important to use qualified and experienced personnel who can accurately identify soil parameters and estimate where a change in soil characteristics is taking place along the pipeline study area. The ability to accurately characterize the area is a critical aspect of collecting the right quantity and quality of data.

Most global soil classification systems use a taxonomic hierarchal framework to organize the knowledge of soils in a reasonable and useable way. For example, the Canadian system uses criteria based on observable and measurable soil properties that reflect the processes of soil genesis and environmental factors[21].

There are five categorical levels, with each level having distinguishable characteristics and criteria to describe a soil. These five levels are:

- Order
- Great Group
- Subgroup
- Family
- Series.

The classification of a soil is dependent on the identification and description of characteristics related to the nature of a soil, dominant soil forming processes, kind and arrangements of horizons, differences in soil textures and parent materials and the detailed features of a soil pedon[2].

Romanoff[22] reported that a reasonable correlation existed between a soil series and the rate of corrosion within that series. With substantial testing in each series along a pipeline's route, it would be possible to estimate the corrosivity based on soil series alone. A soil series is a subdivision of a soil family with a narrower range of variability of properties than the soil family[23].

Unfortunately, with over 13,000 soil series in the United States (for comparison, the Province of Alberta has more than 800 soil series), not including phases[3], this task would require each soil series to be identified and tested for corrosivity. Instead, it is easier to group soils according to their properties (i.e., Family level) and then make comparisons between their properties so that a model of the soils can be developed and used to make predictions for areas that were or were not anticipated to be tested.

Soil Mapping

According to Miller et al.[24], Government soil survey information was available for over 65 percent of the United States in 1981. Most of these surveys were prepared between 1945 and the 1970's, using either field studies or aerial photography in order to map larger areas of terrain at greater scales (typically at 1:50,000 to 1:250,000 levels).

Pedologists, geologists, and engineers all define soil differently. From a pipeline operator's perspective, the pipeline depth will determine the extent to which soil information is required. For most pipelines, this will be between 1 to 2 m, but a soil survey technician may need to confirm the pipe's depth with a pipe probe or depth of cover survey if any doubt exists.

Care must be taken when using the existing historical survey maps to help delineate the soil type surrounding a pipeline. On a typical soil survey, the properties of over 99 percent of the soil in an area of interest are inferred from sampling, including the boundaries dividing different soil types. In many cases it was neither practical nor necessary for a soil survey to do more than generalize the location of a soil boundary or the locations of any small inclusions. Often the

---

[2] A pedon is the smallest three-dimensional mapping unit that is considered a soil.

[3] A soil phase indicates a variation in external features. This may include form, slope angle, rock content, etc.[15]

intended use of these surveys was for agricultural purposes, which does not match the objectives of pipeline operators.

Two factors can cause differences in the soil boundaries on a soil map: map scale and survey intensity. Map scale is based upon the required resolution between different soil types. An area of 1 cm^2 will show 1 ha (approximately 2.24 acres) of land on a 1:10,000-scale map, but will show 625 ha on a 1:250,000 map. Generally, the smallest area allowed on any given map developed for environmental or agricultural purposes is about 0.5 to 1 cm^2. At a 1:1,000 scale the maximum delineation would be 100 m^2, which may not provide enough information for some pipeline threat analysis models.

Survey intensity refers to the number of soil inspections made in a given area of a soil polygon. The higher the intensity for the same area, the more detailed a soil survey will be. A soil boundary delineated from a low intensity survey on one map may actually be a separate soil type on a map completed with a higher intensity. This can result in the misalignment and/or misinterpretation of the polygon data.

Important warnings and recommendations were made by Valentine(25) regarding the use of soil maps at different scales and survey intensities. The delineation of boundaries should not be expected to coincide if the survey intensity is different. The same map unit on a larger scale map can occur within delineations of different map units on a smaller scale map.

With this in mind, one can anticipate that using an agricultural based soil survey may not be sufficient for pipeline integrity purposes. Small, but now mappable, soil units called 'outliers' may be found outside of their delineated areas when conducting a pipeline soil survey. In one example, it was found that the percentage of outliers differed by as much as 15 percent when comparing maps of 1:250,000 and 1:25,000 scales.

Pipeline Soil-Survey Procedure

The first step during a soil survey of a pipeline is similar to the pre-assessment step in the ECDA process. Data about the pipeline are collected from maintenance records, construction records, aerial photography, operating records, and pipeline staff. Information from external and internal corrosion coupon studies is also useful to further delineate potential areas for modeling time dependent threats.

In the field, the pipeline soil survey is typically performed by a two-person crew. The length of each unique terrain condition (mode of deposition, soil texture, drainage, topography) is assessed and documented along the pipeline route. Each discrete unit is measured with a laser rangefinder or a tape measure for short (<15 m) features. The location and crossing length or proximity of any transportation routes, waterways, and public congregation areas is also measured.

During the soil survey some or all of the following information may be collected:

- GPS coordinates
- Topography (i.e., inclined, level, depression)
- Length of each terrain feature and slope angle
- Vegetation
- Soil type (texture for each horizon, mode of deposition)
- Soil drainage

- Resistivity – field measurement
- pH – field measurement
- Redox potential – field measurement
- Carbonates – field test
- Samples for laboratory analysis – general geochemistry
- Transportation, utility or foreign line crossings
- Population proximities (HCA's)
- Evidence of third party activity
- Unique features.

Some of these items can be visually determined during the surveys or evaluated using established field testing techniques. The remaining information would come from results of testing on samples submitted for laboratory analyses. For example, one technique involves a soil core, which is obtained using a hand powered auger. A sample of the entire soil profile can be taken this way and then laid out to perform characterization or field-based chemical tests. Depending on the extent of testing anticipated, up to about 5 kg of soil per sample is required. Such samples should be sealed in a plastic bag (or double bagged) for transport to the laboratory.

When samples are submitted for laboratory analysis, the following tests are usually performed:

- X-Ray Diffraction – analyzes the crystalline mineralogy of a soil
- EDX – analyzes the elemental mineral content of the soil
- Pore Water Analysis – analyzes the properties of the pore water, including pH, conductivity, and general geochemistry
- Grain Size Analysis
- Soil Box – analyzes resistivity and/or conductivity
- Bacteriological Analysis – analyzes for acid producing, iron reducing, and sulfate reducing bacteria.

Because these detailed analyses can be expensive, the number of soil samples submitted for laboratory analysis is usually limited. Often neglected in the interest of cost is the collection of "control samples" away from the pipeline right of way. Control samples allow the operators to evaluate and understand the possible effects of pipeline construction practices such as soil packing, imported bedding and padding, and soil mixing (homogenization) on water drainage patterns and subsequently the susceptibility of the pipeline to external corrosion and SCC. For example, control samples can assist in offsetting concerns that arise from field observations that indicate dry soil down to the pipeline and even a few feet above the invert of the ditch, but the bottom of the ditch is wet, with the ditch apparently acting as a river channel.

Sampling Methods and Sources of Error in Soil Surveys

Most soil samples collected during a soil survey of a pipeline are not taken randomly; soil technicians taking samples usually take a "judgment"(26) sample, which in their opinion is a representative sample of the soil in question. Any confidence in the results relies solely on the judgment of the technician, which also points to the need to have experienced people completing such surveys. Judgment samples are usually taken because more extensive random sampling is more time-consuming and costly for longer stretches of pipeline.

The sampling site for the judgment sample must be chosen carefully. Excavation practices during the construction of a pipeline not only disturb the soil, but may replace the soil in the ditch with a homogeneous mixture instead of material reflecting its original structure. Sand padding of the pipeline may also be used in rocky soils or urban settings. As a result, the soil immediately surrounding the pipeline may have markedly different properties than the undisturbed soil.

Truly random sampling is designed to provide a more accurate set of soil measurements at a known confidence level. Random samples will be taken in a specific area of a soil survey if an accurate measurement of the soil properties is required or if the area is too complex for simple mapping. Random sampling may be conducted if a pipeline operator has had many problems (i.e., failure) in a certain area and requests a more comprehensive study.

According to the Soil Science Society of America (SSSA), three normal sources of error during soil measurements can occur(27) during a soil survey. The first is **sampling error**, and is caused by the fact that most soils are not homogeneous – natural variation in each soil's properties means that the only way to ensure a very accurate measurement would be to measure the soil properties at each location around a pipeline, but this is an impossible task.

Table 7, taken from Miller et al.(24), groups some soil properties according to their coefficient of variability (COV, which is the ratio of the standard deviation and the mean multiplied by 100 to give a percentage), and gives the required number of pedons required to make an estimate of a soil property that would be within +/- 10 percent of the actual value at a 95 percent confidence level.

Table 7. COV and Number of Pedons Required for Various Soil Variables

Coefficient of Variability and Number of Pedons	Variables
CV <15% <10 pedons	• Soil color (hue and value) • Soil pH • Thickness of A horizon • Total silt content • Plasticity limit
CV between 15% and 35% 10 to 35 pedons	• Total sand content • Total clay content • CEC • Base saturation • Soil structure (grade and class) • Liquid Limit • Depth to minimum pH • Calcium carbonate equivalent
CV > 35% >35 pedons	• B2 horizon and solum thickness • Soil color (chroma) • Depth to mottling • Depth of leaching (carbonates) • Exchangeable H, Ca, Mg, and K

	• Fine clay content • Organic matter content • Plasticity index

As Table 7 shows, the more detailed the soil assessment, the more samples that are required to maintain the same confidence limit. For example, to find the exchangeable H, Ca, Mg, and K content, one may need more than 35 pedons.

A second cause of error is related to **sample selection**. If the soil technician decides to take samples well away from the pipeline to ensure that they do not hit the pipeline with the soil auger resulting in coating and possibly pipe damage, there may be an inherent error if soil conditions near the pipeline are quite different than those of the adjacent soil. Another example occurs when sampling soil in a depression that contains water to ensure that samples are taken from the area under the water, not just around the edges of the depression.

A third cause of error in soil sampling is **measurement error**. Measurement errors can be caused by equipment used to do measurements (e.g., calibration errors) or variations in sampling and measuring techniques, such as estimating the depth of where each soil horizon begins.

A fourth and final source of error that must be accounted for is the **time of year and recent weather** in which the soil survey is performed. Resistivity, pH, and redox potential will change with varying soil moisture, which is affected by seasonal or longer-term cyclic changes in precipitation and the water table.

The best way to minimize these errors is to use trained and experienced pipeline soil survey technicians. These technicians must be able to observe small changes in the terrain and understand how these changes affect various soil properties.

History and Development of Soils Models

Soils models have been used to a limited extent for estimating the corrosivity of various soil types in various applications(e.g.,28). For example, the American Water Works Association (AWWA) soils model embeds a measure of corrosivity. More frequently, specific measures such as resistivity that were known to relate to soil corrosivity have been included in external corrosion evaluations, including risk assessment models(e.g., 29). In past pipeline industry applications, soils models were created to identify where stress corrosion cracking (SCC) was likely, as experience with the occurrence of SCC showed an apparent dependence on soils and related topographical parameters(8,30,31).

For the present project, soils models are considered as the basis to interpret soils data collected as part of the pre-assessment step of the NACE ECDA procedure. In this application, predictive soils models are intended to identify and rank those areas along a pipeline system that are likely to be susceptible to integrity threats associated with soil corrosivity and other metrics involving specific soil parameters. The soils model for this project was adapted from one originally developed for SCC, as noted above. That soils model was created to identify areas where "significant" SCC(32) was most anticipated based on known factors that had been empirically observed to correlate with SCC susceptibility. These factors included:

- Coating type

- Year of pipeline installation
- Operating history of the pipeline
- Terrain conditions (soil type, drainage and topography).

As is evident here, soil-specific parameters represent just one of the factors used to assess SCC susceptibility. A similar situation was anticipated for the likely use of soils models in assessing where ECDA might be effective, because factors such as coating condition and CP effectiveness are also known to be useful in assessing susceptibility to external corrosion.

By themselves, predictive models do not directly prevent service failures due to SCC nor do they reduce the consequences of such failures. However, by identifying locations where SCC is most likely to occur, a predictive model allows a company to focus its investigative excavations and other mitigative activities where they will have the most effect. This same effect would apply to the use of predictive models based on soils-specific parameters in ECDA applications.

The subsections below discuss the development of a predictive model, the effectiveness of such models, and how they can be used to manage an SCC-susceptible pipeline. The scenario discussed is analogous to that for ECDA should soils models be found potentially useful in this application.

Development of the Early Soils Model

The information collected by TransCanada during its investigative excavations in the late 1980s suggested that the occurrence of "significant" SCC on a pipeline was strongly related to the terrain conditions surrounding the pipe where there was the potential for pipe coatings to have disbonded. Based on this observation, TransCanada employed J.E. Marr Associates (Canada) Ltd. in 1992 to develop a predictive model for SCC susceptibility that included soils descriptors.

Several other pipeline companies have since developed predictive models for SCC susceptibility. In most cases, these models have been based on the methodology developed by TransCanada and J.E. Marr Associates (Canada) Ltd. At the time of our inquiry, six CEPA member companies were using predictive models to assess the SCC susceptibility of their systems, or portions thereof, and five other member companies were developing predictive models[(31)]. Also, one CAPP member has used a predictive model.

Analysis of data collected by various CEPA members led to the identification of seven sets of specific terrain conditions as being associated with "significant" SCC on polyethylene tape coated pipelines. Another four sets of specific terrain conditions were associated with "significant" SCC on asphalt coated pipelines. These terrain conditions are referred to as "significant terrain conditions," and discussed later in reference to Tables 8 to 10. They involve drainage, topography, and the type of soil. It is important to note that these sets of terrain conditions have been found where "significant" SCC has developed on other pipeline systems – they are not a conclusive indication of SCC. Accordingly, if other conditions necessary for SCC initiation and growth (e.g., coating disbondment, susceptible pipe material, and stress) are not present, SCC will not develop at that location.

In general, the first step in developing a predictive soils model is to review the background information for a specific pipeline. The data typically include, among other things, the pipeline's operating pressure and temperature history, its coating type, and its year of construction. The more current and complete the available pipeline data, the better the initial model.

The second step is to get information about the existing terrain conditions along the system. Aerial photos and soil surveys are used here. The pipeline data are then correlated with the actual terrain conditions to form a database. Finally, the gathered information is cross-referenced with the "significant terrain conditions" known to promote SCC.

Areas along the pipeline system are then identified as being susceptible or non-susceptible to SCC. Areas identified as susceptible to SCC can also be ranked as to their relative susceptibility. As investigative excavations are carried out in these areas, the presence or absence of SCC and specific details on the terrain conditions are recorded. The information collected is then used to verify and enhance the predictive model. As more excavations are performed, the model is further refined and its accuracy improves.

While the information on terrain conditions known to promote SCC susceptibility may be applied to all pipelines in the same area, a predictive model can be used only for the pipeline for which it was developed. That is because the data about each pipeline – its coating, its year of construction, its operating history – may be quite unique and this data is an important part of the predictive model. Consequently, assumptions should not be made about SCC susceptibility on one pipeline system on the basis of a predictive model developed for another system.

Following the National Energy Board inquiry on SCC in 1995, the SCC model became widely used by the majority of major pipeline companies in Canada. Criteria indicating SCC susceptible conditions for both asphalt and tape models have been extensively refined by incorporating data from over 5,000 separate excavations performed around the world.

Implementation Issues for Corrosion Assessment

It is well known that the coating on a pipeline separates the corrosive soil environment from the pipeline. If faults develop in this coating, the cathodic protection system is expected to protect the pipeline and thereby limit corrosion. It follows that models of soil corrosivity reflect one of the conditions essential for corrosion on the pipeline – just as was the case for SCC. This means that if the CP has become ineffective and the coating has failed, soils models could effectively direct ECDA to sites along the RoW that are susceptible to corrosion. If models of soil corrosivity can be shown to be viable in field applications, then predictive models should be effective in directing ECDA to areas where soils are most aggressive and corrosion more likely to occur. The key is to eventually couple such soils models with other field data such as the potential for CP shielding or inadequate CP levels, and historical CP data that indicate severe coating failure.

In the past, development of external corrosion models based on soil survey data for pipelines was not pursued because operators simply did their corrosion-related maintenance based on insight from CP test-post readings and results of close-interval-surveys (CIS). With the advent of ECDA, which formalizes these and other aboveground measures of potential corrosion, there is potential value for such predictive models of pipeline condition – provided that models of soil-corrosivity can be shown potentially useful for such applications.

An external corrosion susceptibility model is developed by combining the results of a soil corrosivity based on a soil survey with other data, such as:

- cathodic protection
- type of coating, coating condition, and controlling factors such as temperature

- historical corrosion information and activities
- data from corrosion and null-hypothesis excavations
- leaks and incident data
- in-line inspection (ILI) data
- population and transportation route exposure for risk analysis.

Taking each of these factors into account, a model can be developed with an empirical severity ranking for each different soil environment along the pipeline, reflecting considerations such as those addressed in Tables 1 to 7. The reliability of such models would depend on the quantity and quality of the soil data, as well as that of the other data used.

The focus here is a model that targets soils corrosivity. This narrow focus opens the door to a model that could be used as a screening tool when other more detailed data for the pipeline are unavailable, unreliable, or difficult to obtain. Such an approach is potentially well suited for older systems, such as early unpiggable segments, which were a primary major target for ECDA, as it was plausible that soil corrosivity dominated corrosion susceptibility for older systems. The upside of success with this approach is that a very simple model could be used to direct ECDA, with much less data needed and little related need for data integration. However, success with this approach comes with the negative implication that the coating must tend to be deteriorated, and/or the CP system less effective.

The Soils Model

Marr Associates created the external corrosion model by aligning the soil survey data with ILI data along twenty five valve sections of different pipeline systems. The valve sections were chosen based on coating type, as different coatings behave quite differently and therefore require separate models. For this model, asphalt/coal tar coatings were chosen. As indicated above, this soils model is an adaptation of the model developed for SCC, for which drainage-topography, drainage-soil type, and topography-soil type are represented by a ranking that ranges from low through moderate to high. As for the SCC model, coating is a conditional overlay on the ranking, based on drainage, soil-type, and topography.

Criteria for the base external corrosion soil model are defined as follows:

- Drainage – the drainage of the soil is a measure of the average soil moisture levels throughout a season. It can range from Well Drained (generally dry) to Very Poorly - Very Poorly Drained (saturated throughout the season). The soil drainage has a large effect on the soil resistivity and oxygen availability within the soil. Depending on the type of coating and soil type, it also can affect how a pipeline's coating will perform.
- Topography – the topography can affect drainage patterns along a pipeline.
- Soil Type – the soil type is based upon the mode of deposition of the soil surrounding the pipeline. Differences within each soil type can affect the corrosivity of the soil, how a pipeline's coating will perform, the soil resistivity, and how effective cathodic protection will be.

Tables 8, 9, and 10 give the model definitions of soil drainage, topography, and soil environment, respectively.

Table 8. Soil Drainage Definitions

Drainage Type	Abbreviation	Description
Well Drained	(W)	• Oxidizing environment • Upland areas
Imperfectly Drained	(I)	• Alternating oxidizing and reducing environments • Dependent upon fluctuation of water table
Poorly Drained	(P)	• Primarily reducing conditions • May be saturated throughout most of the season • Reducing environment
Very Poorly Drained	(VP)	• Reducing conditions throughout entire year • Saturated year round • Low lying to depressional areas
Very Poorly – Very Poorly Drained	(VP-VP)	• As above (VP) • Standing Water • Pipe surrounded by organic soil

Table 9. Topography Definitions

Type	Abbreviation	Description
Undulating	(U)	Regular sequence of gentle slopes from alternating concave and convex patterns (wavelike pattern)
Ridged	(R)	Sharp crested usually with steep side slope
Inclined	(I)	Sloping surface
Depressed	(D)	Topographically low lying area
Level	(L)	Flat to very gently inclined
Side Slope	(S)	Side slope of mountain range

Table 10. Soil Environment Definitions

Soil Environment	Description
Glaciofluvial	• Sandy and/or gravel texture
Moraine Till	• Variable soil texture • Variable size range of stones • Sand and gravel • Clay and silt • >1 m to bedrock
Organic	• Organic over clay
Lacustrine	• Clayey to silty fine textured soils
Organic	• Organic over gravel
Rock	• <1 m of soil cover over rock • Caliche soils
Alluvium	• Various textures
Waterways	• Lakes, swamps, rivers, ditches

The soil model is created by surveying a pipeline and sectioning the line into successive unique environments, based upon the drainage, topography, and soil type. The ILI data are then aligned with the environments using chainage information collected during the soil survey.

The total number of features for each unique Drainage-Topography, Drainage-Soil Type, and Topography-Soil Type combination was divided by the total length of the combination for the section being analyzed. This allowed unique combinations to be compared one against another. (An analysis involving all three parameters was not possible due to software constraints.) Soils-corrosivity herein is embedded in relative terms via soil type, with ten soil types considered.

Susceptibility criteria were established by qualitatively analyzing similarities and differences between drainage-topography, drainage-soil type, and topography-soil type with the number, location, and severity of external corrosion defects along the RoW. Soil surveys provide the data to quantify these parameters, results for which are included in the Appendix, along with photographs and other useful details. When integrated with maintenance records and other related DA surveys, and verified using investigative excavations, such data have the potential to predict locations along the RoW where external corrosion is most likely, all else being equal.

The soils-corrosivity model information was taken from models that were already performed for a SCC model which had the same soil parameters as the target section. These models were created using a combination of aerial photography and field verification.

The external corrosion soils corrosivity model was calibrated by aligning the soil survey data with ILI data in terms of occurrence and severity along twenty five valve sections of different pipeline systems. The valve sections were chosen first based on coating type, as different coatings behave quite differently and therefore require separate models. For the present, the focus is asphalt/coal tar coatings, which were applied on most of the pipelines included in this analysis. CP data can be included, but like the model for low pH SCC, the model will only be useful for coatings that do not shield the pipe from CP. The pipelines that this model was developed for were coated with asphalt, but CP data were not available. A model based on tape coated lines has not yet been developed, as the necessary data set is too sparsely populated.

The soil-corrosivity model is not meant to be used on a stand-alone basis, but rather would be coupled with cathodic protection and coating type and condition to help prioritize pipeline segments for investigation. As more soil data become available along with related data to calibrate corrosion susceptibility, the model will become more accurate and have broader utility.

Table 11 serves an illustrative example of the model development process and indicates how trends were identified. This table shows the incidence of corrosion features as a function of terrain type and drainage type as an example of two parameters that could combine to affect where corrosion occurs – all else being equal. For this example, the combination of Drainage Type B and Terrain Type B stands out as an environment where corrosion was prevalent. Similar trending on other combinations of parameters, for example Drainage-Soil Type and Soil Type-Terrain leads to an empirical basis to rank susceptibility. Trending such as that in this illustration leads to patterns, with a severity ranking evolving via repeated comparisons based on the relative difference between different field environments. By combining data from a number of valve sections, correlations became evident between the number of corrosion features and specific combinations of soil properties. These were ranked on an arbitrary, qualitative scale –

Non-Susceptible, Minor, Moderate, and Severe – to formulate susceptibility criteria used as the basis to assess (predict) susceptibility[4].

Table 11. ILI-Soil Model Correlation Example

Corrosion Features (per meter)	Terrain Type			Total
Drainage Type	**A**	**B**	**C**	
A	1	0	10	11
B	1	143	0	144
C	0	8	0	8
Total	2	151	10	163

A ranking could also be developed correlating corrosion severity, rupture-pressure calculations, growth rate, and other such metrics. Ultimately, with sufficient data, differences in soil properties, coatings, and cathodic protection could be empirically characterized and incorporated in the soils model. Because the preliminary nature of this evaluation limits the scope of data available, this effort has focused on readily available properties that are easily characterized. This preliminary ECDA soils model had to consider a broad range of pipeline environments.

As the database expands, and the number of soils and other parameters characterized increases as excavations continue, the additional data can lead to the development of more refined and comprehensive susceptibility criteria, and to a more generic soils model. Such a model could evolve on a pipeline-specific basis; with a sufficiently comprehensive database, it could be applied more generally. Availability of more data leads to increased confidence in the model, which ultimately could transition from a soils model to one that incorporates parameters such as a poorly applied coating or cathodic protection system problems. Such a model is needed if the role of soils and terrain as embedded in a soils model is to be coupled with cathodic protection and coating survey data to help prioritize pipeline segments for ECDA.

Implementing the empirical trending scheme illustrated above in Table 11 leads to the ranking of corrosion susceptibility expressed as combinations of soil type, topography, and drainage presented in Table 12. This illustration of corrosion susceptibility ranking is specific to asphalt-coated pipe. Depending on the soil type, topography, and drainage, susceptibility ranges from highly susceptible to weakly susceptible (denoted as EC-CT-01 and EC-CT-09, respectively, in Table 12).

[4] None of the criteria are based on SCC susceptibility, although the modeling process parallels the prior work targeting SCC. Soil Type, Topography, and Drainage were retained because they are properties that can be easily obtained to describe a terrain section, which affect soil corrosivity and coating properties (resistivity, acidity, bacteria, etc.) in a historically proven predictable way.

Table 12. Empirically Ranked Corrosion Susceptibility for Asphalt-Coated Pipelines.

External Corrosion Susceptibility Code	Soil Type	Topography Group	Drainage Group
EC-CT-01	7	I, D, L, L-I, I-D	I, W, W-I
EC-CT-02	7	L, L-I	P
EC-CT-03	7	L-U, R-U, R-I	W
EC-CT-04	4	I, L, L-I	I, W, W-I
EC-CT-05	4	L, D, L-D	P, VP, P-VP
EC-CT-06	4	L, L-U, L-R	I-P, P, W
EC-CT-07	6	I, D, I-D	W, P, VP, P-VP
EC-CT-08	6	L, L-R, L-U	P, W
EC-CT-09	6	L-I	P, W

SoilsModels as a Metric of Soil Corrosivity versus Corrosion

Soil surveys alone will only provide the operator with an idea of where corrosion *might* be happening based upon a soil's corrosivity, but will not tell the operator exactly where the corrosion is occurring, nor the extent of it. Combining the soil survey data with the all or part of the data shown above will allow operators to gain a better understanding of the corrosion status of a particular line segment. Such data characterize soil corrosivity. The objective here is to develop soils-based models of corrosivity in regard to sites considered in the prior ECDA project, and thereafter evaluate their potential utility to the ECDA process. However, as noted above, soil corrosivity is but one of three factors that control where corrosion occurs. For example, a pipeline located in a poorly drained clay soil with a very low resistivity might be expected to develop severe corrosion, but if the coating on the pipeline is in good condition and the pipeline is receiving adequate CP, no corrosion would be expected to occur, even though the environment might be categorized as highly corrosive. In contrast, corrosion could be active on the same pipeline in a mildly corrosive environment if adequate CP is not reaching the pipeline and the coating has failed at a particular location.

It follows that soils models of corrosivity must be augmented by information that characterizes the effectiveness of the CP system and the coating condition in order to quantify where along the pipeline corrosion might be occurring. Consequently, if the soils-modeling appears beneficial, then issues such as CP effectiveness and coating condition, quantified for example from historic test-post records, should be added to fully characterize corrosion susceptibility as a guide for ECDA.

Soils Models and Data Integration

Most soils models incorporate a continuous improvement and refinement process in their development and application similar to the direct assessment (DA) process. As more information is gathered from excavations and other related surveys, the data are fed back into the model to modify criteria used to determine which areas along the pipeline are likely to be the most susceptible to corrosion. This increases the accuracy and confidence in the model.

At first glance, soil surveys may not seem necessary for pipelines that can be inspected by ILI tools. However, some pipeline systems, including those designed to be piggable or retrofitted to facilitate ILI, have segments that a pig cannot pass. One example is a crossover on a gas transmission system; another example is a drip. Consequently, ECDA has a role even on piggable systems.

What is more important is the fact that ILI surveys locate and size external corrosion (and other features, depending on the particular ILI technology used), but only characterize the past history of a pipeline that led to corrosion detected. That is, they capture the current condition in regard to metal loss, but do not indicate where corrosion is currently active or where metal loss might result in future failure. ECDA can provide insight into where corrosion is active; a soils model, guided by soils data such as corrosivity, can provide insight as to where the corrosion growth rate may be high. Multiple ILI runs could provide similar guidance, but this approach would require an entire segment to be pigged; whereas ECDA can be targeted to areas of high corrosivity. It follows that integrating ILI data with soil survey and other information can guide an operator to improved and more efficient integrity management, while identifying areas of future concern along a pipeline. The operator could instead take a proactive approach and check the cathodic protection levels in the area, recoat the pipeline, or review and implement other mitigative actions to ensure safe and reliable operations.

Results

Data Collection Task – Field Excavations

Marr Associates managed the data collection task, which was conducted as part of field excavations to collect soils samples and characterize terrain and drainage at several sites along six pipelines each with a different operator. The six operators are labeled from A to F in the following summaries. The same reference scheme is used in Appendix A, which presents a more comprehensive perspective for these sites.

Operator A

Eight sites were chosen for excavation along this pipeline. All sites were located in lacustrine silt, with drainages ranging from well to poor. The sites were chosen based on conditions for asphalt coating, but two of the sites (Null Hypothesis site and Site 1) had double wrap tape coating, for which a soil model has not evolved. Only one corrosion feature, located at the Null Hypothesis site, was found. The soil environment at two of the asphalt coating sites was classified severe, and at the other four was classified minor. So, for this site the methods for controlling external corrosion at this site were effective, which is inconsistent with the use of corrosivity as the metric to prioritize ECDA.

Operator B

Five sites were excavated along this pipeline. Three sites were located in poor or very poorly drained lacustrine clay, one site was located in very poorly drained clay till, and one was located in well drained rock. The soil environment was considered to be moderately corrosive at the lacustrine sites and non-corrosive at the bedrock site. No other soil model for the clay till site is available yet. Two corrosion features were found at the bedrock site, and one corrosion feature was found at each of the lacustrine clay sites.

Operator C

A survey of approximately 366 m of soils was conducted at four sites in the excavation area. The survey classified this area as an imperfect to poorly drained fluvial soil in level topography. No other criteria exist for this soil type. After more extensive excavation, it was found that the soil was actually imperfect to poorly drained lacustrine clay or silt overlaying fluvial sand. The discrepancy was caused because the depth limitation of the initial core survey was exceeded during the subsequent full excavation. No corrosion features were found at these excavations, for which soil corrosivity was considered to be minor at all sites.

Operator D

A survey of 4,555 m of soil was conducted at nine sites on this pipeline. The soil consisted of fluvial sand which traversed through different terrain and drainage types. The nine excavations were located in areas with well, well to imperfect, or imperfectly drained fluvial sands. No corrosion features were found during these excavations. A susceptibility criterion does not exist for this soil type yet from any other models.

Operator E

A survey of 4,641 m of pipeline was conducted, with 3,452 m of the pipeline in soils classified as a minor corrosion threat, and 34 m of pipeline in soils classified as a moderate corrosion threat. The remaining 1,155 m of pipeline was in non-susceptible soils. Four sites were chosen for excavation along this line. Two of the sites were in moderately susceptible soils, which were very poorly drained lacustrine in a level topography. The two other sites had fluvial silts, one well drained, the other imperfect to poorly drained, for which soil severity criteria have not been developed yet.

Operator E also continued to apply the external corrosion criteria to other sections of its lines. An additional survey of 98,000 m was conducted over 19 segments of pipeline, and 24,000 m (more than 24 percent) of the line was found to be in terrain conditions that were deemed either non-susceptible or as posing only a minor threat of external corrosion, based on past models. The non-susceptible terrain for each segment was estimated to range from 10 to 52 percent of the total length surveyed, based on prior models.

Operator F

No soil survey was performed for the excavations along this pipeline because of the soil type found. Nine excavations were located in clay, rock, or sand till soils, for which no soil criteria exist yet. Corrosion was found at two excavations; one located in very poorly drained sand till and the other located in well drained rock till.

Summary

Table 13 provides a tabulation of the data from each operators' site, listing the number of corrosion features and indicating whether application of the existing soils database from SCC would have predicted the observed corrosion from the soil corrosivity. The existing model does not include till or fluvial soils at this time, so the listing in the table is N/A.

Table 13. Soils-Based Data and Measures of Corrosion Susceptibility for Sites Excavated Along Pipelines of Six Operators[5]

Operator Code & Site	Coating Type	Topo-graphy	Drainage	Soil Type	Susceptibility Acc. to Soil Model	Soil Resistivity (Ohm-cm)	Soil pH	Susceptibility Acc. to Resistivity/ pH
Pipeline Operator A								
A – Null Hypothesis Site	Tape - Double Wrap	Inclined	Well	Lacustrine Silt	N/A	2,450	6.11	Moderate
A – 1	Tape - Double Wrap	Level	Well	Lacustrine Silt	N/A	2,450	6.56	Neutral
A – 2	Asphalt	Level	Imperfect-Poor	Lacustrine Silt	Minor	2,100	5.97	Moderate
A – 3	Asphalt, Tape	Level	Imperfect	Lacustrine Silt	Severe	2,400	5.56	Moderate
A – 4	Asphalt	Level	Imperfect-Poor	Lacustrine Silt	Minor	2,100	5.56	Moderate
A – 5	Asphalt	Inclined	Well	Lacustrine Silt	Severe	2,370	5.34	Moderate
A – 6	Asphalt	Level	Imperfect-Poor	Lacustrine Silt	Minor	2,450	5.7	Moderate
A – 7	Asphalt	Level	Imperfect-Poor/Poor	Lacustrine Silt	Minor	29,000/1,500	5.79	Moderate
Pipeline Operator B								
B – 1	Coal Tar	Level	Very Poor	Clay Till	N/A	24,416	N/A	Low
B – 1A & B – 2	Coal Tar	Ridged	Well	Rock	Non-susceptible	11,490	N/A	Low
B – 3A	Coal Tar	Level	Very Poor	Lacustrine Clay	Moderate	8,790	N/A	Low
B – 3	Coal Tar	Level	Poor	Lacustrine Clay	Moderate	41,364	N/A	Low
B – 4	Coal Tar	Level	Very Poor	Lacustrine Clay	Moderate	22,405	N/A	Low
Pipeline Operator C								
Validation Site	Coal Tar	Level	Imperfect-Poor	Lacustrine Clay Overlying Fluvial Sand	Minor	790/3,900	6.4/5.2	Severe

[5] N/A for tape models because model applies to asphalt/coal tar lines only. N/A for fluvial sands and other unique combinations because not enough of that soil type/topo/drainage combination was available in the database for comparisons to be made. Some soil measurements were not taken during the program (mostly operator D).

Operator Code & Site	Coating Type	Topo-graphy	Drainage	Soil Type	Susceptibility Acc. to Soil Model	Soil Resistivity (Ohm-cm)	Soil pH	Susceptibility Acc. to Resistivity/ pH
C – 1	Coal Tar	Level	Imperfect-Poor	Lacustrine Silt Overlying Fluvial Sand	Minor	1,300	6	Moderate
C – 2	Coal Tar	Level	Imperfect-Poor	Lacustrine Silt Overlying Fluvial Sand	Minor	1,600/34,000	6.2/6.4	Moderate
C – 3	Coal Tar	Level	Imperfect-Poor	Lacustrine Clay Overlying Fluvial Sand	Minor	470/59,000	6.2/6.4	Moderate
Pipeline Operator D								
Null Hypothesis Site	Coal Tar	Level	Imperfect	Fluvial Sand	Minor	N/A	N/A	N/A
D – 1	Coal Tar	Level	Well	Fluvial Sand	Moderate	N/A	N/A	N/A
D – 2	Coal Tar	Level	Imperfect	Fluvial Sand	Minor	N/A	N/A	N/A
D – 3	Coal Tar	Level	Well-Imperfect	Fluvial Sand	Minor	N/A	N/A	N/A
D – 4	Coal Tar	Level	Imperfect	Fluvial Sand	Minor	N/A	N/A	N/A
D – 5	Coal Tar	Inclined	Imperfect	Fluvial Sand	Minor	N/A	N/A	N/A
D – 6	Coal Tar	Inclined	Well-Imperfect	Fluvial Sand	Minor	N/A	N/A	N/A
D – 7	Coal Tar	Depress ion	Imperfect	Fluvial Sand	Minor	N/A	N/A	N/A
D – 8	Coal Tar	Depress ion	Imperfect	Fluvial Sand	Minor	N/A	N/A	N/A
Pipeline Operator E								
E – 1 Line G	Asphalt	Level	Imperfect-Poor	Fluvial Silt	Minor	840	6.34	Severe
E – 2 Line G	Tape, Mastic, Shrink Sleeves, FBE	Level	Well	Fluvial Silt	N/A	930	6.45	Severe
E – 2 Line F	Coal Tar	Level	Very Poor	Lacustrine VFS	Moderate	5,000/10,000	N/A	Minor
E – 3 Line F	Coal Tar	Level	Very Poor	Lacustrine VFS	Moderate	1,900/25,000	N/A	Moderate

Operator Code & Site	Coating Type	Topo-graphy	Drainage	Soil Type	Susceptibility Acc. to Soil Model	Soil Resistivity (Ohm-cm)	Soil pH	Susceptibility Acc. to Resistivity/ pH
Pipeline Operator F								
A-113 to A-116	Coal Tar with Rock Shield	Inclined	Very Poor	Sand Till	N/A	59,360	6.4	
A-92 to A-94, CD-17	Coal Tar with Rock Shield	Ridged	Well	Rock Till	N/A	230,000	N/A	Moderate
CD-5	Coal Tar	Inclined	Well	Sand Till	N/A	95,755	6.8	Minor
CD-4	Coal Tar	Inclined	Well	Sand Till	N/A	95,755	6.6	Minor
A-37	Coal Tar	Inclined	Clay Till: Very Poor Shale Bedrock: Poor	Clay Till overlying Shale Bedrock	N/A	36,387	5.8	Moderate
1	Coal Tar	Inclined	Well	Sand Till overlying Shale Bedrock	N/A	55,056	N/A	Minor
CD-28 CD-29	Coal Tar	Inclined	Very Poor	Clay Till	N/A	40,217	7	Minor
Dig 2 (Dent)	Coal Tar with Rock Shield	Inclined	Well	Sand Till	N/A	210,000	N/A	Minor
Dig 3 (Dent)	Coal Tar with Rock Shield	Inclined	Well	Sand Till	N/A	N/A	N/A	N/A

Further Comment on Soils Corrosivity as a Metric for Pipeline Corrosion

As discussed previously, simple definitions of corrosion susceptibility that involve only soils parameters and focus on corrosivity ignore the effects of coating condition and CP effectiveness. However, one target for ECDA is early-vintage unpiggable pipelines that, because of their age, may have degraded coatings and may have a history of CP effectiveness issues.. Accordingly, key concerns related to variability in CP or problems with the coating have been ignored. Thus, interaction between environment and the coating are lost. For example, it is known that coal tar and asphalt coatings tend to become brittle and will disbond in dry soils – but will stay pliable and bonded in soils that are constantly moist. It is also known that clay soils will swell when wet; and that constantly wet versus alternating wet and dry cycles can cause soil stresses on the pipeline coating. This interaction between coating and environment, which can lead to wrinkles in tape coatings, is also lost, as are other similar aspects.

As can be seen from Table 13, there is essentially no correlation between pipeline corrosion susceptibility based on soils-corrosivity expressed in terms of soils-type, topography, and drainage as compared to simpler measures of corrosivity such as resistivity and pH. While an attempt has been made to calibrate these measures of susceptibility using ILI data for corrosion incidence and severity, the actual frequency of corrosion was limited which confounds this process.

Soils Corrosivity Model Evaluation

In Table 14, observed corrosion incidence is compared to susceptibility based on measures of corrosivity and resistivity/pH. Examining the frequency of corrosion, one finds that 17 patches of corrosion were found at only seven of 46 sites; with one site accounting for almost half of the observations. It follows that too little data have been gathered to appropriately calibrate these models to make them effective. While the observation that a soils corrosivity model correctly identifies the location of seven patches of severe corrosion is a positive outcome, it is equally apparent that other sites with corrosion are missed. On this basis it is clear that soils corrosivity by itself fails as a measure of pipeline corrosion susceptibility. In turn this implies that soils corrosivity models by themselves have little potential to enhance the ECDA process.

From the data considered herein, there is no evidence to support soils-corrosivity models as screening tools when other data is not available, unreliable, or difficult to obtain. Likewise, there is no evidence to support the viability of such simpler models as soil corrosivity was not could to dominate corrosion susceptibility even in cases where field circumstances suggest it might. The upside here is the implication that coatings and CP remain effective in older well maintained systems. The downside is that a more general soils-based model that incorporates CP and coating will be needed to direct ECDA, supported by field data and data integration.

Table 14. Soils-Based Prediction of Corrosion Susceptibility (Ignoring Coating and CP) for Sites Excavated by Six Pipeline Operators

Operator Code & Site Name	# of EC Features	Susceptibility Acc. to Corrosivity	Susceptibility Acc. to Resistivity/pH
Pipeline Operator A			
Null Hypothesis Site	1	N/A	Moderate
1	0	N/A	Neutral
2	0	Minor	Moderate
3	0	Severe	Moderate
4	0	Minor	Moderate
5	0	Severe	Moderate
6	0	Minor	Moderate
7	0	Minor	Moderate
Pipeline Operator B			
1	0	N/A	Low
1A	2	Non-susceptible	Low
2	1		
3A	1	Moderate	Low
3	1	Moderate	Low
4	0	Moderate	Low
Pipeline Operator C			
Validation Site	0	Minor	Severe
1	0	Minor	Moderate
2	0	Minor	Moderate
3	0	Minor	Moderate
Pipeline Operator D			
Null Hypothesis Site	0	Minor	N/A
1	0	Moderate	N/A
2	0	Minor	N/A
3	0	Minor	N/A
4	0	Minor	N/A
5	0	Minor	N/A
6	0	Minor	N/A
7	0	Minor	N/A
8	2	Minor	N/A
Pipeline Operator E			
1	0	Minor	Severe
Line G	0		
2	0	N/A	Severe
Line G	7		
2	2	Moderate	Minor
Line F	0		
3	0	Moderate	Moderate
Line F	0		

Pipeline Operator F			
A-113 to A116	0	N/A	
A-92 to A-94, CD-17	0	N/A	Moderate
CD-5	0	N/A	Minor
CD-4		N/A	Minor
A-37		N/A	Moderate
1		N/A	Minor
CD-28		N/A	Minor
CD-29		N/A	Minor
Dig 2 (Dent)		N/A	Minor
Dig 3 (Dent)		N/A	N/A

Discussion

Figure 1 provides some perspective for the observations thus far. It schematically indicates the interplay between coating condition and the effectiveness of CP and corrosivity in producing corrosion susceptibility. On the left hand side of the figure are the three primary factors driving the observation of external corrosion. Each of soil "corrosivity", coating integrity, and the cathodic protection system play a role over time. If the coating fails and the CP system is functioning properly, then it does not matter how corrosive the environment is, one would not expect to see corrosion. If both the coating and the CP system fail, then the corrosivity of the soil is very important to corrosion.

Figure 1 indicates that each of the primary factors can develop over time ranging from slight to severe, as shown for each of the bars for each of those factors. Whether it is slight or severe variability depends on several factors that vary over time. Seasonal variations, and CP maintenance to correct deficiencies, for example, can change the relative importance of any one of these factors, or all of them. So, at any given point in time the "environment" at the pipe surface is a combination of these three primary variables in the continuum of response possibilities. And, since this is effectively coupling the process to time, the extent of any observable or significant external corrosion will be a function of many complex variables. So, the development of a soils model, i.e., the corrosivity part of the equation, to predict external corrosion as part of ECDA is a very difficult task.

Soils models have been successful for SCC, so discussion is warranted to provide perspective for their success. Generally, SCC occurs under disbonded coatings and coatings that shield the pipe surface from CP current. Even if the aboveground measurements indicate a good coating and the CP system is well maintained, SCC can occur under the right environmental conditions of, temperature, metallurgical condition, and state of localized stress. Given the construction practice of the past and operational practice today, many line segments are within the proper range for SCC to be observed, if one is considering only these variables. However, since it occurs infrequently, other factors are at play. It follows that modeling the role of soils parameters in regard to SCC lacks much of the interplay discussed in regard to Figure 1, with soils corrosivity being the controlling factor for many applications. Thus, success for SCC is uncoupled from success for corrosion susceptibility.

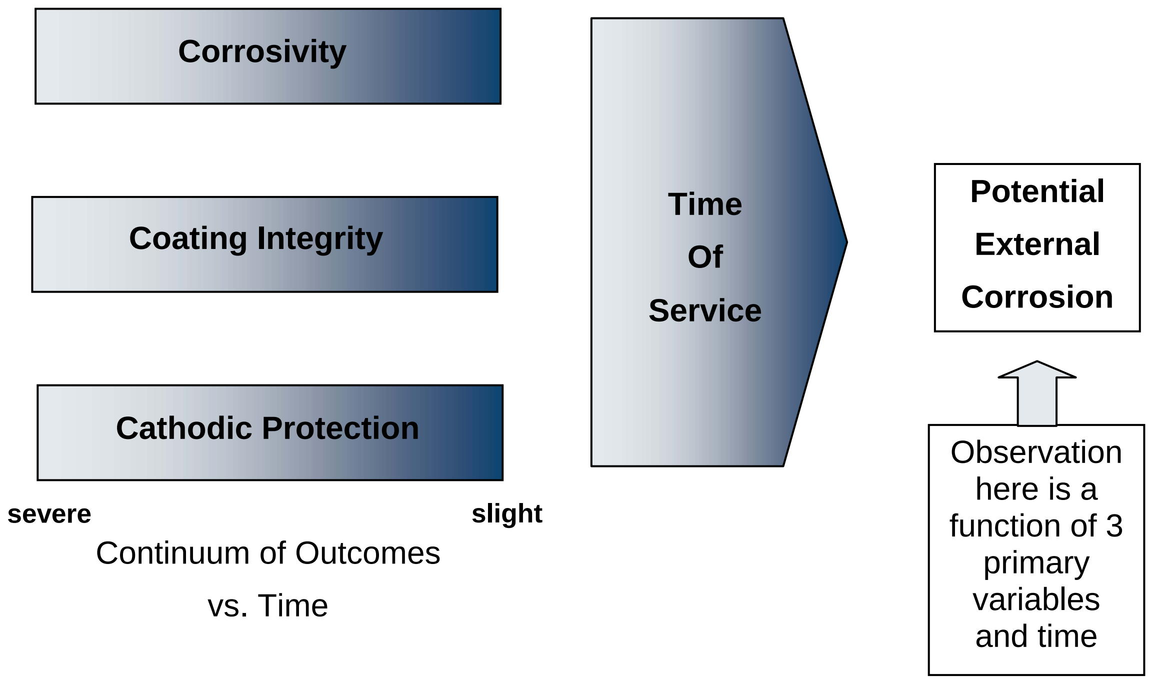

Figure 1. Interaction of Corrosivity, Coating Integrity, and CP Controls Corrosion Susceptibility

In summary, a model that is accurate enough to guide ECDA is not yet available. The modeling done as part of this project is a major step toward characterizing corrosion susceptibility, and could be instructive for ECDA if coupled with operator data regarding CP history and the insight it provides for coating condition. Additional data and field calibration will be needed to adequately address the interplay evident at a very high level in Figure 1.

Summary and Conclusions

Much of the nation's pipeline infrastructure was constructed decades ago, and is maintained and improved to minimize any disruption in service. One important aspect is external corrosion, which has received considerable attention over the years. Such corrosion occurs when unprotected line-pipe steel comes in contact with moist or wet soil. External corrosion is mitigated by application of a coating system prior to burying the system and by the application of a cathodic protection (CP) system to protect the pipeline over time. To broaden the effectiveness of the technologies used to ensure corrosion control, the industry formulated a comprehensive best practice known as ECDA that codified techniques that had already been in use for many years.

This project evaluated whether soils data could be used in a model to predict locations that are susceptible to external corrosion. If a soils model developed to interpret soils data collected as part of the ECDA datasets could be used to predict consistently which areas are prone to corrosion, then operators would have an additional tool at their disposal to help maintain the country's natural gas pipeline infrastructure and keep it operating safely and reliably.

The approach capitalized on the observation that external corrosion of a buried pipeline depends on the corrosivity of the soil in balance with the quality and condition of the pipeline's coating and the effectiveness of the CP. Soils corrosivity was selected for closer examination for the simple reason that if it were a dominant factor in degradation in certain situations, a very simple model could be developed as a screening tool. The model could be useful even when other data are unavailable, unreliable, or difficult to obtain. The project was divided into three technical tasks, and a reporting task. The first technical task covered data development activities (collection, quality review, interactions with pipeline companies). The second technical task covered analysis activities (data alignment and developing confidence measures), and the third technical task covered modeling activities (data inputs, model predictions, and process evaluation).

After considering a simple modeling approach based on pH and resistivity, a model for characterizing soil corrosivity was developed by coupling soils type with topography and drainage. The results indicated that there is essentially no correlation between soil characteristics and corrosion susceptibility based on soils corrosivity as expressed in terms of these two models. Our attempt to calibrate measures of susceptibility using ILI data for corrosion incidence and severity was not successful, apparently because of the lack of data on frequency of corrosion for the sites evaluated.

The important conclusions drawn from this work are as follows.

1. Little correlation was observed between external corrosion and soils corrosivity for data gathered at excavations along pipeline segments for the six operators who participated in this project. It follows that soils corrosivity cannot be considered the dominant factor controlling corrosion susceptibility – even for aging pipeline systems – unless CP is ineffective and the coating is degraded based on CP history.
2. The lack of correlation is not surprising given the effectiveness of CP and coating integrity at the sites evaluated.
3. Soils-related models that are developed to guide ECDA must consider CP and coating integrity. The fact that a local condition is more corrosive at one site versus another is not important if the coating and/or CP system are working well. Consequently, site selection for ECDA should first consider the CP history to differentiate between areas where CP is effective and/or the coating functional and areas where CP is not effect and the coating is likely to be susceptible to corrosion.
4. If the ECDA process identifies deficiencies in either coating or CP, then higher level measurements of corrosivity (e.g., resistivity) will probably suffice to identify locations for further examination as part of the ECDA process.

References

1. Bubenik, T. A., Leis, B. N., Burgoon, D. A., Rust, S. W., Clark, E. B., Garrity, K., Veith, P. H., and van Oostendorp, D., “Direct Assessment and Validation”, GRI Report-00/0231, Gas Research Institute, December 2000
2. Haines, H. H. and Powell, D., “Guidelines for Implementing the External Corrosion Direct Assessment (ECDA) Process,” PRCI Catalog No. L52196, May 2004
3. Clark, E. B. and Colwell, J. A., “ECDA Inspections and Excavations,” PRCI Catalog No. L52123, July 2005.
4. “ECDA Validation & Soils Model (Develop Improved ECDA Validation Data Sets),” PRCI Catalog L52198, Advantica, 2005
5. “External Corrosion Direct Assessment,” NACE RP 0502, NACE, Houston.
6. “ASME Code Supplement on Integrity Management for Pressure Piping”, B31.8S, Revision 1, 2002.
7. “Managing System Integrity for Hazardous Liquid Lines”, 1st Ed., API Standard 1160-2001, November 2001.
8. “Report of the Inquiry: Stress Corrosion Cracking on Canadian Oil and Gas Pipelines,” National Energy Board of Canada, Calgary, 1996, pp. 125, 126.
9. Escalante, E., “Concepts of Underground Corrosion,” Effects of Soil Characteristics on Corrosion, ASTM STP 1013, “Effects of Soil characteristics on Corrosion,” V. Chaker and J.D. Palmer, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 81-94.
10. Escalante, E., Oka, T., and Bertocci, U., “Effect of Oxygen Transport and Resistivity of the Environment on the Corrosion of Steel,” National Institute of Standards and Technology, Gaithersburg, MD, 1990.
11. “Uhlig’s Corrosion Handbook, 2nd Edition,” Revie, R.W. Editor, John Wiley and Sons, New York, 2000.
12. Camitz, G. and Vinka, T-G., “Corrosion of Steel and Metal-Coated Steel in Swedish Soils - Effects of Soil Parameters,” ASTM STP 1013, “Effects of Soil characteristics on Corrosion,” V. Chaker and J.D. Palmer, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 37-53.
13. Peabody, A.W., 2001, “Peabody’s Control of Pipeline Corrosion,” Bianchetti, R.L. editor, NACE, Houston, TX pp. 91.
14. Robinson, W., “Testing Soil for Corrosiveness,” *Materials Performance*, 32, 1993, pp. 56-58.
15. van Eck, W.A., “Proceedings, 11th Annual Underground Corrosion Short Course”, West Virginia University Engineering Experimental Station Bulletin No. 80, pp. 125-137.
16. Romanoff, M., “Underground Corrosion,” NBS Circular 579, Gaithersburg, MD, 1957, pp. 154.
17. Ibid., pp. 167.
18. Starkey, R.L., Wight, K.M., “Anaerobic Corrosion of Iron in Soils,” Final Report of the American Gas Association Corrosion Research Fellowship, 1945.

19. Bohn, H.L., “Redox Potentials,” *Soil Science,* Vol. 112, 1971, pp. 39-44.
20. Spickelmire, B., “Corrosion Considerations for Ductile Iron Pipe,” *Materials Performance,* Vol. 41 pp. 16-23.
21. “Field Manual for Describing Soils in Ontario,” 4th Edition, Ontario Centre for Soil Resource Evaluation, 1993.
22. Romanoff, M., “Underground Corrosion,” NBS Circular 579, Gaithersburg, MD, 1957, pp. 150.
23. “The Canadian System of Soil Classification,” 3rd Edition, National Research Council of Canada, Ottawa, ON, 1998, pp. 146.
24. Miller, F.P., Foss, J.E., and Wolf, D.C., “Soils Surveys: Their Synthesis Confidence Limits, and Utilization for Corrosion Assessment of Soil,” ASTM STP 741, “Underground Corrosion,” V. Chaker Ed, 1981, pp. 3-23.
25. Valentine, K.W.G., “How Soil Map Units and Delineations Change with Survey Intensity and Map Scale,” *Canadian Journal of Soil Science*, 61, 1981, pp. 535-551.
26. “Methods of Soil Analysis Part 1 - Physical and Mineralogical Methods,” Soil Science Society of America, A. Klute Ed, 1986, pp. 35-36.
27. Ibid., pp. 44-45.
28. Palmer, J.D.; “Environmental Characteristics Controlling the Soil Corrosion of Ferrous Piping” in ASTM STP 1013, “Effects of Soil Characteristics on Corrosion,” V. Chaker and J.D. Palmer, Eds., American Society for Testing and Materials, Philadelphia, 1989, pp. 37-53.
29. Maulbauer, K., Pipeline Risk Management Manual: Ideas, Techniques, and Resources, CHIPS, 3 rd Edition, 1999.
30. “Report of the Inquiry: Stress Corrosion Cracking on Canadian Oil and Gas Pipelines,” National Energy Board of Canada, Calgary, AB, pp. 60-63.Testimony of Marr at NEB Hearings
31. “Stress-Corrosion – Recommended Practices,” Canadian Energy Pipeline Association (CEPA) Handbook, May, 1997.
32. “Report of the Inquiry: Stress Corrosion Cracking on Canadian Oil and Gas Pipelines,” National Energy Board of Canada, Calgary, AB, 1996, pp. 101.

Appendix A – Field Data

The basis for a soils model was field excavation data from ECDA projects that were conducted by six operators at sites that had been selected for direct examination. This appendix provides details concerning the direct examination work and the data collected for each operator.

Marr Associates conducted the field excavations to collect the soils samples and characterize the terrain and drainage, and managed the data collection task. Detailed investigation and documentation conducted at each dig site included pipe-related conditions such as coating type and condition, pH of fluids under disbonded coatings, corrosion product identification and evaluation, corrosion feature dimensions, and pipe surface NDT. The primary data sets that have potential for use in soils model development include terrain conditions, soil type, drainage characteristics, topography, site location on slope, soil resistivity, pipe-to-soil ("on") potential at the pipe depth within the excavation, and analysis for MIC if such activity was suspected at the site. Other data associated with the investigation include the number of pipe lengths examined, girth weld and longitudinal seam locations, location information, and photographic documentation.

The components of the terrain analyses including soil type characteristics are given in the following four tables. Table A-1 provides descriptions of the six soil type classifications considered in this report.

Table A-1.   Description of Soil Type Classifications

Soil Type	Description
Glaciofluvial/Fluvial	Sorted and stratified, sandy and/or gravel-textured material, which includes alluvial sand and gravel derived from relict watercourses.
Till (Morainal)	Variable soil texture with a variable-size range of unsorted stones. Includes gravel, sand, clay, and silt that were glacial in origin.
Lacustrine	Typically fine-textured deposits, clay to silt, with well-defined stratification. Deposits are typically formed in standing bodies of water.
Alluvial	Commonly cobbles, gravel and sand-textured sediments that are stream-derived and are highly variable concerning stratification.
Eolian	Wind-derived material, usually fine to very fine textured sands.
Organic	Partially to wholly decomposed organic material.

Soil drainage characteristics were determined at the pipe depth, considering features such as the depth of mottling and gleying or the absence of soil drainage impediments from the soil surface. Table A-2 provides definitions of drainage classifications applied in this report.

Table A-2. Description of Soil Drainage Classifications

Drainage Type	Description
Well Drained (W)	Oxidizing environment throughout the year.
Imperfectly Drained (I)	Alternating oxidizing and reducing environment. The environment is dependent on the fluctuation and amount of soil moisture.
Poorly Drained (P)	Primarily reducing conditions. The environment may be saturated throughout most of the season.
Very Poorly Drained (VP)	Reducing conditions throughout the entire year. The environment is saturated year-round. (ie. anerobic)
Very Poorly – Very Poorly Drained (VP-VP)	Reducing conditions throughout the entire year. The soil consists of organic material and the environment is saturated year-round. Standing bodies of water are present on surface topography.

The factors that can be used to assist in assessing the soil drainage characteristics include:

- Presence of an organic layer
- Water table depth
- Presence, abundance, and depth of mottles in mineral soil
- Presence and depth of gley colors in the mineral soil
- Delineation of recharge and discharge areas.

The presence of an organic layer on top of mineral soil and evidence of changes in water table depth can be used to evaluate soil drainage characteristics. For example, an organic layer with an approximate depth of 16 inches or more indicates a very poorly drained soil as defined in Table A-2 above. Similarly, in a mineral soil, if the water table is above the top of the pipe throughout the year, the drainage is classified as very poor.

Soil mottling appears as blotches or spots of a different color or different shade, generally with yellow to red hues as compared to the general soil color. Mottled soils are indicators of a fluctuating water table that produces alternating reducing and oxidizing conditions, and are mainly associated with imperfect or poorly drained soils as defined in Table A-2. Gleying appears as a grey to blue or green color within the soil matrix. Gleyed soils are indicative of continuing saturated or reducing conditions, and are mainly associated with poorly or very poorly drained soils. Under different hydrological situations, the soil profile does not need to exhibit mottling or gleying if the drainage characteristics can be described as imperfect, poor, or very poor. This can be found in localized or regional discharge groundwater.

Topography is another site characteristic that can play a role in a soils model. In this report, topography has been documented according to the landscape pattern using the classification descriptions shown in Table A-3.

Table A-3. Topography Classifications and Descriptions

Topography	Description
Undulating (U)	Regular sequence of gentle slopes from alternating concave and convex patterns.
Ridged (R)	Sharp crested or dome shaped.
Inclined (I)	Sloping surface.
Level (L)	Flat to very gently inclined.
Depressed (D)	Topographically low-lying area.
Side Slope (S)	Side slope of an incline, perpendicular to the pipeline right-of-way.

A more specific local topographic feature that characterizes the site position according to its position on a slope has also been applied in this report. Table A-4 provides the site position classification system used and the descriptions for each.

Table A-4. Site Position Classifications and Descriptions

Site Position	Description
Crest	The uppermost portion or apex of a slope.
Upper Slope	The uppermost portion of a slope immediately below the crest.
Middle Slope	The area between the upper and lower slope.
Lower Slope	The lower portion of the slope immediately above the toe.
Toe	The lowermost portion of the slope.
Depression	Any area that is concave in all directions.
Level	Any level area.

The soil classifications and description terminology described above apply to the methodology applied at each of the direct examination sites. More site-specific soils characterizations and test results were included in the form of graphics and tables that summarized the results at each site. Figure A-1 shows an example of a graphic used to describe the site along with soil conditions.

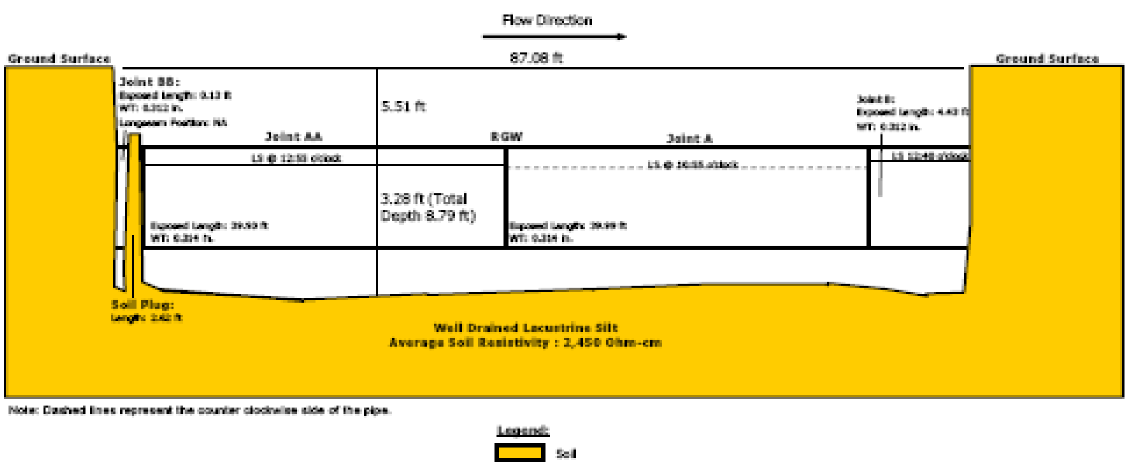

Figure A-1. Typical Summary Graphic Illustrating the Excavation and Soils Data

Figure A-2 shows an example of the additional tables that provide a summary of the soils assessment and that were included for each excavation site.

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-42 ft 8 in. to 44 ft 5 in	0 in. to 105.5 in.	Lacustrine	Inclined	Well	Silt	Middle

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-42 ft 8 in. to 44 ft 5 in	0 in. to 105.5 in.	False	Clay, Silt, Very Fine Sand	Trace (0-10%)	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-42 ft 8 in. to 44 ft 5 in	No	> 105.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-42 ft 8 in. to 44 ft 5 in	Easy/Trencher	Deep (> 9ft 10in)	None

Figure A-2. Typical Soils Assessment Summary Table Included for Each Excavation Site in Appendix A

The following sections present field excavation data collected by six operators under a task managed by Marr Associates to identify site-specific soils data and related data that could be candidates for inclusion in a soils model.

Operator A

The pipeline of Operator A was constructed from 30-inch OD, DSAW pipe in 1960. Originally, the pipeline was coated with field-applied asphalt. At a later date, some areas of the line were recoated with hand-applied double-wrap tape.

Excavations for ECDA project direct examinations were conducted at eight sites downstream from a compressor station, all located within a stretch of about 3 miles. All sites were selected by the pipeline operator. Seven of the eight sites were investigated to validate the indirect inspection results. The eighth site, identified in this report as "Site "0", was selected as the "null hypothesis" site based on a suspected low probability of finding any type of coating anomaly or external corrosion. This same site was used to verify the extent of external wall loss that had occurred prior to the remediation program during which the corroded area was recoated with double-wrap tape. The site was found to be in excellent condition; thus, the probability of an occurrence of additional external corrosion after recoating was deemed to be minimal.

The operator identified 19 pipe lengths and 11 girth welds totaling 425 ft of pipe for excavation and inspection for coating defects. All sites were inspected for the presence of external corrosion and other relevant indications of surface defects. Disbonded coating was removed from a total of 264 ft of the pipe surface to facilitate evaluation of any pipe surface defects. No external corrosion was found. At Site 0, the presence of pre-existing external corrosion was confirmed.

Little variability of soil type was found within the eight sites, and the area was characterized as lacustrine soil. The dominant soil texture consisted of silts with minor soil textures of clays and very fine sands. Site 7 was the only site that exhibited a small change in dominant soil texture. The dominant soil type for a portion of the excavation length at Site 7 was lacustrine sand, but at the end of the excavation the dominant soil returned to lacustrine silt.

The topography of the eight excavation sites was also assessed. Six of the eight sites exhibited level topography and site position. Imperfect to poorly and poorly drained soil was generally found in the level topography characterized at five of these six sites (with the exception of Site 1). Relatively wet soil at these five sites was determined by the presence of mottled or gleyed soils. Sites 0 and 5, the only locations where the topography was inclined, had well drained soil. Site 1 was the only site with level topography that also exhibited well-drained soil.

Soil type and drainage are also associated with soil resistivity results. Soil can increase its conductivity when water is contained within the soil pores; therefore, the soil resistivity is reduced in soils with higher water contents. This relationship between soil type, drainage, and conductivity allows CP system currents to travel more efficiently in wetter soil. Soil pore and cohesion are soil characteristics that can affect the rate of water percolating through the soil. During the field investigation, it was determined that all of the sites had lacustrine silt containing clay and very fine sand. The presence of the clay and silt textures along with the imperfect to poor and poorly drained soils may result in the lower soil resistivities that were determined at these sites. The higher soil resistivities at Site 7 compared to the other sites may be due to the dominant sandy texture of the soil.

After culling a single value that was considered to be an outlier (29,000 ohm-cm) from the data collected during the investigation, the average resistivity of the soils at the eight sites was determined to be 2,227 ohm-cm, indicating a mildly corrosive soil. Table A-5 lists the average, minimum, and maximum values for the soil resistivities measured at the eight excavation sites.

Table A-5. Soil Resistivity Summary, Operator A's Sites

	Soil Resistivity (Ohm-cm)
Average	2,227
Minimum	1,500
Maximum	29,000

The CP "on" potential readings versus a $Cu/CuSO_4$ reference electrode were obtained at the pipe level typically at each end of the excavation. Table A-6 summarizes the CP values recorded at all eight sites.

The CP "on" measurements for the investigated sites were above -1.000 volts except for Sites 5 and 7. The terrain conditions and soil resistivity at Site 5 were very similar to the other sites that have CP "on" measurements above -1.000 volts; therefore the lower CP "on" measurement at Site 5 may be due to possible interference of the CP current to the pipeline. The CP measurements at Site 7 were lower than -1.000 volts, which may be due to the dominant texture of sand in the soil profile of the site. The sandy textured soil along with the lower CP "on" measurements could illustrate the relationship between the factors contributing to soil resistivity as discussed earlier in this report. Due to the lack of external corrosion or any other relevant surface indications on the pipe surface under disbonded coating, the CP current seen in these areas appears to be adequate at this time to protect the pipe surface, although the typical recognized minimum CP criterion (i.e., -0.850 volts) is not been met at Site 5. It should be noted that the coating condition at Site 5 was rated as "very poor."

Table A-6. Pipe-to-Soil Potentials, Operator A's Sites

Site Name	CP "On" (volts)
Site 0	-1.272
Site 1	-1.038
Site 2	-1.067 -1.097
Site 3	-1.112 -1.368
Site 4	-1.247 -1.033
Site 5	-0.818
Site 6	-1.135 -1.124
Site 7	-0.912 -1.282

Table A-7 summarizes the soil parameters of the eight excavation sites that are candidates for inclusion in an external corrosion model and/or soils model. The pH of any fluids found under the coating is also included in Table A-7 as the electrolyte pH. If no electrolyte pH values are reported, the pipe surface was dry. Additional soil-related parameters collected at each excavation site are shown in Tables A-8 through A-15.

Table A-7. Summary of Corrosivity Parameters of Excavation Sites of Operator A

	Resistivity (Ohm-cm)	Electrolyte pH	Soil pH	Texture	Drainage
Site 0	2,450	Not determined	6.11	Lacustrine Silt	Well
Site 1	2,450	Not determined	6.56	Lacustrine Silt	Well
Site 2	2,100	7.0	5.97	Lacustrine Silt	Imperfect to Poor
Site 3	2,400	6.0	5.56	Lacustrine Silt	Imperfect to Poor
Site 4	2,100	10.0	5.56	Lacustrine Silt	Imperfect to Poor
Site 5	2,370	11.5	5.34	Lacustrine Silt	Well
Site 6	2,450	8.5	5.70	Lacustrine Silt	Imperfect to Poor
Site 7	29,000 1,500	Not determined	5.79 5.97	Lacustrine Sand Lacustrine Silt	Imperfect to Poor

Table A-8. Site 0 Soils Data Summary from Operator A

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-42 ft 8 in. to 44 ft 5 in	0 in. to 105.5 in.	Lacustrine	Inclined	Well	Silt	Middle

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-42 ft 8 in. to 44 ft 5 in	0 in. to 105.5 in.	False	Clay, Silt, Very Fine Sand	Trace (0-10%)	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-42 ft 8 in. to 44 ft 5 in	No	> 105.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-42 ft 8 in. to 44 ft 5 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-9. Site 1 Soils Data Summary from Operator A

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-15 ft 10 in. to 15 ft 4 in	0 in. to 107.9 in.	Lacustrine	Level	Well	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-15 ft 10 in. to 15 ft 4 in	0 in. to 107.9 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-15 ft 10 in. to 15 ft 4 in	No	> 107.9 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-15 ft 10 in. to 15 ft 4 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-10. Site 2 Soils Data Summary from Operator A

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-1 ft 9 in. to 20 ft 10 in	0 in. to 115 in.	Lacustrine	Level	Imperfect - Poor	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-1 ft 9 in. to 20 ft 10 in	0 in. to 115 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-1 ft 9 in. to 20 ft 10 in	0.4 to > 115 in.	0.4 to > 115 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-1 ft 9 in. to 20 ft 10 in	No	> 115 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-1 ft 9 in. to 20 ft 10 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-11. Site 3 Soils Data Summary from Operator A

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
0 ft 0 in. to 13 ft 9 in	0 in. to 95.3 in.	Lacustrine	Level	Imperfect	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
0 ft 0 in. to 13 ft 9 in	0 in. to 95.3 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
0 ft 0 in. to 13 ft 9 in	0.4 to > 95.3 in.	0.4 to > 95.3 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
0 ft 0 in. to 13 ft 9 in	No	> 95.3 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
0 ft 0 in. to 13 ft 9 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-12. Site 4 Soils Data Summary from Operator A

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
0 ft 0 in. to 13 ft 5 in	0 in. to 120.9 in.	Lacustrine	Level	Imperfect - Poor	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
0 ft 0 in. to 13 ft 5 in	0 in. to 120.9 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
0 ft 0 in. to 13 ft 5 in	31.5 to > 120.9 in.	39.4 to > 120.9 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
0 ft 0 in. to 13 ft 5 in	No	> 120.9 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
0 ft 0 in. to 13 ft 5 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-13. Site 5 Soils Data Summary from Operator A

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
0 ft 0 in. to 17 ft 9 in	0 in. to 137.8 in.	Lacustrine	Inclined	Well	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
0 ft 0 in. to 17 ft 9 in	0 in. to 137.8 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
0 ft 0 in. to 17 ft 9 in	No	> 137.8 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
0 ft 0 in. to 17 ft 9 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-14. Site 6 Soils Data Summary from Operator A

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-29 ft 2 in. to 36 ft 5 in	0 in. to 96.1 in.	Lacustrine	Level	Imperfect - Poor	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-29 ft 2 in. to 36 ft 5 in	0 in. to 96.1 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-29 ft 2 in. to 36 ft 5 in	35.4 to > 96.1 in.	43.3 to > 96.1 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-29 ft 2 in. to 36 ft 5 in	No	= 96.1 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-29 ft 2 in. to 36 ft 5 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-15. Site 7 Soils Data Summary from Operator A

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-6 ft 10 in. to 79 ft 0 in	0 in. to 102 in.	Lacustrine	Level	Imperfect - Poor	Sand	Level
79 ft 0 in. to 169 ft 11 in	0 in. to 102 in.	Lacustrine	Level	Poor	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-6 ft 10 in. to 79 ft 0 in	0 in. to 102 in.	False	Clay, Silt, Very Fine Sand, Sand	None	None	None
79 ft 0 in. to 169 ft 11 in	0 in. to 102 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-6 ft 10 in. to 79 ft 0 in	39.4 to > 102 in.	45.3 to > 102 in.
79 ft 0 in. to 169 ft 11 in	29.5 to > 102 in.	31.5 to = 78.7 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-6 ft 10 in. to 79 ft 0 in	No	> 102 in.
79 ft 0 in. to 169 ft 11 in	No	> 102 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-6 ft 10 in. to 79 ft 0 in	Easy/Trencher	Deep (> 9ft 10in)	None
79 ft 0 in. to 169 ft 11 in	Easy/Trencher	Deep (> 9ft 10in)	None

Operator B

Soils assessment was conducted by Operator B at five sites: three sites located in poor or very poorly drained lacustrine clay, one site located in very poorly drained clay till, and one located in well drained rock. The soil environment was considered to be moderately corrosive at the lacustrine sites and noncorrosive at the bedrock site. No other soil model for the clay till site is currently available. Two corrosion features were found at the bedrock site, and one corrosion feature was found at each of the lacustrine clay sites.

The 10.75-inch OD pipeline of Operator B was constructed in 1958 using ERW pipe and coated with field-applied coal tar enamel. The RoW in the area investigated is located along the edge of a gravel road adjacent to several residential areas. Field investigation included five sites that were excavated between 42.5 and 44.3 miles downstream from the nearest compressor station. These sites were selected based upon results from a prior in-line inspection and the pre-assessment step of an ECDA project. This evaluation was conducted as the direct examination step of the ECDA project. A total of nine pipe lengths including five girth welds (~181 ft of pipe) were inspected for coating defects, the presence of external corrosion, and other relevant surface indications. Disbonded coating was removed from a total of ~26 ft of pipe to facilitate inspection of pipe defects. Five external corrosion features, one dent, and two gouges were found.

Although the pipeline was coated with field applied coal tar at all five excavation sites, a felt rock shield was only applied at Site 1A and 2. At all sites except Site 3, the coating was in very poor condition, with numerous holidays due to rock or mechanical damage and/or general disbondment due to poor adhesion. At Site 3 the coating was in good condition, with holidays due to rock damage and only one area of poor adhesion. Poor adhesion of field applied coal tar coating is usually the result of poor cleaning and application procedures. Calcium carbonate and iron oxide/hydroxide corrosion deposits were found at all of the sites. Apparently, some CP current shielding was occurring; it was at these areas that the corrosion features were found.

Four of the five sites were located in level topography, and one (Site 1A and 2) was located on a ridge. The soil at three of the four sites in the level topography was characterized as a lacustrine clay soil. The soil at the other site (Site 1) was characterized as clay till. Because these sites were located under the edge of a gravel road, an 8-in deep layer of gravel was present at the top of each of these soil profiles. Site 1A and 2 was located within gneiss bedrock, and had no gravel layer. The bedrock at Site 1A and 2 was classified as well drained. The pipeline was being used as a drainage conduit for water at Site 1. Gleying was evident only around the pipeline itself. It should be noted that a soil survey may classify this area as being imperfectly drained because borehole samples are taken away from the pipeline; the actual drainage of the site was poor. Drainage at the other four sites was classified as very poor.

Soil resistivity values collected during the investigation indicated that the clay soil sites averaged 24,169 ohm-cm, which indicates the soil at the sites is not corrosive. The 114,900 ohm-cm value collected at Site 1A and 2 was considered to be an outlier that would artificially skew the data and thus was culled before calculating the average resistivity. All of the soil resistivity readings were taken at a pin spacing of 0.91 m (3 ft). Table A-16 summarizes the resistivity values at the five sites.

Table A-16. Soil Resistivity Summary, Operator B's Sites

	Soil Resistivity (Ω-cm)
Average	24,169
Minimum	8,790
Maximum	114,900

Table A-17. Pipe-to-Soil Potential Summary, Operator B's Sites

Site Name	CP "On" (volts)
Site 1	-1.200
Site 1A and 2	N/A
Site 3	-1.200
Site 3A	-1.200
Site 4	-1.200

The CP "on" potential readings using a $Cu/CuSO_4$ electrode were obtained at the pipe level near the upstream end of each excavation site, with the exception of Site 1A and 2. The average CP level for each investigated site was -1.200 volts, which exceeds the typical industry criterion of -0.850 volts. Because external corrosion was present at all sites except Site 1, it is possible that the CP is being shielded from the pipeline. Table A-17 summarizes the CP values recorded at all five sites.

Table A-18 summarizes the soil parameters collected at the five excavation sites that could be included in an external corrosion model and/or soils model. The pH of any fluids found under the coating have also been included in Table A-18. Where an electrolyte pH value has not been indicated, the under coating conditions were dry. Soil pH values were not obtained.

Table A-18. Summary of Excavation Site Corrosivity Parameters

	Resistivity, Ohm-cm	Electrolyte pH	Soil pH	Texture	Drainage
Site 1	24,416	7.0	Not determined	Gravel fill overlaying Clay Till	Very Poor
Site 1A and 2	114,900	Not determined	Not determined	Gneiss Bedrock	Well
Site 3	8790	Not determined	Not Determined	Gravel fill overlaying Lacustrine Clay	Poor
Site 3A	41,364	6.5-7.5	Not Determined	Gravel fill overlaying Lacustrine Clay	Very Poor
Site 4	22,406	Not determined	Not Determined	Gravel fill overlaying Lacustrine Clay	Very Poor

Additional soil related parameters collected at each excavation site are shown in Tables A-19 through A-24.

Table A-19. Site 1 Soils Data Summary from Operator B

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-0.15 to 14.73 m	0 to 0.38 m	Gravel Fill	Level	NA	Gravel	Level
-0.15 to 14.73 m	0.38 to 1.28 m	Till	Level	Very Poor	Clay	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-0.15 to 14.73 m	0 to 0.38 m	False	Gravel	Numerous (>50%)	Trace (0-10%)	None
-0.15 to 14.73 m	0.38 to 1.28 m	False	Clay, Silt, Very Fine Sand, Sand, Gravel	Trace (0-10%)	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-0.15 to 14.73 m	38 to > 128 cm	30 to = 70 cm

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-0.15 to 14.73 m	No	> 128 cm

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-0.15 to 14.73 m	Easy/Trencher	NA	None
-0.15 to 14.73 m	Moderate/Backhoe	NA	None

Table A-20. Site 1A and 2 Soils Data Summary from Operator B

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-3.8 to 17.66 m	0 to 1.85 m	Rock	Ridged	Well	Gneiss	Crest

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-3.8 to 17.66 m	0 to 1.85 m	False	Rock, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-3.8 to 17.66 m	No	> 185 cm

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-3.8 to 17.66 m	Difficult/Backhoe/Blast	Shallow (0-1m)	Knob

Table A-21. Site 3 Soils Data Summary from Operator B

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
0 to 14.61 m	0 to 0.3 m	Gravel Fill	Level	NA	Gravel	Level
0 to 14.61 m	0.3 to 1.3 m	Lacustrine	Level	Poor	Clay	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
0 to 14.61 m	0 to 0.3 m	False	Gravel	Numerous (>50%)	None	None
0 to 14.61 m	0.3 to 1.3 m	False	Clay, Silt, Very Fine Sand	Trace (0-10%)	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
0 to 14.61 m	30 to = 90 cm	90 to > 130 cm

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
0 to 14.61 m	No	NA
0 to 14.61 m	Yes	NA

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
0 to 14.61 m	Easy/Trencher	Moderate (1-3m)	None
0 to 14.61 m	NA	NA	None

Table A-22. Site 3A Soils Data Summary from Operator B

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-1 to 14.5 m	0 to 0.2 m	Gravel Fill	Level	NA	Gravel	Level
-1 to 14.5 m	0.2 to 1.5 m	Lacustrine	Level	Very Poor	Clay	Level
-1 to 14.5 m	1.5 to 1.6 m	Lacustrine	Level	Very Poor	Clay	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-1 to 14.5 m	0 to 0.2 m	False	Gravel	Numerous (>50%)	None	None
-1 to 14.5 m	0.2 to 1.5 m	False	Clay, Silt, Very Fine Sand	Trace (0-10%)	None	Partial (10-50%)
-1 to 14.5 m	1.5 to 1.6 m	False	Clay, Silt, Very Fine Sand	Trace (0-10%)	None	Partial (10-50%)

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-1 to 14.5 m	20 to > 150 cm	20 to > 150 cm

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-1 to 14.5 m	No	> 20 cm
-1 to 14.5 m	Yes	= 130 cm

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-1 to 14.5 m	Difficult/Backhoe/Blast	Moderate (1 -3m)	None
-1 to 14.5 m	Easy/Trencher	Moderate (1 -3m)	None
-1 to 14.5 m	NA	NA	None

Table A-23. Site 4 Soils Data Summary from Operator B

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-3.65 to 2.4 m	0 to 0.39 m	Gravel Fill	Level	NA	Gravel	Level
-3.65 to 2.4 m	0.39 to 1.1 m	Lacustrine	Level	Very Poor	Clay	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-3.65 to 2.4 m	0 to 0.39 m	False	Gravel	Numerous (>50%)	Trace (0-10%)	None
-3.65 to 2.4 m	0.39 to 1.1 m	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-3.65 to 2.4 m	0.39 to = 0.75 cm	0.39 to > 1.1 cm

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-3.65 to 2.4 m	No	> 39.0 cm
-3.65 to 2.4 m	Yes	= 100.0 cm

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-3.65 to 2.4 m	Easy/Trencher	Moderate (1 -3m)	None

Operator C

Four sites were excavated along this pipeline segment, which is located in agricultural fields and does not cross any roads or waterways. Approximately 1200 ft of soil in the excavation area were examined during the survey. The initial soil survey classified this area as an imperfect to poorly drained fluvial soil in level topography. After more extensive excavation, it was found that the soil was actually imperfect to poorly drained lacustrine clay or silt overlaying fluvial sand. The discrepancy arose due to the depth limitation of the initial core survey, which was later exceeded during the full excavation.

Following the more extensive excavation, the soil was classified as a either a lacustrine clay or lacustrine silt overlying fluvial sand. The pipe was fully within the lacustrine soil at the Validation Site and Site 1, fully within the fluvial soil at Site 2, but was in both the lacustrine and fluvial soils at Site 3. Mottling and gleying of the soil occurred throughout the soil profile at each site. Carbonates were also present throughout the soil profile at each site. All of the sites had imperfect to poor drainage.

The 24-inch OD pipeline was constructed in 1949 using ERW pipe and coated with field-applied coal tar enamel. The field investigation excavation locations were located between 58.9 and 59.1 miles downstream from a main line valve reference location. The sites were selected based upon results from an in-line inspection and an ECDA project, and comprised the direct examination step of the ECDA project. Seven partial joints and three girth welds totaling 22.7 ft of pipe were excavated and inspected for coating defects, the presence of external corrosion, and other relevant surface indications. Disbonded coating was removed from a 15.7 ft of pipe to facilitate inspection for pipe defects and external corrosion. Very minor (depths <5% of the pipe wall thickness) external corrosion was found on the pipeline.

With the exception of the Validation Site, the coating was generally in fair condition. Moderate disbondment due to poor adhesion was found at these sites. Two holidays due to the effect of soil stresses on the coating were found at Site 2. The coating at the validation Site was in excellent condition.

The lacustrine soil sites had soil resistivities between very corrosive to the moderately corrosive categories. The fluvial sand soils had one resistivity in the mildly corrosive category, but the remaining readings were considered noncorrosive. Table A-24 summarizes the soil resistivities according to soil type at each site.

Table A-24. Soil Resistivity Summary, Operator C's Sites

Site	Lacustrine Soil Resistivity (O-cm)	Fluvial Soil Resistivity (O-cm)
Validation	790	3,900
1	1,300	N/A
2	1,600	34,000
3	470	59,000

The soils in this study are weakly acidic and would fall into the Moderate category when the corrosivity is based upon pH. The fluvial soil at the Validation Site did have a pH of 5.2, but the pipeline is not located within this soil. Table A-25 summarizes the pH readings found at the sites.

Table A-25. Soil pH Summary, Operator C's Sites

Site	Lacustrine Soil pH	Fluvial Soil pH
Validation	6.4	5.2
1	6.0	N/A
2	6.2	6.4
3	6.2	6.4

The low soil resistivities of the lacustrine soils and their acidic pH values classify these soils as corrosive to very corrosive. In addition, a vertical potential gradient could form between the two different soils, with the fluvial sand being cathodic to the lacustrine soils because of its higher resistivity. However, the CP "on" levels at the sites investigated were above industry standards, and provided sufficient protection against the corrosive environment.

The resistivity of the lacustrine soils was 5 to 125 times lower than the resistivity of the fluvial sand, but the pH of the soils was similar, except at the validation site.

CP "on" pipe-to-soil potential values were obtained utilizing a saturated Cu/CuSO4 reference electrode. Readings were taken at the upstream end of each excavation at the pipe level. Table A-26 summarizes the CP values at all of the sites investigated. A CP reading was not obtained at the validation site because the coating was not removed. All of the CP readings taken exceed the typical industry minimum acceptance criterion of -0.850 volts.

Table A-26. Site CP Level Summary, Operator C's Sites

Site Name	CP "On" (volts)
Validation Site	N/A
Site 1	-1.095
Site 2	-1.174
Site 3	-1.135

Table A-27 summarizes the soil parameters collected at the five excavation sites that could be included in an external corrosion model and/or soils model. The pipe surface under the coating removed at Sites 1-3 was dry so no electrolyte pH evaluation was conducted. Coating was not removed at the validation site.

Additional soil-related parameters collected at each excavation site are shown in Tables A-28 through A-31.

Table A-27. Summary of Excavation Site Corrosivity Parameters

	Resistivity (lacustrine/ fluvial) (Ohm-cm)	Electrolyte pH	Soil pH (lacustrine/ fluvial)	Texture	Drainage
Validation	790/3,900	Not Determined	6.4/5.2	Lacustrine Clay overlaying Fluvial Sand	Imperfect to Poor
Site 1	1,300/NA	Not Determined	6.0/NA	Lacustrine Clay overlaying Fluvial Sand	Imperfect to Poor
Site 2	1,600/34,000	Not Determined	6.2/6.4	Lacustrine Clay overlaying Fluvial Sand	Imperfect to Poor
Site 3	470/59,000	Not Determined	6.2/6.4	Lacustrine Clay overlaying Fluvial Sand	Imperfect to Poor

Table A-28. Validation Site Soils Data Summary from Operator C

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
0 ft 0 in. to 3 ft 11 in	0 in. to 76.8 in.	Lacustrine	Level	Imperfect - Poor	Clay	Level
0 ft 0 in. to 3 ft 11 in	76.8 in. to 82.7 in.	Fluvial	Level	Imperfect - Poor	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
0 ft 0 in. to 3 ft 11 in	0 in. to 76.8 in.	False	Clay, Silt	None	None	None
0 ft 0 in. to 3 ft 11 in	76.8 in. to 82.7 in.	False	Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
0 ft 0 in. to 3 ft 11 in	0 to > 82.7 in.	0 to > 82.7 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth
0 ft 0 in. to 3 ft 11 in	None	0 to 82.7 in.

Water Table

From - To	Ground Water	Depth To Water Table
0 ft 0 in. to 3 ft 11 in	No	> 82.7 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
0 ft 0 in. to 3 ft 11 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-29. Site 1 Soils Data Summary from Operator C

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-4 ft 5 in. to 2 ft 7 in	0 in. to 66.9 in.	Lacustrine	Level	Imperfect - Poor	Silt	Level
-4 ft 5 in. to 2 ft 7 in	66.9 in. to 73.6 in.	Fluvial	Level	Imperfect - Poor	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-4 ft 5 in. to 2 ft 7 in	0 in. to 66.9 in.	False	Clay, Silt	None	None	None
-4 ft 5 in. to 2 ft 7 in	66.9 in. to 73.6 in.	False	Silt, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-4 ft 5 in. to 2 ft 7 in	0 to = 73.6 in.	0 to = 73.6 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth
-4 ft 5 in. to 2 ft 7 in	None	0 to 73.6 in.

Water Table

From - To	Ground Water	Depth To Water Table
-4 ft 5 in. to 2 ft 7 in	No	> 73.6 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-4 ft 5 in. to 2 ft 7 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-30. Site 2 Soils Data Summary from Operator C

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-0 ft 2 in. to 3 ft 6 in	0 in. to 45.7 in.	Lacustrine	Level	Imperfect - Poor	Silt	Level
-0 ft 2 in. to 3 ft 6 in	45.7 in. to 75.6 in.	Fluvial	Level	Imperfect - Poor	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-0 ft 2 in. to 3 ft 6 in	0 in. to 45.7 in.	False	Silt	None	None	None
-0 ft 2 in. to 3 ft 6 in	45.7 in. to 75.6 in.	False	Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-0 ft 2 in. to 3 ft 6 in	0 to > 75.6 in.	0 to > 75.6 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth
-0 ft 2 in. to 3 ft 6 in	None	0 to 75.6 in.

Water Table

From - To	Ground Water	Depth To Water Table
-0 ft 2 in. to 3 ft 6 in	No	> 75.6 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-0 ft 2 in. to 3 ft 6 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-31. Site 3 Soils Data Summary from Operator C

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-0 ft 4 in. to 7 ft 9 in	0 in. to 53.5 in.	Lacustrine	Level	Imperfect - Poor	Clay	Level
-0 ft 4 in. to 7 ft 9 in	53.5 in. to 71.3 in.	Fluvial	Level	Imperfect - Poor	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-0 ft 4 in. to 7 ft 9 in	0 in. to 53.5 in.	False	Clay, Silt	None	None	None
-0 ft 4 in. to 7 ft 9 in	53.5 in. to 71.3 in.	False	Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-0 ft 4 in. to 7 ft 9 in	0 to > 71.3 in.	0 to > 71.3 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth
-0 ft 4 in. to 7 ft 9 in	None	0 to 71.3 in.

Water Table

From - To	Ground Water	Depth To Water Table
-0 ft 4 in. to 7 ft 9 in	No	> 71.3 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-0 ft 4 in. to 7 ft 9 in	Easy/Trencher	Deep (> 9ft 10in)	None

Operator D

A total of nine sites including one validation site were excavated and 2.83 miles of soil was surveyed. The examined pipeline section is located in woodland areas. The soil consisted of fluvial sand which traversed through different terrain and drainage types. The nine excavations were located in areas with well, well to imperfect, or imperfectly drained fluvial sands. A corrosion model does not currently exist for this soil type.

The topography of most of the sites was level, with the exceptions of Site 7, which was located in a depression, and Sites 5 and 6, which were located on inclines. All of the sites were located within woodland areas. The soil at all of the sites was fluvial sand. The drainage was classified as well drained at Site 1, well drained to imperfectly drained at Site 3 and Site 6, and imperfectly drained at the remaining sites. Soil mottling was observed at all of the sites except for Site 1.

This segment of the pipeline examined included 30-inch OD pipe constructed in 1951 and coated with field-applied coal tar. Excavations, that constituted the direct examination step of the ECDA process, were conducted at eight sites with anomalies and one validation site. These sites were selected based upon results from ILI and the results of the ECDA process indirect inspection step. The nine excavations covered a total of 181.4 feet that included thirteen partial joints and six girth welds. Each site was inspected for coating defects and the coating was then removed to facilitate examination for pipe defects and external corrosion.

With the exception of the validation site, the coating was generally in good to fair condition. Wrinkling of the coating and porosity within the coating was noted at Sites 1, 2, 5, 7, and 8. Splits or tears of the coating were noted along the bottom of the pipe at Sites 1 and 2, and along the long seam of joint A at Site 8. The coating at the validation site was in excellent condition. Uneven coating thicknesses were noted at Sites 1 and 2. The coating thickness on the bottom of the pipe (approximately from the 4:00 to the 8:00 pipe positions) averaged about 39 mils, the sides averaged 197 to 236 mils, and the top averaged 157 mils. The uneven thickness, tearing, wrinkling, and porosity in the coating are usually the result of improper coating application procedures. Such defects can occur if an improper curing time is used, the coating is not applied evenly, or when the coating is applied to the pipe when it is too hot. Six external corrosion features were found at Site 3, but this corrosion had apparently occurred before the pipeline was installed. The maximum depth of the external corrosion features was 7.1 percent of the measured wall thickness. The coating at these features was well bonded which suggested that this corrosion had occurred before the pipeline was coated, most likely during storage before construction.

Corrosion product deposits were observed at all but the validation site. In addition to the corrosion deposits, an oily textured green liquid was found within coating blisters and wrinkles at Sites 2, 5, 7, and 8. This liquid was not in contact with the pipe or soil and had a high pH ranging between 13 and 14. Since the liquid was trapped in the pores and voids of the coating, it is possible that it was rainwater or groundwater that had been trapped in the coating during the time of construction. The high pH of the liquid can be attributed to the effect of the cathodic protection current on the fluid.

The cathodic protection (CP) "on" potential values were obtained versus a saturated Cu/CuSO4 reference electrode Readings were taken at the upstream and/or downstream ends of the excavations at the pipe level. Table A-32 summarizes the CP values at the five of the nine sites evaluated. The average CP "on" measurements for all of the sites was -1.396 v.

Table A-32. CP Level Summary, Operator D's Sites

Site Name	Average CP "On" (V)
Site 2	-1.411
Site 3	-1.400
Site 6	-1.440
Site 7	-1.352
Site 8	-1.378

Table A-33 summarizes the soil parameters collected at the nine excavation sites that could be included in an external corrosion model and/or soils model. No electrolyte pH values have been indicated in Table A-33 since the under coating conditions were dry. No soil pH values or resistivity data were collected at these excavation sites.

Additional soil-related parameters collected at each excavation site are shown in Tables A-34 through A-42.

Table A-33. Summary of Corrosivity Parameters, Operator D's Sites

	Resistivity (Ohm-cm)	Electrolyte pH	Soil pH	Texture	Drainage
Validation	No data	NA	NA	Fluvial Sand	Imperfect
Site 1	No data	NA	NA	Fluvial Sand	Well
Site 2	No data	NA	NA	Fluvial Sand	Imperfect
Site 3	No data	NA	NA	Fluvial Sand	Well to Imperfect
Site 4	No data	NA	NA	Fluvial Sand	Imperfect
Site 5	No data	NA	NA	Fluvial Sand	Imperfect
Site 6	No data	NA	NA	Fluvial Sand	Well to Imperfect
Site 7	No data	NA	NA	Fluvial Sand	Imperfect
Site 8	No data	NA	NA	Fluvial Sand	Imperfect

Table A-34. Validation Site Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
12 ft 6 in. to 17 ft 9 in	0 in. to 96.5 in.	Fluvial	Level	Imperfect	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
12 ft 6 in. to 17 ft 9 in	0 in. to 96.5 in.	False	Silt, Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
12 ft 6 in. to 17 ft 9 in	13.8 to > 96.5 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
12 ft 6 in. to 17 ft 9 in	No	> 96.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
12 ft 6 in. to 17 ft 9 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-35. Site 1 Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-25 ft 4 in. to 0 ft 0 in	0 in. to 98.4 in.	Fluvial	Level	Well	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-25 ft 4 in. to 0 ft 0 in	0 in. to 98.4 in.	False	Silt, Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-25 ft 4 in. to 0 ft 0 in	No	> 98.4 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-25 ft 4 in. to 0 ft 0 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-36. Site 2 Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-0 ft 10 in. to 28 ft 1 in	0 in. to 88.6 in.	Fluvial	Level	Imperfect	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-0 ft 10 in. to 28 ft 1 in	0 in. to 88.6 in.	False	Silt, Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-0 ft 10 in. to 29 ft 0 in	19.7 to > 88.6 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-0 ft 10 in. to 28 ft 1 in	No	> 88.6 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-0 ft 10 in. to 28 ft 1 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-37. Site 3 Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-18 ft 1 in. to 1 ft 10 in	0 in. to 90.6 in.	Fluvial	Level	Well - Imperfect	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-18 ft 1 in. to 1 ft 10 in	0 in. to 90.6 in.	False	Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-18 ft 1 in. to 1 ft 10 in	9.8 to > 90.6 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-18 ft 1 in. to 1 ft 10 in	Yes	= 89.8 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-18 ft 1 in. to 1 ft 10 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-38. Site 4 Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
17 ft 9 in. to 30 ft 2 in	0 in. to 96.5 in.	Fluvial	Level	Imperfect	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
17 ft 9 in. to 30 ft 2 in	0 in. to 96.5 in.	False	Silt, Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
17 ft 9 in. to 30 ft 2 in	13.8 to > 96.5 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
17 ft 9 in. to 30 ft 2 in	No	> 96.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
17 ft 9 in. to 30 ft 2 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-39. Site 5 Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
0 ft 0 in. to 28 ft 5 in	0 in. to 92.5 in.	Fluvial	Inclined	Imperfect	Sand	Lower

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
0 ft 0 in. to 28 ft 5 in	0 in. to 92.5 in.	False	Clay, Silt, Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
0 ft 0 in. to 28 ft 5 in	15.7 to > 92.5 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
0 ft 0 in. to 28 ft 5 in	No	> 92.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
0 ft 0 in. to 28 ft 5 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-40. Site 6 Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-0 ft 8 in. to 25 ft 9 in	0 in. to 98.4 in.	Fluvial	Inclined	Well - Imperfect	Sand	Middle

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-0 ft 8 in. to 25 ft 9 in	0 in. to 98.4 in.	False	Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-0 ft 8 in. to 25 ft 9 in	47.2 to > 98.4 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-0 ft 8 in. to 25 ft 9 in	No	> 98.4 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-0 ft 8 in. to 25 ft 9 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-41. Site 7 Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
0 ft 0 in. to 13 ft 9 in	0 in. to 92.5 in.	Fluvial	Depression	Imperfect	Sand	Depression

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
0 ft 0 in. to 13 ft 9 in	0 in. to 92.5 in.	False	Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
0 ft 0 in. to 13 ft 9 in	14.2 to > 92.5 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
0 ft 0 in. to 13 ft 9 in	Yes	= 90.6 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
0 ft 0 in. to 13 ft 9 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-42. Site 8 Soils Data Summary from Operator D

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-9 ft 11 in. to 11 ft 2 in	0 in. to 104.3 in.	Fluvial	Level	Imperfect	Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-9 ft 11 in. to 11 ft 2 in	0 in. to 104.3 in.	False	Silt, Very Fine Sand, Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-9 ft 11 in. to 11 ft 2 in	39.4 to > 104.3 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-9 ft 11 in. to 11 ft 2 in	No	> 104.3 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-9 ft 11 in. to 11 ft 2 in	Easy/Trencher	Deep (> 9ft 10in)	None

Operator E

The evaluations conducted by Operator E included two dig sites on two different pipelines that have been identified as Lines F and G herein. Details concerning the excavations made on each pipeline are included in separate subsections.

Excavation of Line F

Both of the sites excavated (Nos. 2 and 3) were located in level topography with the soil classified as lacustrine very fine sand. The drainage at all of the sites was classified as very poor. Ground water seepage was present in both excavations. Mottling of the soil occurred throughout the soil profile at each site. Gleying completely surrounded the pipe at Site 3, and surrounded the bottom half of the pipe at Site 2.

This 30-inch OD pipeline system was constructed in 1950 and coated with field-applied coal tar. A total of four partial pipe lengths and two girth welds totaling 82.6 ft of pipe were excavated and inspected for the presence of external corrosion and other relevant surface indications. The sites were chosen based upon results selected from an ECDA project indirect inspection with the excavations described constituting the direct examinations step of the ECDA process.

Disbonded coating from the pipe surface was removed for a total of 74.3 ft to facilitate inspection for pipe defects and external corrosion. The pipeline was coated with field-applied coal tar at both sites. At Site 3 there was field-applied mastic over the coal tar near the RGW because of poor application of the coal tar. The coating was in excellent to fair condition at Site 2, and fair to very poor condition Site 3. Disbondment was due to poor adhesion on the pipe. Site 2 had moderate disbondment, and Site 3 moderate to major disbondment. Poor adhesion of the coal tar coating is usually the result of poor cleaning and application procedures used at the time of installation

Calcium carbonate, iron oxide/hydroxide and iron carbonate corrosion deposits were found on the pipe at most of the disbonded locations. The presence of soil mottling indicates an alternating anaerobic and aerobic environment. Gleying of the soil was also present at both sites, and encased most or all of the pipeline. The pipeline was in a moist anaerobic environment for long periods of time, a factor that may contribute to external corrosion. However, as mentioned earlier, the presence of calcium carbonate at all disbonded locations may indicate that the CP system was functional. Consequently, this may offer an explanation for the lack of external corrosion present on the pipe surface, as the CP seems to be effectively protecting the pipe. No external corrosion was found on the pipeline at these two sites.

The soil resistivity seen in this investigation indicates a mildly corrosive environment at Site 2, and mildly corrosive to progressively less corrosive at Site 3. Table A-42 summarizes the average, minimum, and maximum resistivities obtained from this examination.

Table A-43 Line F Soil Resistivity Summary, Operator E's Sites

Site Name	Minimum Resistivity (O-cm)	Maximum Resistivity (O-cm)	Average Resistivity (O-cm)
Site 2	5,000	10,000	7,500
Site 3	1,900	25,000	10,667

Table A-44 summarizes the cathodic protection "on" values at pipe level The average cathodic protection (CP) potential was -1.509V.

Table A-44. Line F CP Level Summary, Operator E's Sites

Site Name	Upstream CP "On" (volts)	Downstream CP "On' (volts)	Average CP "On" (volts)
Site 2	-1.503	-1.506	-1.505
Site 3	-1.525	-1.500	-1.513

The soil was classified as lacustrine very fine sand, with very poor drainage in both sites. The low resistivity values categorize the soils as moderately corrosive to progressively less corrosive. Groundwater seepage, as well as the presence of mottling and gleying indicates that the pipe was encased in a moist environment. This moisture facilitates cathodic protection, in that it may lower the resistivity of the soil, easing the movement of current to the pipeline. The CP "on" levels at these excavation sites were indicated that protection was being achieved in accordance with typical industry standard "on" pipe-to-soil potential (i.e., -0.85 v vs. $Cu/CuSO_4$ reference electrode).

Excavation of Line G

Both excavation sites on Line G, identified as Sites 1 and 2, were located in a floodplain region area with level topography. The soil at both sites was classified as fluvial silt mixed with clay and very fine sands. Drainage conditions were considered to be imperfect to poorly drained at Site 1 and well-drained at Site 2. Gleying of the soil occurred from a depth of 39 inches to the excavation depth encasing the pipeline was evident at Site 1. Ground water seepage also present in the excavation at Site 1 at 61 inches below the ground surface. Site 2 was located adjacent to a concrete drainage canal.

The two excavation sites were selected during an ECDA project and comprised the direct examination step of the process. Four partial pipe lengths and two girth welds totaling 41.5 ft of pipe were excavated and inspected for coating defects. Disbonded coating was removed for a total of 23.6 ft to facilitate inspection for pipe defects and external corrosion The 16-inch OD pipeline system was constructed in 1950 from ERW pipe was coated with factory-applied asphalt, fusion bond epoxy (FBE), field-applied mastic, and single wrap tape.

Excavations revealed that the pipeline was coated with factory-applied asphalt at Site 1. At Site 2, the pipeline was coated with field-applied tape single-wrap, shrink sleeves, and mastic, as well as factory-applied asphalt and fusion bond epoxy. The coating was in excellent to fair condition at Site 1, and excellent to good condition Site 2. Two stopple fittings and a tap at Site 2 had bare surfaces. Minor disbondment of the coating noted at both sites was due to soil stress on the pipe. The presence of corrosion deposits at indicated both sites may have an effective CP system. The corrosion deposits also may indicate Site 1 has an anaerobic environment. Two external corrosion features were found at Site 1.

Calcium carbonate and iron oxide/ hydroxide corrosion deposits were found on the pipe at most of the disbonded locations. The presence of gleyed soils encasing the pipeline at Site 1 indicates that it was exposed to saturated or reducing conditions throughout the year. This statement is further supported in that the anaerobic iron carbonate deposit was found only at this site.

The soil resistivity ranged was from 840 ohm-cm to 930 ohm-cm, as indicted in Table A-45 that categorize the soils as corrosive.

Table A-45. Line G Soil Resistivity Summary, Operator E's Sites

Site Name	Resistivity (Ω-cm)
Site 1	840
Site 2	930

The presence of finer soils (a dominant silt soil mixed with clay) at both sites can partially account for the relatively low resistivity values. The moisture present at and consistent soil types at both sites also partially accounts for the low resistivity values. Site 1 clearly indicates the presence of stagnant water in that the soil was gleyed, the drainage was imperfect to poor, and there was groundwater seepage. Though the drainage at Site 2 was well, it was located beside a drainage canal, which may account for high levels of water movement around the pipeline.

Soil pH at both sites was slightly acidic, which is another indication of the corrosive environment. Table A-46 illustrates the pH values obtained during this investigation.

Table A-46- Line G pH Summary, Operator E's Sites

Site Name	pH
Site 1	6.34
Site 2	6.45

The CP "on" potential values were obtained utilizing a saturated Cu/CuSO4 reference electrode. CP "on" measurements were taken at the upstream end of each excavation.

Table A-46 summarizes the CP values taken at pipe levels at both sites and exceed the typical industry criterion of -0.850 volts "on". A rectifier was located at Site 1 was out of service due to damaged cables.

Table A-47. Line G CP Level Summary, Operator E's Sites

Site Name	Upstream CP "On" (volts)	Downstream CP "On' (volts)	Average CP "On" (volts)
Site 1	-1.096	-1.177	-1.137
Site 2	-1.329	-1.335	-1.332

Table A-48 summarizes the soil parameters collected at the four excavation sites on Lines F and G that could be included in an external corrosion model and/or soils model. The pH of any fluids found under the coating (electrolyte pH) have and soils pH have been included in Table A-48.

Table A-48. Summary of Excavation Site Corrosivity Parameters, Operator E's Sites

	Resistivity (Ohm-cm)	Electrolyte pH	Soil pH	Texture	Drainage
Line F					
Site 2	5,000-10,100	8.0	No data	Lacustrine Very Fine Sand	Very Poor
Site 3	1,900-25,000	No data	No data	Lacustrine Very Fine Sand	Very Poor
Line G					
Site 1	840	7.0	6.34	Fluvial Silt	Imperfect to poor
Site 2	930	No data	6.45	Fluvial Silt	Well

Additional soil-related parameters collected at each excavation site are shown in Tables A-49 through A-52.

Table A-49. Line F, Site2 Soils Data Summary from Operator E

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-13 ft 11 in. to 27 ft 1 in	0 in. to 102.4 in.	Lacustrine	Level	Very Poor	Very Fine Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-13 ft 11 in. to 27 ft 1 in	0 in. to 102.4 in.	False	Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-13 ft 11 in. to 27 ft 1 in	0 to > 102.4 in.	59.1 to > 102.4 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-13 ft 11 in. to 27 ft 1 in	Yes	> 98.4 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-13 ft 11 in. to 27 ft 1 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-50. Line F, Site 3 Soils Data Summary from Operator E

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-26 ft 10 in. to 14 ft 9 in	0 in. to 102.4 in.	Lacustrine	Level	Very Poor	Very Fine Sand	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-26 ft 10 in. to 14 ft 9 in	0 in. to 102.4 in.	False	Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-26 ft 10 in. to 14 ft 9 in	0 to > 102.4 in.	47.2 to > 102.4 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-26 ft 10 in. to 14 ft 9 in	Yes	> 94.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-26 ft 10 in. to 14 ft 9 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-51. Line G, Site 1-Soil Data Summary from Operator E

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-22 ft 6 in. to 1 ft 4 in	0 in. to 63 in.	Fluvial	Level	Imperfect - Poor	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-22 ft 6 in. to 1 ft 4 in	0 in. to 63 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
0 ft 0 in. to -22 ft 6 in	None	29.5 to = 61 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-22 ft 6 in. to 1 ft 4 in	Yes	> 61 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-22 ft 6 in. to 1 ft 4 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-52. Line G, Site 2 Soils Data Summary from Operator E

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-1 ft 0 in. to 0 ft 0 in	0 in. to 54.7 in.	Fluvial	Level	Well	Silt	Level
0 ft 0 in. to 16 ft 8 in	0 in. to 50 in.	Fluvial	Level	Well	Silt	Level

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-1 ft 0 in. to 0 ft 0 in	0 in. to 54.7 in.	False	Clay, Silt, Very Fine Sand	None	None	None
0 ft 0 in. to 16 ft 8 in	0 in. to 50 in.	False	Clay, Silt, Very Fine Sand	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-1 ft 0 in. to 0 ft 0 in	No	> 54.7 in.
0 ft 0 in. to 16 ft 8 in	No	> 50 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-1 ft 0 in. to 0 ft 0 in	Easy/Trencher	Deep (> 9ft 10in)	None
0 ft 0 in. to 16 ft 8 in	Easy/Trencher	Deep (> 9ft 10in)	None

Operator F

Nine sites were excavated over a total length of 296.7 feet of pipe. This included five full pipe lengths, 18 partial lengths, and 15 girth welds. These sites were selected for direct examination as part of an ECDA project.

Most of the sites were located in inclined topography, with the exception of Site A-92 to A-94, CD-17 which was ridged. The soil type at Sites A-113 to A-116, CD-5, CD-4, Dig 2 (Dent) and Dig 3 (Dent) was sand till. The soil type at Site A-92 to A-94, CD-17 was rock till. The soil type at Site A-37 was clay till over shale bedrock. The soil type at Site CD-28/CD-29 was clay till. The soil type at Site 1 was sand till overlying shale bedrock. The drainage was classified as very poor at Sites A-113 to A-116, A-37, and CD-28. Sites A-92 to A-94, CD-17, CD-5, CD-4, Site 1, Dig 2 (Dent) and Dig 3 (Dent) were well drained. Mottling and or gleying was present at Sites A-113 to A-116, A-37, CD-28/CD-29. Ground water seepage was present at Sites A-113 to A-116 and A-37.

Drainage characteristics at Sites A-113 to A-116, A-37 and CD-28/CD-29 were very poor, while Sites A-92 to A-94, CD-17, CD-5, CD-4, Site 1, Dig 2 (Dent) and Dig 3 (Dent) were considered to be well-drained. At Site A-113 to A-116 gleying of the soil occurred from 85 in. to 115 in. encasing the pipeline. At Site A-37 mottling of the soil occurred from 8 in. to 51 in. below the ground surface, and gleying of the soil occurred from 12 in. to 51 in. below the ground surface, ground water seepage occurred at 104 in. below the ground surface. At Site CD-28/CD-29 mottling of the soil occurred from 16 in. below the ground surface to the depth of excavation, and gleying occurred from 24 in. below the ground surface to the depth of excavation. At Site Dig 3 (Dent) mottling occurred from 19 in. below the ground surface to the depth of excavation.

Table A-53 presents the resistivities obtained during this investigation. Soil resistivities were obtained using the Wenner 4-pin method with 10 ft pin spacing.

Table A-53. Soil Resistivity Summary, Operator F's Sites

Site Name	Resistivity (Ω-cm)
A-113 to A-116	59,360
A-92 to A-94, CD-17	230,000
CD-5	95,755
CD-4	95,755
A-37	36,387
Site 1	55,056
CD-28/CD-29	40,217
Dig 2 (Dent)	210,000
Dig 3 (Dent)	Not Obtained

The soil resistivities indicated in Table A-54 indicate a less aggressive corrosive environment at all nine sites. Soil characteristics described above contribute to this environment. The lower resistivity values are characteristic of soils that do not aggressively promote corrosion.

Soil pH at the nine sites were slightly acidic to neutral as shown in Table A-55. Soil pH values were obtained using either a field probe or a field kit.

Table A-54. Excavation Site pH Summary, Operator F's Sites

Site Name	pH
A-113 to A-116	6.4
A-92 to A-94, CD-17	Not Obtained
CD-5	6.8
CD-4	6.6
A-37	5.8
Site 1	Not Obtained
CD-28/CD-29	7.0
Dig 2 (Dent)	Not Obtained
Dig 3 (Dent)	Not Obtained

The CP "on" potential values were obtained versus saturated Cu/CuSO4 reference electrode. Pipe-to-soil potential data was obtained at all of the sites investigated at either the upstream or downstream end of the excavations at pipe level as indicated in Table A-55.

Table A-55. Excavation Site CP Level Summary, Operator F's Sites

Site Name	Upstream CP "On" (volts)	Downstream CP "On' (volts)
A-113 to A-116	-1.167	
A-92 to A-94, CD-17		-1.151
CD-5	-1.079	
CD-4	-1.637	
A-37	-1.627	
Site 1	-4.01	-4.13
CD-28/CD-29	-1.146	
Dig 2 (Dent)	-1.269	
Dig 3 (Dent)	-1.328	

Table A-56 summarizes the soil parameters collected at the excavation sites that could be included in an external corrosion model and/or soils model. Additional soil-related parameters collected at each excavation site are shown in Tables A-57 through A-65.

Table A-56. Summary of Excavation Site Corrosivity Parameters, Operator F's Sites

	Resistivity (Ohm-cm)	Electrolyte pH	Soil pH	Texture	Drainage
A-113 to A-116	59,360	9.0	6.4	Sand Till	Very Poor
A-92 to A-94, CD-17	230,000	4.0-5.0	Not obtained	Rock Till	Well
CD-5	95,755	Not obtained	6.8	Sand Till	Well
CD-4	95,755	Not obtained	6.6	Sand Till	Well
A-37	36,387	Not obtained	5.8	Fluvial Sand	Poorly to Very Poor
Site 1	55,056	11.0-12.0	Not obtained	Sand Till overlaying Shale Bedrock	Well
CD-28/CD-29	40,217	Not obtained	7.0	Clay Till	Very Poor
Dig 2 (Dent)	210,000	8.0	Not obtained	Sand Till	Well
Dig 3 (Dent)	Not obtained	8.0	4.0	Sand Till	Well

Table A-57. Site A-113 to A-116 Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-0 ft 4 in. to 44 ft 0 in	0 in. to 143.7 in.	Till	Inclined	Very Poor	Sand	Middle

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-0 ft 4 in. to 44 ft 0 in	0 in. to 143.7 in.	False	Clay, Rock, Sand	Partial (10-50%)	Partial (10-50%)	Trace (0-10%)

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-0 ft 4 in. to 44 ft 0 in	None	84.6 to = 114.6 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-0 ft 4 in. to 44 ft 0 in	No	> 143.7 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-0 ft 4 in. to 44 ft 0 in	Moderate/Backhoe	Deep (> 9ft 10in)	None

Table A-58. Site A-92 to A-94, CD-17 Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-26 ft 3 in. to 0 ft 12 in	0 in. to 102.4 in.	Till	Ridged	Well	Rock	Crest

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-26 ft 3 in. to 0 ft 12 in	0 in. to 102.4 in.	False	Silt, Very Fine Sand, Rock	Partial (10-50%)	Numerous (>50%)	Numerous (>50%)

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-26 ft 3 in. to 0 ft 12 in	No	> 102.4 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-26 ft 3 in. to 0 ft 12 in	Difficult/Backhoe/Blast	Shallow (0ft - 3ft 3 in.	Bedrock

Table A-59. Site CD-5 Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-34 ft 9 in. to 10 ft 2 in	0 in. to 96.5 in.	Till	Inclined	Well	Sand	Middle

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-34 ft 9 in. to 10 ft 2 in	0 in. to 96.5 in.	False	Clay, Rock, Sand, Gravel	Partial (10-50%)	Partial (10-50%)	Trace (0-10%)

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-34 ft 9 in. to 10 ft 2 in	No	> 96.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-34 ft 9 in. to 10 ft 2 in	Moderate/Backhoe	Deep (> 9ft 10in)	None

Table A-60. Site CD-4 Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-4 ft 7 in. to 42 ft 1 in	0 in. to 96.5 in.	Till	Inclined	Well	Sand	Middle

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-4 ft 7 in. to 42 ft 1 in	0 in. to 96.5 in.	False	Clay, Rock, Sand, Gravel	Partial (10-50%)	Partial (10-50%)	Trace (0-10%)

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-4 ft 7 in. to 42 ft 1 in	No	> 96.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-4 ft 7 in. to 42 ft 1 in	Moderate/Backhoe	Deep (> 9ft 10in)	None

Table A-61. Site A-37 Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-28 ft 7 in. to 3 ft 5 in	0 in. to 51.2 in.	Till	Inclined	Very Poor	Clay	Toe
-28 ft 7 in. to 3 ft 5 in	51.2 in. to 106.3 in.	Rock	Inclined	Poor	Limestone/Shale	Toe

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-28 ft 7 in. to 3 ft 5 in	0 in. to 51.2 in.	False	Clay, Silt, Sand	Trace (0-10%)	Trace (0-10%)	None
-28 ft 7 in. to 3 ft 5 in	51.2 in. to 106.3 in.	False	Rock	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-28 ft 7 in. to 3 ft 5 in	7.9 to = 51.2 in.	11.8 to = 51.2 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-28 ft 7 in. to 3 ft 5 in	Yes	= 104.3 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-28 ft 7 in. to 3 ft 5 in	Difficult/Backhoe/Blast	Moderate (3ft 3in. - 9ft 10in.)	None
-28 ft 7 in. to 3 ft 5 in	Difficult/Backhoe/Blast	Moderate (3ft 3in. - 9ft 10in.)	Bedrock

Table A-62. Site 1 Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-0 ft 7 in. to 10 ft 0 in	0 in. to 78.7 in.	Till	Inclined	Well	Sand	Middle
-0 ft 7 in. to 10 ft 0 in	78.7 in. to 88.6 in.	Rock	Inclined	Well	Rock	Middle

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-0 ft 7 in. to 10 ft 0 in	0 in. to 78.7 in.	False	Silt, Very Fine Sand, Rock, Sand	Trace (0-10%)	Partial (10-50%)	Partial (10-50%)
-0 ft 7 in. to 10 ft 0 in	78.7 in. to 88.6 in.	False	Rock	None	None	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-0 ft 7 in. to 10 ft 0 in	No	> 88.6 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-0 ft 7 in. to 10 ft 0 in	Moderate/Backhoe	Moderate (3ft 3in. - 9ft 10in.)	None
-0 ft 7 in. to 10 ft 0 in	Moderate/Backhoe	Moderate (3ft 3in. - 9ft 10in.)	Bedrock

Table A-63. Site CD-28/CD-29 Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-23 ft 7 in. to 59 ft 9 in	0 in. to 106.3 in.	Till	Inclined	Very Poor	Clay	Upper

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-23 ft 7 in. to 59 ft 9 in	0 in. to 106.3 in.	False	Clay, Silt, Sand	Trace (0-10%)	Trace (0-10%)	None

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-23 ft 7 in. to 59 ft 9 in	15.7 to > 106.3 in.	23.6 to > 106.3 in.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-23 ft 7 in. to 59 ft 9 in	No	> 106.3 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-23 ft 7 in. to 59 ft 9 in	Easy/Trencher	Deep (> 9ft 10in)	None

Table A-64. Dig 2 (Dent) Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-1 ft 4 in. to 4 ft 11 in	0 in. to 143.7 in.	Till	Inclined	Well	Sand	Upper

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-1 ft 4 in. to 4 ft 11 in	0 in. to 143.7 in.	False	Silt, Rock, Sand	Partial (10-50%)	Partial (10-50%)	Numerous (>50%)

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth

No Mottling or Gleying was found at this site.

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-1 ft 4 in. to 4 ft 11 in	No	> 143.7 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-1 ft 4 in. to 4 ft 11 in	Difficult/Backhoe/Blast	Shallow (0ft - 3ft 3 in.	Bedrock

Table A-65. Dig 3 (Dent) Soils Data Summary from Operator F

Soils Assessment

From - To	Depth	Soil Type	Topography	Drainage	Dominant	Site Position
-7 ft 2 in. to 3 ft 3 in	0 in. to 216.5 in.	Till	Inclined	Well	Sand	Upper

Soil Details

From - To	Depth	Side Slope	Soil Textures	Gravel Percentage	Cobble Percentage	Boulder Percentage
-7 ft 2 in. to 3 ft 3 in	0 in. to 216.5 in.	True	Silt, Rock, Sand	Trace (0-10%)	Partial (10-50%)	Numerous (>50%)

Mottling and Gleying

From - To	Mottling Depth	Gleying Depth
-7 ft 2 in. to 3 ft 3 in	199.2 to > 216.5 in.	None

Organics and Carbonates

From - To	Organics Depth	Carbonates Depth

No Carbonates or Organics were found at this site.

Water Table

From - To	Ground Water	Depth To Water Table
-7 ft 2 in. to 3 ft 3 in	No	> 216.5 in.

Diggability

From - To	Diggability	Depth to Bedrock	Obstructions
-7 ft 2 in. to 3 ft 3 in	Difficult/Backhoe/Blast	Shallow (0ft - 3ft 3 in.	Bedrock