CAAP Annual Report

Date of Report: *10/09/2024*

Prepared for: *U.S. DOT Pipeline and Hazardous Materials Safety Administration*

Annual Period: **From** *(09, 29, 2023)* **to** *(09, 29, 2024)*

Contract Number: *693JK32350002CAAP*

Project Title: *A Novel Reliability-Based Approach for Assessing Pipeline Cathodic Protection (CP) Systems in External Corrosion Management*

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Section A: Business and Activities

(a) Contract Activities

- Contract Modifications: NA
- Educational Activities:
  - Student mentoring:

    Emad Farahani, a Ph.D. student in Civil, Construction and Environmental Engineering at Marquette University has been working on the project since the project was launched.

    Yuhan Su, a Ph.D. student in Chemical Engineering at The University of Akron is working on the project starting the 3rd quarter of this project.

    Abby Murray, an undergraduate student in Corrosion Engineering at The University of Akron is working on the project starting the 3rd quarter of this project.

  - Student internship: NA
  - Educational activities:

    The PI (Dr. Huang) discussed about risk evaluation of pipeline system in the graduate course, *Engineering Risk Analysis*, at Marquette University

  - Career employed: NA
  - Others: NA
- Dissemination of Project Outcomes: NA
- Citations of The Publications: NA
- Others: NA

(b) Financial Summary

- Federal Cost Activities:
  - PI/Co-PIs/students involvement:

    One graduate student from Marquette University was partially charged from this project for the salary during this reporting period.

  - Materials purchased/travel/contractual (consultants/subcontractors):

    Software subscription has been purchased.

    InferModel as the hired consultant has helped on Task 2 (Data collection and analysis)

- Cost Share Activities:
    - Cost share contribution: The cost share of Dr. Huang's academic salary from Marquette University has been charged as planned.

(c) Project Schedule Update

- Project Schedule:
  Table A shows the original proposed schedule.

Table A. Original schedule and milestones of proposed tasks

Tasks	Year 1				Year 2				Year 3			
Task 1. Literature Review												
Task 2. Data collection and analysis												
Task 3. Stray current corrosion												
Task 4. Probabilistic defect growth modeling												
Task 5. Time-dependent reliability												
Task 6. CP performance and management												
Final Report												

- Corrective Actions:
  Table B shows the updated research tasks. Task 1 took more time than originally planned, which was necessary to make sure the research team thoroughly understands the mechanics of cathodic protection systems, the current practice on external corrosion management, and state-of-art research that related to the project. Task 2 took more than the original planned as well due to the complexity and large size of the data types and the needed various data validations.

Table B. Updated schedule and milestones of proposed tasks

Tasks	Year 1				Year 2				Year 3			
Task 1. Literature Review												
Task 2. Data collection and analysis												
Task 3. Stray current corrosion												
Task 4. Probabilistic defect growth modeling												
Task 5. Time-dependent reliability												
Task 6. CP performance and management												
Final Report												

(d) Status Update of the 4th Quarter Technical Activities

- Task 1: Literature review
  In the 4th Quarter, the literature review has focused on state-of-the-art research papers. This task has been completed.

- Task 2: Data collection and analysis (in progress)

90% of work has been completed by the end of the 4th Quarter. In the part quarter, it has focused on two aspects: foreign pipelines and powerline data collection and analysis, and cathodic protection test station, bonds and rectifier data collection and analysis. The future work on this task (that is detailed in Section 5) will be completed in next quarter.

- Task 3: Stray current corrosion (in progress)
  This task started in the 4th quarter. During the past quarter, the students conduct literature review to understand DC conditions and characterization methods on the corrosion behavior of metals in previous lab testing studies. The lab testing at UAkron will start in the next quarter.

- Task 4: Probabilistic defect growth modeling

  This task will start in the 5th quarter.

- Task 5: Time-dependent reliability analysis

  This task will start in the 7th quarter.

- Task 6: CP performance and management

  This task will start in the 7th quarter.

Section B: Detailed Technical Results in the Report Period

1. Background and Objectives in the 1st Annual Report Period

1.1. Background

The purpose of this research project is to develop a novel reliability-based approach for assessing pipeline cathodic protection systems for the prevention of external corrosion. To develop a novel approach, a thorough literature review and data engineering initiative is required.

Existing structural reliability frameworks on the corrosion response of inline inspections (ILI) detected anomalies have been reviewed. These frameworks apply effective area burst pressure estimations on corrosion clusters while explicitly accounting for material uncertainties, sizing uncertainties, model uncertainties and growth uncertainties. This leads to a burst pressure distribution that can be compared against an operating pressure distribution towards assessing pipeline reliability. These reliability assessments provide informative information around excavation decisions, re-inspection intervals, and can perhaps provide additional insights on decision making around corrosion prevention, especially around impressed current cathodic protection systems. These decisions can involve budget allocation around the replacement of anode beds, increasing rectifier currents, or performing Closed Interval Surveys (CIS) for more granular information around the effectiveness of cathodic protection systems.

1.2. Objectives in the 1st Annual Report Period

During this reporting period, there are three main objectives:

- Conduct a thorough literature review
- Collect and analyze relevant data of transmission pipelines from industry partners
- Review the past lab testing of samples under CP with DC inference

2. Task 1 Literature Review

Pipeline integrity management includes monitoring, assessing, and maintaining the physical condition of pipelines to prevent leaks and failures. It could involve advanced technologies, such as smart pigs, along with rigorous inspection protocols to ensure compliance with safety standards. Effectiveness of the risk management strategies are critical for mitigating potential environmental impacts and ensuring public safety. Coating and cathodic protection (CP) systems play crucial roles in pipeline management by preventing external corrosion, which is one of the leading failure causes of steel transmission pipelines. The CP systems work by using either impressed current or sacrificial anodes to protect the pipeline from electrochemical corrosion.

Detailed explanations on CP systems can be found in textbooks (e.g., [1], [2]) and publicly-available materials (e.g., *Appalachian Underground Corrosion Short Course (AUCSC)* [3],

[4], [5], [6]). The following lists the topics covered in each of the four AUCSC courses, which are reviewed in Task 1.

FUNDAMENTALS [6]

- Fundamental of Corrosion Mathematics and Electricity
- Pipeline Locating
- Fundamentals of Corrosion
- Introduction to Cathodic Protection
- Pipeline Electrical Isolation Methods
- Fundamental Introduction to Pipeline Coatings
- Fundamentals of Rectifier Monitoring
- Introduction to Pipe-to-Soil Potential Measurements

BASICS [5]

- Basic Electricity
- Corrosion Fundamentals
- Corrosion Control Methods
- Introduction to Pipeline Coatings
- Potential Measurements
- Current Measurements
- Resistance Measurements
- Rectifier Basics

INTERMEDIATE [4]

- Corrosion Cells in Action
- Installation of Galvanic Anodes
- Installation of Impressed Current Cathodic Protection Systems
- Criteria for Cathodic Protection
- Corrosion Control for Pipelines
- Static Stray Current Interference Testing
- Troubleshooting Cathodic Protection Systems
- Rectifier Maintenance

ADVANCED [3]

- Pipe-to-Soil Potential Surveys and Analysis
- AC Interference Mechanisms and Mitigation Strategies
- Materials for Cathodic Protection
- Evaluation of Underground Coatings Using Aboveground Techniques
- Dynamic Stray Current Analysis
- Design of Impressed Current Cathodic Protection Systems

- Design of Galvanic Cathodic Protection Systems
- MIC Inspection and Testing

As the purpose of this project is to investigate the effectiveness of CP on pipeline integrity, relevant research studies are reviewed as well, which are summarized in the following.

2.1. Integrated External Corrosion Management (IECM)

External corrosion in pipeline integrity management is a major concern for the safety and reliability of transmission pipelines used for transporting fluids, including oil and gas. Some pipeline operators have been working on developing programs that employ cutting-edge inspection and simulation techniques to prescribe interventions for mitigating external corrosion. For example, Enbridge developed a program, called Integrated External Corrosion Management (IECM), which tackles complex challenges by gathering, analyzing, and integrating environmental, pipeline integrity, and corrosion control data through a predictive and integrated approach. Using robust engineering models (including mechanistic, reliability, and risk), it aims to predict and prevent external corrosion risks [7]. Parker et al. [7] described the foundation of IECM program which includes four phases: Risk Assessment (Predict) Phase, IECM Response (Measure) Phase, Validation (Study / Correct) Phase, and Continuous Improvement Phase.

The IECM process has been previously summarized in several publications (e.g., [8], [9], [10], [11]). Recently, Parker et al. [12] reviewed the findings of a collection of case studies performed by the IECM program since 2021 and discussed some improvements to the IECM. For example, the model validation requirements were revised and appropriate model applications were defined based on model accuracy. As another improvement, IECM assessment period is defined as the period from the most recent ILI to the current year, which removes subjectivity selection of historical field data to compare with models [12].

2.2. Pipeline Integrity Analysis Approaches

In the literature, pipeline integrity evaluation and the analysis of pipeline CP effectiveness have been conducted using statistical and machine learning analysis and mechanistic modelling.

Statistical and machine learning analysis

Techniques like regression analysis, probabilistic analysis have been used to help identifying trends in historical corrosion data, quantifying the relationship between influencing variables (e.g., soil type, coating condition) and their impact on corrosion behavior (e.g., [13], [14]). Review of different methodologies to model corrosion growth path and corrosion growth rate using statistical and machine learning techniques is provided in [14], [15], [16]. In addition, machine learning algorithms have been adopted to train on historical data to predict corrosion rates and failure probabilities. For example, Hayden et al. [17] highlighted machine learning's role in the IECM framework, and Xiang et al. [18] employed supervised machine learning to predict corrosion features quantities and the likelihood of failure.

Mechanistic modelling (digital twin)

CP surveys are usually conducted at rectifiers and test stations (points), with occasional close-interval surveys between the rectifier/test stations. Pipeline CP surveys offer only an indirect measure of the corrosion risk and are either labor intensive or do not provide sufficient granularity to identify corrosion features in a timely manner [19].

A digital twin of a pipeline can involve building a computer model of the pipeline network and calibrating the model based on the available In-Line Inspection (ILI) and CP survey data. The concept of digital twins does not necessarily require 3D modeling or Finite Element Modeling (FEM). It can exist in various formats and resolutions, from detailed 3D modeling to lower resolution 2D pipeline schematics. This is particularly relevant when the assets under study cover large geographic areas, and extensive 3D modeling may be cost prohibitive [17].

A mechanistic model developed by Elsyca ([19], [20]) allows the user to compute quantities of interest including the CP potentials, current densities, and corrosion rates with a granularity at the joint level, and can also consider the impact of high voltage AC powerline systems and DC transit systems where applicable. More details on employing the concept of digital twin and mechanistic modelling and the corresponding results can be found in [19], [20], [21], [22], [23]. However, it is not clear how the uncertainty in the data sources that were utilized for the model development (e.g., CP measurements and soil survey data) propagates into their mechanistic model.

2.3. Alternating and Direct Current Effect on Pipelines Corrosion

More often, pipelines right-of-ways (ROWs) are shared with overhead high-voltage power lines, traction systems, and other pipeline systems due to limited land availability. This shared use of ROWs raises concerns about AC and DC current interference from adjacent structures and parallel pipelines in these utility corridors [20].

NACE International has also standardized the effect of AC on cathodically protected pipelines and metallic structures [24], [25]. Recently, Farahani et al. [26] reviewed the state-of-the-art on AC corrosion of cathodically protected pipeline steel, which covered influencing factors in AC corrosion for pipelines under CP, existing AC protection criteria, corrosion risk assessment based on probability of failure, numerical simulation in AC corrosion, and mitigation of AC corrosion. Baete and Dolgikh [27] utilized mechanistic modelling to prioritize pipelines based on AC threat; they estimated the level of the AC threat and determined critical regions of 66,000 miles of pipelines depending on the operational mode of AC threat.

DC interference, on the other hand, can take place from foreign pipeline CP systems. Not only are there different pipeline operators sharing ROWs, but there are crossings of systems that can impact the levels and adequacy of CP. Other sources of DC interference are DC transit systems and telluric current influence [4], [5]. These interferences vary depending upon the system and where it is located. DC transit systems in the US tend to be localized to major cities on each of the coasts but there are a few in Chicago, Salt Lake City, and other places.

In summary, the key influencing factors of AC interference that contribute to CP effectiveness are AC current density, CP current density, CP potential, metal type, and soil conditions. The key influencing factors of DC interferences currently identified are: CP levels, DC interference duration time, and soil conditions.

2.4. CP Test Station Location

When it comes to CP survey, test station measurements provide valuable data that can be used for CP system effectiveness monitoring, regulatory compliance, and data collection, aiding decision-making regarding CP systems. Therefore, determination of the number of test station and their locations is crucial important in CP management.

In the United States, the Pipeline and Hazardous Materials Safety Administration (PHMSA) gas and hazardous liquid pipelines regulations are included in Section 49 of the Code of Federal Regulations (CFR), specifically in 49 CFR Part 192 [28] titled *the transportation of natural gas through pipelines*, and 49 CFR Part 195 [29] titled *the transportation of hazardous liquids through pipelines*.

Sections 192.469 [28] and 195.567(b)(1) [29] have the requirements for the location of test leads which are provided as following, respectively:

> Section 192.469: "*Each pipeline under cathodic protection required by this subpart must have sufficient test stations or other contact points for electrical measurement to determine the adequacy of cathodic protection.*"
>
> Section 195.567(b)(1): "*Locate the leads at intervals frequent enough to obtain electrical measurements indicating the adequacy of cathodic protection.*"

However, there is no specific requirement on the test stations distance and placement. Historically, many operators have placed test stations at typically a 1-to-3-mile interval to demonstrate compliance with the associated regulations [30], [31]. Recently, Hayden et al. [30] performed a statistical analysis using annual test station data and close-interval potential survey to understand how informative and meaningful test station data are and attempted to develop a metric to determine the informativeness of a current configuration of test points. In addition, Stevensen et al. [31] developed a methodology to identify which Test Points (TPs) are essential to identifying unchanged satisfactory performance of the CP system and which TPs could be considered supplemental without compromising integrity or increasing risk from corrosion; they concluded that the effective assessment of annual CP system performance can be achieved without the need to necessarily gather data from every TP each year [31].

2.5. Instant-OFF Potential Measurement Error

Section 6.2.1. of NACE SP0169 [32] provides three general criteria for CP for steel and gray or ductile cast-iron piping as below:

- "Criteria that have been documented through empirical evidence"
- "A minimum of 100 mV of cathodic polarization. Either the formation or the decay of polarization must be measured to satisfy this criterion."
- "A structure-to-electrolyte potential of –850 mV or more negative as measured with

respect to a saturated copper/copper sulfate (CSE) reference electrode."

As mentioned, the instant-OFF potential (i.e. the polarized potential) of pipelines to soil is a key quantity in determining the compliance of a pipeline. However, research has shown that these measurements are difficult to be accurately measured and might have inherent error [33], [34], [35]. Especially, Wakelin and Fieltsch [33] discussed how the polarization of certain soils might result in off-potential measurements that are more electronegative than the true polarized potentials of a cathodically protected pipeline. In addition, Fingas et al. [34] introduced two significant sources of potential error, namely metallic IR-drops and equalization currents, which both test station surveys and close-interval potential surveys might be subjected to and provided guidance on identifying these issues. Dimond and Ansuini [35] investigated common sources of error in potential measurements which include measurement circuit IR drop, external IR drop, and problems with the reference electrode, and provided recommendations to reduce these errors.

3. Task 2 Data Collection and Analysis

3.1. Inline Inspection Data Collection

An ILI database containing information from 14 different Axial Magnetic Flux Leakage (MFL-A) ILI runs has been built for this project. This contains information from five different pipeline segments making up 1,263 miles of pipeline in the U.S. across two to four separate tool runs. These inspections are shown in Table 1 with anonymized names for public viewing. Older inspections provided clusters, while newer inspections further included callbox child anomalies that provide a more thorough understanding on the extent of corrosion and more accuracy around burst pressure estimations.

Table 1: Summary of Inline Inspections Collected in the Study

Pipe Number	Segment	Run Date	ILI ID	Child Features
1	A	2019-08-07	1	1
1	A	2014-08-20	2	0
2	B	2022-12-05	3	1
2	B	2018-07-22	4	1
2	B	2013-02-24	5	0
2	B	2008-03-01	6	0
2	C	2022-12-13	7	1
2	C	2020-01-19	8	1
2	C	2015-10-19	9	1
2	C	2010-10-06	10	0
3	D	2020-07-13	11	1
3	D	2015-08-30	12	1
3	E	2020-07-31	13	1
3	E	2015-09-10	14	1

Approximately 1.14 million external corrosion metal loss measurements from the ILIs have been compiled into a single database table structure for this study. Corrosion clusters, callbox child features making up a cluster, and single metal loss anomalies have been correctly classified. Unique external corrosion anomaly IDs have also been created across the 14 inspections to easily identify each individual corrosion feature at a given moment in time. In

ILIs with callbox child features, the vendor corrosion clustering algorithm has been re-performed internally as part of this project to map callbox anomalies to clusters for the purpose of accurately assessing the reliability of cluster anomalies with the effective area method.

A comprehensive review of each vendor report for each ILI was performed to better understand the data provided from vendors from a probabilistic lens. The ILI tool sizing tolerances for each anomaly are crucial towards assessing the reliability of corrosion anomalies as it quantifies the uncertainty around depth and length. Similarly, the ILI probability of detection of each anomaly is to estimate the extent of undetected anomalies.

The ILI data used in this study was linked to unique girth weld identifiers that are constant across different inspections. All geospatial linking with external datasets was performed on the most recent inspection of each pipeline segment. This information was then mapped to prior inspections using the upstream girth weld number and distance from the girth weld for each separate pipeline segment.

Additional necessary pipeline attributes unavailable in the ILI data were obtained and mapped to pipeline joints. This includes coating type, installation date, seam weld type, manufacturer, and depth of cover, and nominal pipeline measurements. Whenever continuous data was unavailable, a gap and island algorithm has been applied. This approach spatially correlates the nearest upstream and downstream pipeline joints to approximate the pipeline attributes between known values.

3.2. Inline Inspection Data Analysis

ILI validation has been performed for this project to assess the quality of corrosion sizing data. The method used for this validation was the *Agresti-Coull* method described in API 1163 Level 2 assessments. This validation approach was performed on ILIs with 10 or more validation field sizing available, which most commonly included the most recent inspections. **Figure 1** provides ILI sizing validation on wall loss in decimal format using 13 field verifications: 77% of measurements were within the specified sizing errors provided by ILI vendors with 80% confidence. When accounting for sizing uncertainty on the proportion of measurements within specified sizing errors, the true portion of anomalies within specifications is between 64% and 90% with 80% confidence. This means that the statistical hypothesis test does not reject the claimed ILI sizing errors.

The specified sizing tolerance bounds at 80% confidence in **Figure 1** are a simplification that is for using tool errors for extended corrosion at the pipe body. Feature specific ILI sizing error based on morphology and pipeline material have been incorporated for this assessment. Furthermore, NDE sizing error of +/- 0.50 mm at 80% confidence for pit gauge measurements, +/- 0.31 mm at 80% confidence for Ultrasonic probes, and +/- 0% for laser scan measurements were also accounted for in the assessment. In addition, Table 2 provides a summary on the API 1163 Level 2 Assessment. Severe outliers were characterized by ILI to field sizing differences above three standard deviations in sizing errors.

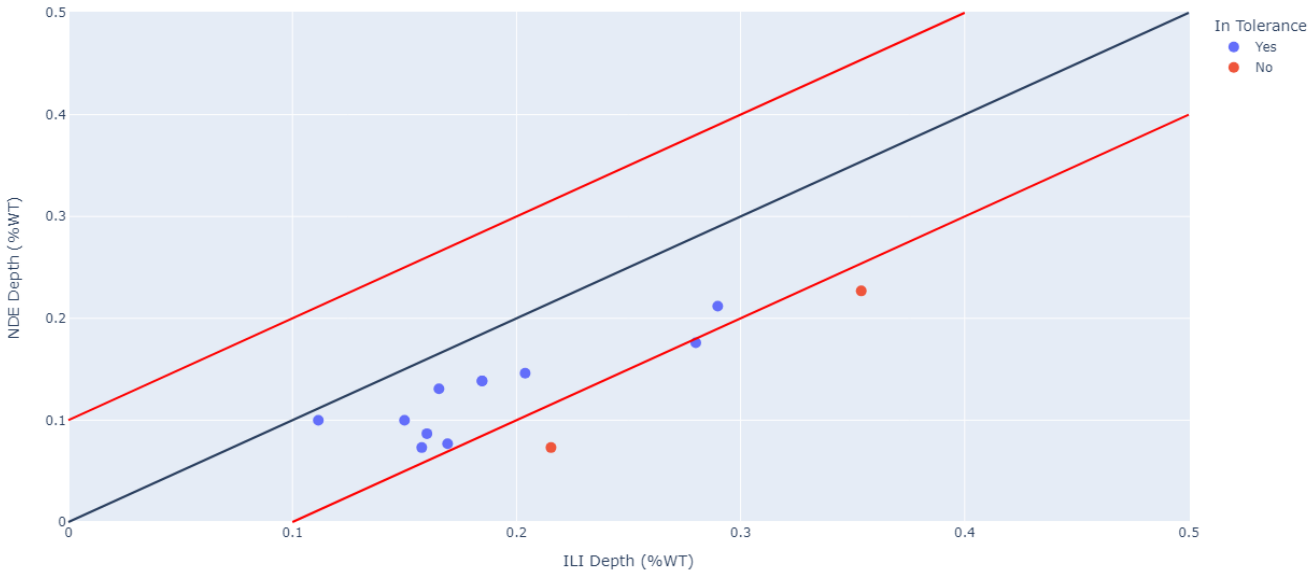

Figure 1: Validation of ILI 1

Table 2: Summary of API 1163 Level 2 Assessments

ILI ID	# of Field Validations	# of Severe Outliers	Mean Proportion in Tolerance	Upper Proportion at 80% Confidence	Passes API 1163 Level 2 Assessment?
1	13	0	77%	90%	Yes
3	52	4	75%	85%	Yes
7	32	0	94%	96%	Yes
8	25	0	96%	97%	Yes
13	21	0	62%	73%	No*

* While ILI 13 did not pass the API 1163 Level 2 Assessment using the 20% significance level commonly used in the pipeline industry, it does pass the assessment when using the 5% significance level commonly used in most other industries.

3.3. Repair Data Collection and Analysis

The identification of external corrosion repairs is a crucial aspect of pipeline integrity and is often overlooked. To this day, a significant portion corrosion management resources are spent on excavating previously repaired anomalies due to poor repair management systems. The most trustworthy source of repairs is from *ILI detected repairs*. Whenever pipeline sleeves are placed onto pipelines to mitigate external corrosion, they often include magnetic indications that ILIs are capable of detecting. The second most reliable source of repairs was *ILI Response Assessment Sheet* obtained for each ILI when available from subject matter experts most familiar with the pipeline used in this study. These sheets have a repair flag for each anomaly that was used for dig decision making. The third source of repair information was the *ILI/NDE Field Trending Automation* available from an industry partner to match ILI data to field information. The final source of repair information was the excavation span and pipeline joints repaired made available by an industry partner.

For this study, pipeline joints and corrosion anomalies were only identified as repaired if the repair excavation occurred before the ILI run date. The repair method such as recoat, clock spring, pipe sleeve, excavation date, and field sizing information has been linked to each external corrosion anomaly when applicable. Approximately 14,224 different external corrosion anomalies have been identified as repaired as part of this study.

3.4. Operating Pressure Data Collection and Analysis

An extreme value analysis (EVA) has been conducted to model the maximum operating pressure (MOP) of the liquid pipelines downstream of different compressor stations as a distribution, and to estimate their respective annual likelihood of an overpressure event. This is an important aspect in assessing the reliability of liquid pipelines as pressure fluctuations are much more common and less controlled in comparison to natural gas pipelines. This was performed using daily historical MOP information at compressor stations between the beginning of 2021 to the end of 2023.

Shut off periods were filtered from the daily MOP dataset, and the data was aggregated into maximum pressure per month. These historical maximum monthly pressures were used to build a MOP distribution. This distribution was then fit to five commonly used distributions (Log Normal, Weibull, Exponential, Gamma, and Rayleigh) where the Akaike Information Criteria was used to assess the goodness of fit, and to select the best distribution for daily MOP.

The EVA analysis provides an annual MOP distribution that is based on a Gumbel distribution. The best fit distribution parameters of the daily MOP distribution, and annual occurrence rate were then used to estimate the characteristic extreme and dispersion factor of Gumbel distribution using analytical equations derived in *Guideline for Reliability Based Design and Assessment of Onshore Natural Gas Pipelines.* These annual maximum pressure distributions have been compared against maximum allowable operating pressure to assess the annual likelihood of overpressure event. **Figure 2** provides an example of this for *Pipe 1* where there is an annual chance of 1.3% of overpressure relative to the maximum allowable operating pressure of 1790 psi. This assessment has been performed at all stations on the pipelines of interest.

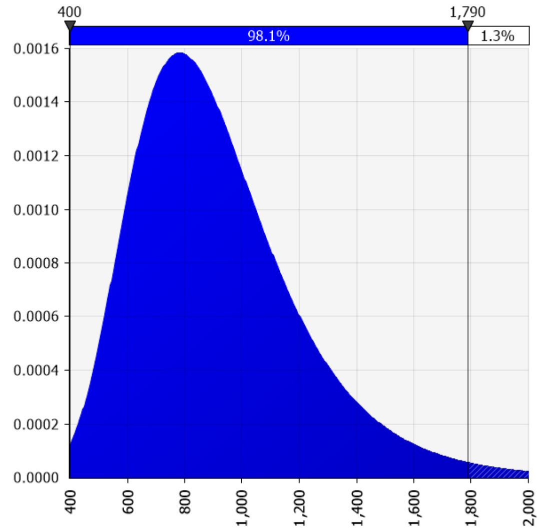

Figure 2: Annual Likelihood of an Overpressure Event for Pipe 1

3.5. Growth Rate Data Collection and Analysis

Box-to-Box (B2B) matched growth rates were estimated across different inspections of the 5 pipeline segments of interest in this study. Signal to Signal (S2S), also called RunCom, growth rates were also collected. A comprehensive review was conducted comparing the quality of B2B growth rates to S2S growth rates whenever an external corrosion anomaly had both attributes. Due to poor correlations, even when isolating corrosion anomalies to single metal loss situations less prone to anomaly mismatches, it was decided to emit the B2B growth rates from this study. The root issue of the B2B growth mismatch has been identified during this study, and this has been communicated to the industry partner that has provided the pipeline ILI data. The tool error uncertainty on S2S growth rates have been estimated using error propagation techniques. A statistical hypothesis test has been applied to identify external corrosion anomalies with statistically significant S2S growth rates.

3.6. Soil Data Collection and Analysis

The publicly available soil database *SSURGO* has been used to enrich the ILI database with environmental information that can influence corrosion susceptibility and the reliability of cathodic protection systems. Among approximately 865 available variables, 75 were explored for use in this study. This included information on soil type (% sand, % silt, % clay), pH, soil conductivity, annual rainfall, drainage, soil temperature, the concentration of gypsum, carbonate, and salt and the seasonal water table level.

Figure 3 provides a visualization of pH for Pipe 1 using the representative soil component for each pipeline joint. It demonstrates that soil surrounding the pipeline joint is of a near neutral pH. **Figure 4** provides another example of soil property correlated to the pipe joints of Pipe 1 – in this instance soil electrical conductivity in decisiemens per meter. The logarithm with base 10 is used to estimate the order of magnitude of soil resistivity. **Figure 5** provides soil resistivity distributions color coded for the different pipelines used in this study.

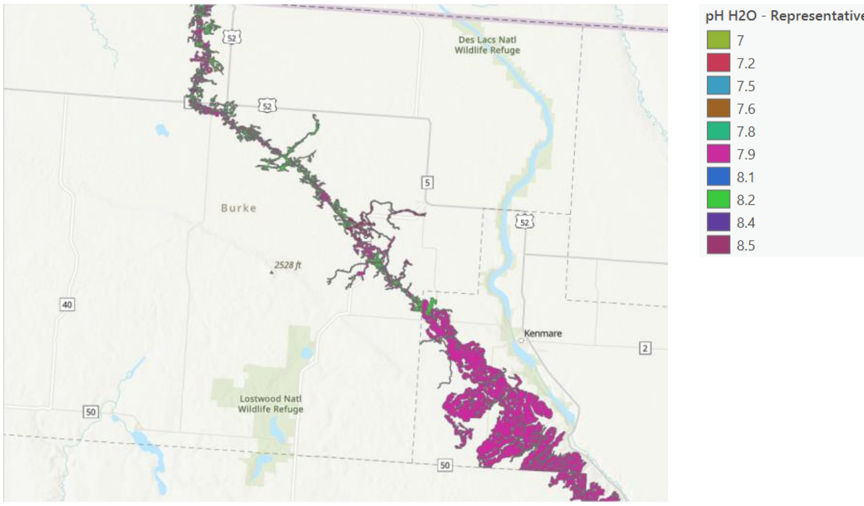

Figure 3: The variation of pH on Pipe1

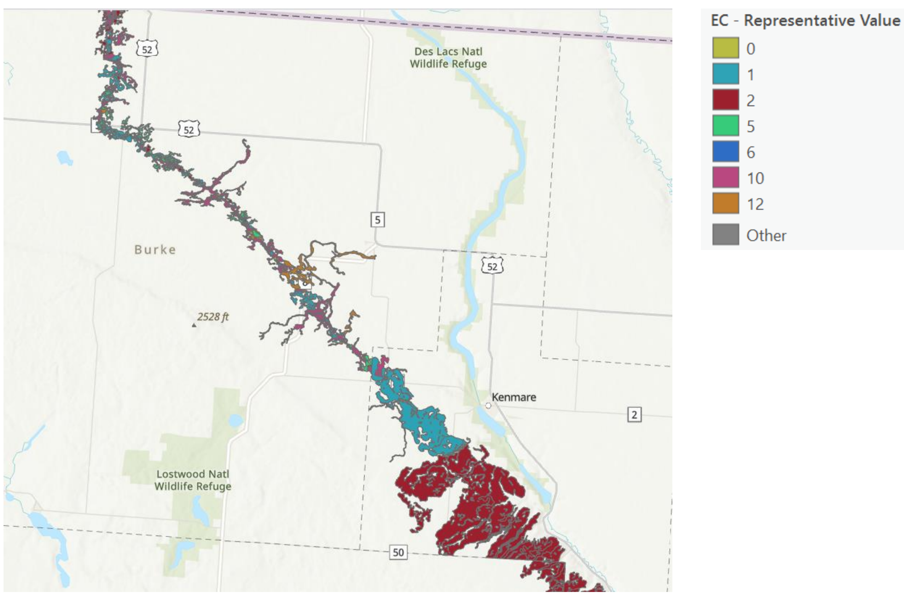

Figure 4: The variation of Soil Electrical Conductivity (dS/m) on Pipe1

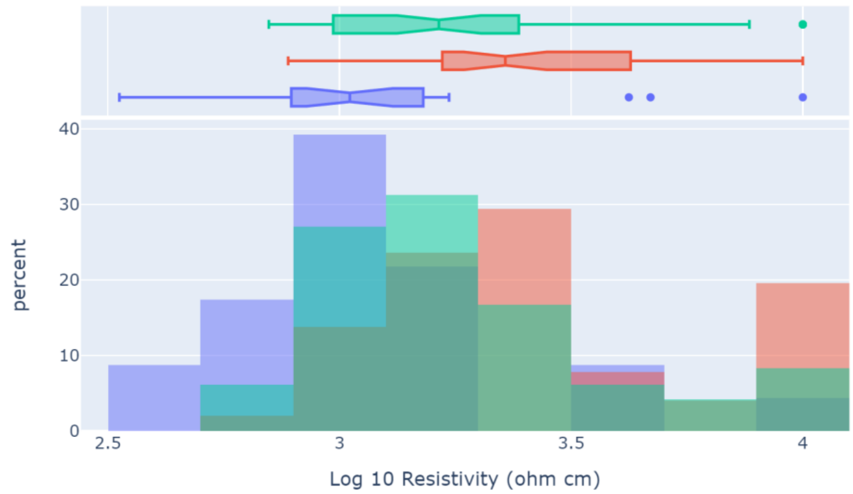

Figure 5: The Variation of Soil Resistivity Among Different Pipelines

In addition, all available field measurements from an industry partner have been collected and compiled into a database table. The electrical resistivities collected near pipeline joints during excavations were correlated to SSURGO electrical resistivities to assess the quality of the data. As shown in **Figure 6**, the SSURGO dataset does not correlate well with field measurements, and that the SSURGO estimates have a model error standard deviation of about half an order of magnitude in comparison to the field measurements.

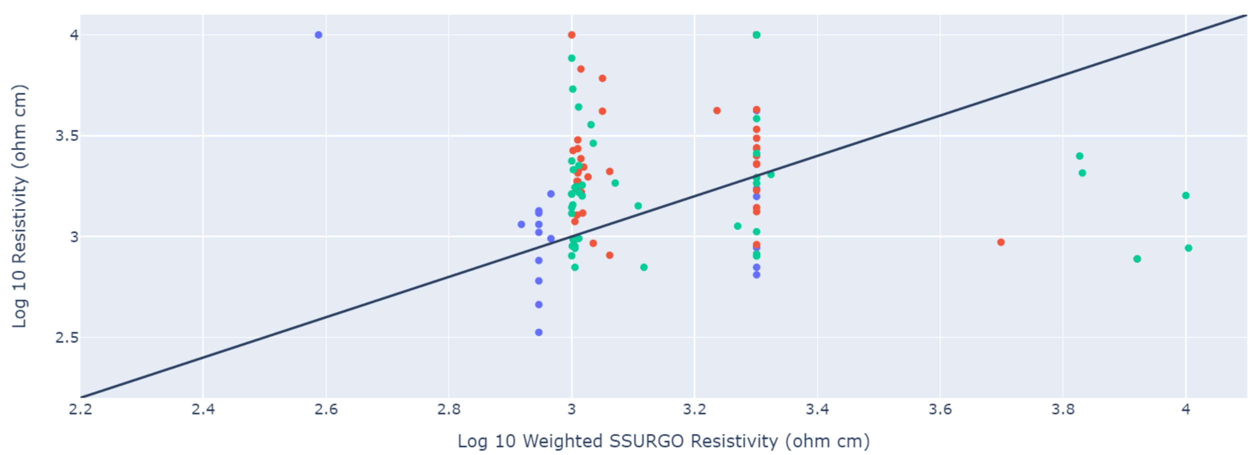

Figure 6: Field Validation of SSURGO Electrical Conductivity (green: Line 1, red: Line 2, and green: Line 3)

3.7. Foreign Pipelines and Powerlines Data Collection and Analysis

The geo-locations of foreign pipelines have been collected from an industry partner. Similarly, powerline geo-location and maximum voltage information has been collected from the Homeland Infrastructure Foundation and OpenStreetMap file geodatabases.

For each pipeline joint, its distance to a foreign pipeline or powerline was calculated in situation where the pipe is less than 300 meters from the foreign object. Understanding whether pipeline joints were parallel or perpendicular to the foreign object, and the angular distance between them for stray current modelling was also estimated. A haversine approximation on the shape of the Earth was applied for these calculations. The bearing of each pipeline joint and of the foreign object can be approximated relative to the north pole using equation below where the starting point of the pipeline joint or foreign object are represented with the coordinates $(latitude_1, longitude_1)$ and end points are represented with $(latitude_2, longitude_2)$

$$\theta = arctan2(\sin(\Delta longitude) * \cos(latitude_2), \cos(latitude_1) * \sin(latitude_2) - \sin(latitude_1) * \cos(latitude_2) * cos(\Delta longitude))$$

The difference between the bearing of the pipeline joint and foreign object was then used to approximate the angular distance between them. When the angular distance was between 0 to 20 degrees or 160 to 180 degrees, the geometry was classified as parallel, while when the angular distance was between 70 to 110 degrees, the geometry was classified as perpendicular.

3.8. Cathodic Protection Test Station, Bonds and Rectifiers Data Collection and Analysis

Cathodic Protection information provided by the industry partner on historical test station measurements, bond measurement and rectifier measurements has been geo-correlated to the nearest pipeline joints. A 200-meter spatial buffer was used to for test station measurements and bond measurements, while a 500-meter spatial buffer was applied for rectifier information since rectifiers can be far from pipelines in some instances. Approximately 19,000 On and Off Potentials from test station measurements, 4,372 bond measurements, and 35,060 rectifier measurements have been correlated to pipeline joints with a temporal time stamp for use in this study.

At test stations, annual on and off potentials on the pipeline are consistently available. Additionally complementary information on AC and DC current density is available in some instances. For bonds, the bond current and shunt rating is readily available. At rectifiers, voltage and current information are readily available. Substantially more cathodic protection information has been collected and correlated to pipeline joints; however, data gaps and more review is needed to properly use the additional supplementary information in a reliability model.

4. Task 3 Corrosion Behavior Under Stray Current Interference

4.1. Background and Objectives in the 1st Annual Report Period

The influence of AC interference is complex under different CP conditions and surrounding environments. The research team has obtained a good understanding of the key influencing factors in AC corrosion that contribute to CP effectiveness: AC current density, CP current density, and CP potential for a given metal in a soil environment, through a recently completed

PHMSA CAAP project. In the meanwhile, it is known that DC interference cannot be ignored for pipelines under cathodic protection, especially for non-stationary dynamic DC interference. The objective of Task 3 in this reporting period is to understand DC conditions and characterization methods on the corrosion behavior of metals in previous studies.

4.2. Research Progress in the 1st Annual Report Period

As shown in Table , most metals examined in the corrosion study under DC interference are API X series steels, although some studies used Q235 steels or other low-carbon steel. These are commonly used steels in pipelines.

Table 3: Metals used in corrosion study under DC interference.

Metal	Reference
Q235 steel pipe	[36]
	[37]
	[38]
API X52 steel pipe	[39]
	[40]
	[41]
	[42]
UNS G10180 ~API 5L X52	[43]
	[44]
	[45]
API X65 steel pipe	[46]
API X70 steel pipe	[47]
	[48]
	[49]
API X80 steel pipe	[50]
Low-carbon steel; 10 wt.% Cr steel	[51]

The testing environment, as the simulated soil solution, is summarized in Table for the corrosion studies under DC interference. The solution used varied a lot with different compositions that could demonstrate the properties of soils at different locations.

Table 4: Solution used in corrosion study under DC interference.

Solution	**Reference**
NaCl	[38]
$NaHCO_3$, NaCl, $NaNO_3$, Na_2SO_4, K_2SO_4, $CaSO_4 \cdot 2H_2O$, $MgSO_4 \cdot 7H_2O$, NaOH	[39]
$NaHCO_3$, NaCl, $NaNO_3$, Na_2SO_4, K_2SO_4, $CaSO_4 \cdot 2H_2O$, $MgSO_4 \cdot 7H_2O$	[40]
NaCl, $CaSO_4 \cdot 2H_2O$	[43]
Na_2SO_4, NaCl	[44]
$NaHCO_3$	[41]
NaCl, $CaCl_2$, $MgCl_2 \cdot 6H_2O$, Na_2SO_4, $NaHCO_3$, KNO_3	[47]
	[48]
NaCl, Ca $(OH)_2$	[51]
NaCl, Na_2SO_4, $NaHCO_3$	[36]
NaCl	[50]
$NaHCO_3$, NaCl, Na_2SO_4	[19]

Cl^-, SO_4^{2-}, HCO^{3-}	[46]
NaCl, $CaCl_2$, Na_2SO_4, $MgSO_4 \cdot 7H_2O$, KNO_3, $NaHCO_3$	[42]
NaCl, Na_2SO_4	[45]
KCl, $NaHCO_3$, $CaCl_2$, $MgSO_4 \cdot 7H_2O$	[37]

As learned from published works on the corrosion study of metals under DC interference, a common way to introduce DC is by applying an anodic current (0-200 A/m^2) through a working station. Some work introduced DC by applying a voltage through a DC power supply. Only a few works coupled cathodic protection with DC interference. These works selected the CP potential at or above the conventional CP standard when the metal was in the DC interference. The DC interference was studied with a duration from 1 minute to 1 day. The DC interference conditions, CP levels, and DC interference duration time are summarized in Table .

A set of testing methods was adopted to systematically study the corrosion behavior of metals under DC interference, as shown in **Table** . Most published works used potential monitoring, current monitoring, EIS tests, SEM tests, weight loss tests, pH tests, and Tafel tests. Some papers used another experimental technique, including the cathodic disbondment (CD) test, cyclic voltammetry (CV) test, FTIR, etc.

Table 5: DC interference, CP levels, and DC interference period in previous corrosion studies.

DC interference current (anodic interference) A/m^2	CP level/ V vs. CSE	DC interference period	Reference
2, 4, 8, 16 V (voltage)	-	-	[38]
0, 2, 5, 10 and 20 V (voltage)	-	-	[39]
0.1, 0.5, 1, 2, 5, 10	-0.85 / -1.00	-	[40]
0.1-1; -0.7~-0.1V vs. CSE	-1.1 (200 mA/m^2)	1hr/1d; 1min duration	[43]
0.1, 1.0, 10	-0.95 ~ -1.25	1hr/1d;1, 2, 5, 60 min duration	[44]
0.5, 1, 2, 3, 4, 5	-	Waveform: sinusoidal, triangular, and square forms	[41]
±100	-	5, 10, 30, 60, 80, 160, 900 s, 30 min, 1, and 2 hrs.	[47]
±100	-	10, 30, 60, 80, 100, 160, 300, 900 s, 30 min, 1, 2, 4, 8, and 16 hrs.	[48]
20	-	-	[51]
0.05 A, 0.1 A, and 0.2 A	-	-	[36]
0, 20, 40, 60, 80, 100	-	-	[50]
30	-	-	[49]
0, 10, 30, 40, 70, 100, 120, 150, 200	-	-	[46]
0.5 V			[32]

0.1, 1.0, and 10	-0.85 V / -1.12 V CSE	1min-1h	[45]
0, 10, 20, and 30	-	-	[37]

Table 6: Characterization methods used in corrosion study under DC interference.

Reference	Potential monitor	EIS	SEM	Weight loss test	pH	Tafel	Current monitor	Others
[38]		X	X					CD test
[39]		X	X					Water permeability test, FTIR
[40]	X			X	X		X	
[43]	X			X			X	
[44]				X	X			
[41]	X	X	X	X				
[47]	X	X		X	X			CV test
[48]	X	X	X	X	X			CV test; XRD
[51]		X	3D SEM					AFM, XPS,
[36]		X	X			X		EDS
[50]	X					X		CD test; 3D microscope,
[49]			X	X				Pit depth, pit measurement
[46]			X			X		
[42]		X	X	X			X	EDS; 3D image
[45]	X			X				
[37]		X		X		X		

4.3. Conclusions

The DC conditions and characterization methods on the corrosion behavior of metals have been understood through the study of previously published works. The metals, simulated soil solutions, DC and CP testing conditions, and evaluation methods have been summarized.

5. Future work

For Task 2, further information will be collected, which includes: mapping all existing and available closed interval survey information to pipeline joints and correlating these measurements to corrosion growth, correlating field measurements to environmental data on SSURGO, comparing different existing cathodic protection model predictions to test station and CIS measurements, as well as comparing different types of cathodic protection field measurements to each other, and investigating the data for issues, packaging it in a format ideal for model development, and performing data assumptions to complete the dataset. This can be an iterative process and will lead to a user-friendly dataset that can be used for the success of the project.

For Task 3, an experimental design and testing protocols for investigating metal corrosion under DC interference with cathodic protection will be undertaken. The metal, testing solution, and testing conditions for DC and CP will be identified and investigated.

For Task 4, the corrosion behavior will be modeled using the ILI and all possible influencing variables.

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