CAAP Quarterly Report
December 30th, 2025

Project Name: Development of a Framework for Assessing Cathodic Protection (CP) Effectiveness in Pipelines Based on Artificial Intelligence (AI)

Contract Number: 693JK32350005CAAP

Prime University: ***Texas A&M Engineering Experiment Station***

Prepared By: PI Homero Castaneda-Lopez Professor, hcastaneda@tamu.edu,
phone: 9794589844

Reporting Period: October 1st – December 30th, 2025

Project Activities for Reporting Period:

Task 1. Development and optimizing macro/micro physical prototypes in laboratory and field conditions for validation of deterministic modeling.

The validation of the developed deterministic model across both macro/micro scales has been performed at the laboratory scale (full control), field scale with survey databases. In this case we will combine field conditions with control anomalies, focusing on different distinct cases. The physical model will run under different conditions based on the current test set up to identify and characterize different local conditions. The pipeline is used for water transportation and is about 51 yards of length. The pipeline is 4inch diameter and is buried in clay soil. The steel pipeline is not coated and is a straight line with different top layer conditions. Some parts are soil and other parts are concrete along the right of way.

The experimental matrix is set based on different local conditions of the pipeline, cathodic protection system (impress and sacrificial) and locations of the anomalies or conditions along the right of way.

Schematic of the pipeline set up

Figure 1 presents the schematic layout of the field site used for pipeline corrosion. The figure shows the relative locations of the pipeline, the concrete section, the sacrificial anode, and the coupon exposure sites, along with the reference marker for each component.

The pipeline starting point is marked at Point No. 1 and extends longitudinally across the test area. From the start point, the first section of the pipeline runs approximately 14 m before reaching a concrete-encased driveway. This driveway section spans a length of 20 m, after which the pipeline continues for an additional 33m to the End point of the test section. This arrangement allows comparison of pipeline behavior in soil-exposed regions before and after the concrete encasement. Close to the starting point, a pipeline connection structure is present inside a manhole. From this location, a wired connection has been made to connect to the galvanic anode. A magnesium sacrificial anode is installed at a horizontal distance of approximately 10 m from this buried pipeline segment. The anode serves as the sacrificial cathodic protection for the pipeline in this area.

Three coupon exposure sites are installed along the pipeline to monitor the state of the pipe in the soil and the effectiveness of cathodic protection. Coupon Site 1 is located near the first soil-exposed pipeline section, upstream of the concrete encasement and relatively close to the magnesium anode.

Coupon Site 2 and Coupon Site 3 will be located downstream of the concrete section, along the final pipeline segment. These sites are positioned at different locations along the pipeline to assess changes in protection level and corrosion behavior with increasing distance from the anode. Pipe-to-soil (on mode) potential measurements were taken along the pipeline at intervals of 1 m over the length of the test section. At each measurement point, a $Cu/CuSO_4$ reference electrode was placed on the soil surface directly above or adjacent to the pipeline to ensure localized and consistent potential measurements. The same reference electrode was also used for coupon potential measurements, positioned close to the burial location of each coupon to minimize IR drop and local soil effects.

In addition to potential measurements, soil resistivity measurements were conducted along a route parallel to the pipeline, with measurement locations spaced at 4 m intervals. Soil resistivity was measured using the four-pin method, in which four equally spaced electrodes were inserted in a straight line and the resistance of the soil. This method provides an average resistivity value representative of the soil volume influencing cathodic protection current distribution.

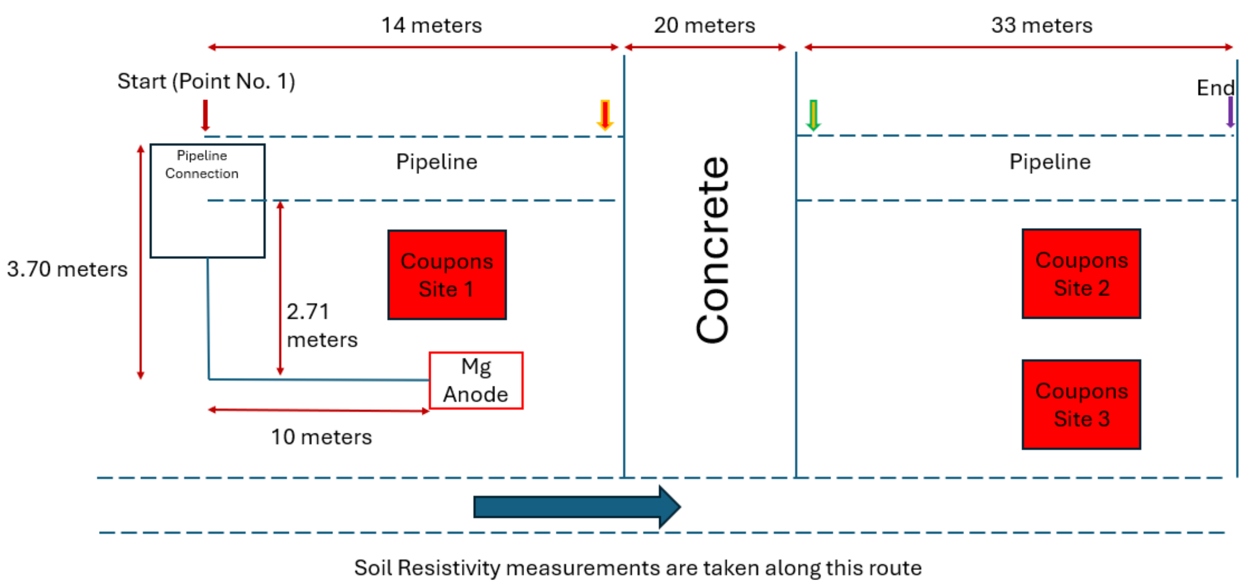

Figure 1. Schematic of the pipeline

Task 2: Integrating field inspection, theoretical, with experimental data by applying pattern recognition techniques relating the pipeline-coating-soil system with CP. Proposed framework

Figure 2 shows the pipe-to-soil ON potential measurements collected along the pipeline at 1 m spacing, plotted as a function of measurement point number for five different survey dates. Across all dates, the ON potentials are consistently negative, indicating that the pipeline remains under cathodic protection along the entire monitored length. A clear spatial trend is observed near the initial section of the line, where the potentials are more negative and show greater scatter, likely reflecting proximity to the magnesium anode and local variations in soil conditions. Temporal differences between survey dates are also evident: some dates show slightly more negative potential overall, while others exhibit less polarization, indicating changes in CP current output, soil resistivity, or environmental conditions over time.

Soil resistivity measurements collected along the pipeline at 4 m spacing are shown in figure 3, plotted as a function of measurement point number for multiple survey dates. The resistivity values vary along the route, indicating non-uniform soil conditions across the test section. Lower resistivity values are generally observed near the initial measurement points, while higher resistivity regions appear further along the line, particularly in the mid-to-downstream portion of the pipeline. Although the overall spatial trend is similar for all survey dates, noticeable differences in absolute resistivity are present between survey dates, suggesting temporal variability likely associated with changes in soil moisture content, temperature, or recent environmental conditions.

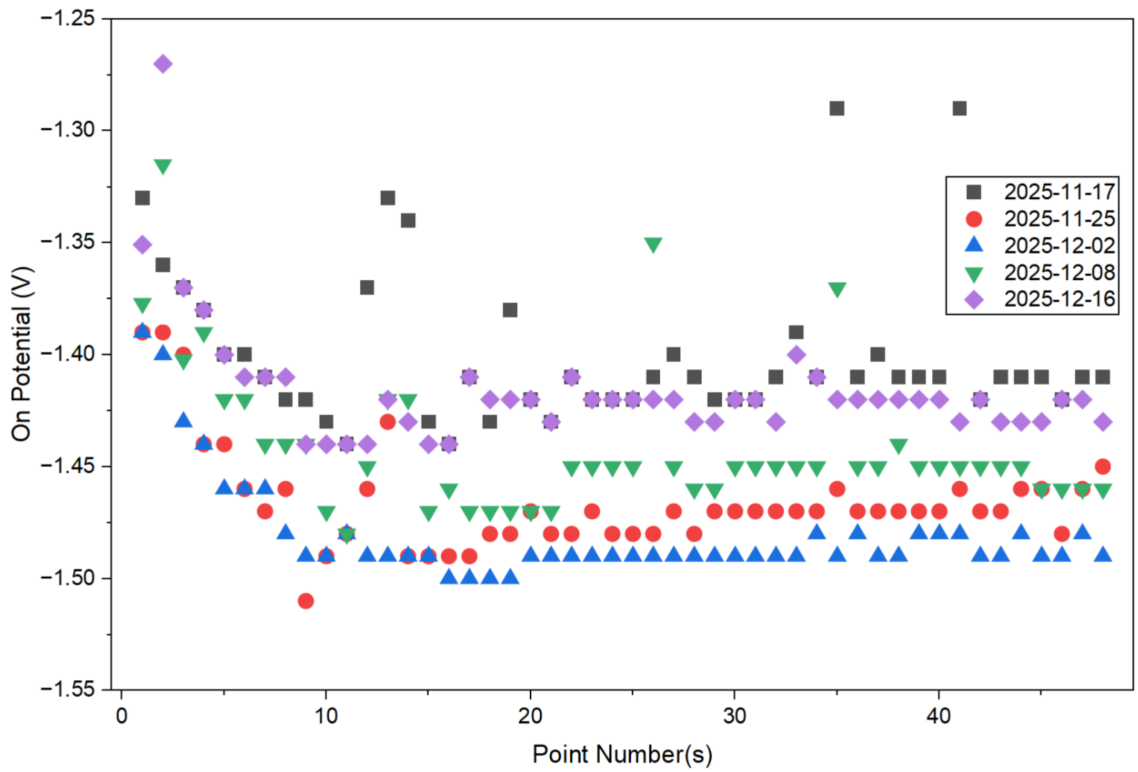

Figure 2. Pipe-to-soil ON potential measurements collected along the pipeline at 1 m spacing for multiple survey dates.

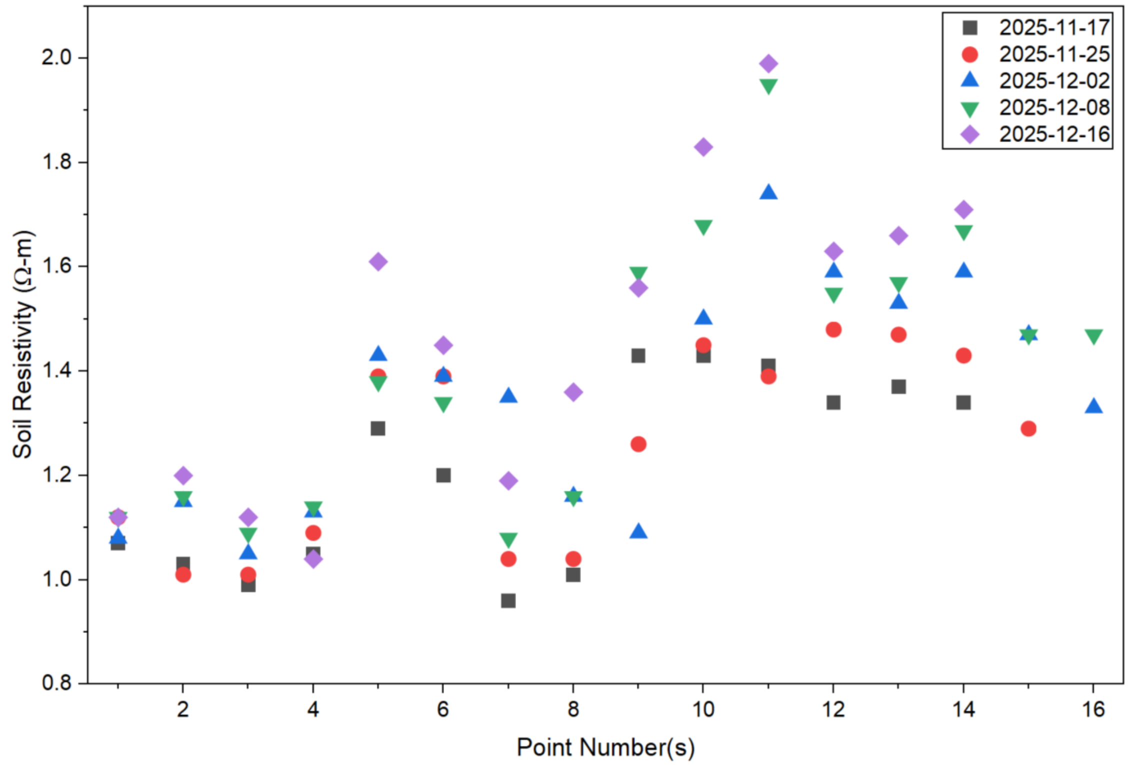

Figure 3. Soil resistivity measurements obtained along the pipeline.

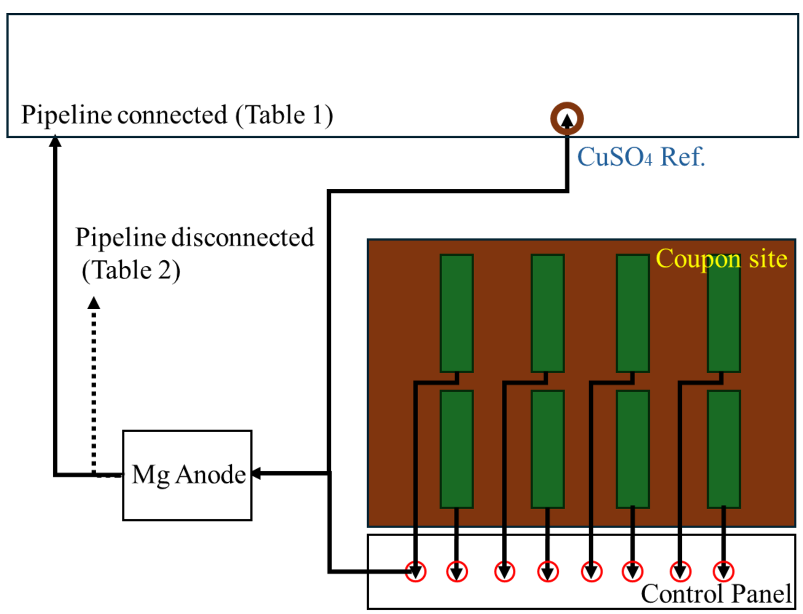

Figure 4. Potential measurements from different coupon

As shown in Figure 4, the coupons were buried at regular intervals at each site and embedded at locations more than 30 cm below the ground surface. Each coupon was connected in series to the control panel, while individual measurements were conducted separately by connecting each coupon to the magnesium sacrificial anode.

Table 1 and Table 2 present the ON potential measurements obtained from the different coated and bare steel coupons under controlled field conditions. In Table 1, the measurements were conducted while the pipeline was electrically connected to the magnesium sacrificial anode, representing cathodic protection conditions. In contrast, Table 2 corresponds to measurements taken with the pipeline electrically disconnected from the anode, allowing evaluation of coupon potentials in the absence of cathodic protection current (off potential).

To obtain the values reported for the anode-disconnected condition (Table 2), the electrical connection between the pipeline and the magnesium anode was momentarily interrupted during the measurement. The disconnection was kept brief to avoid significant depolarization of the system, thereby allowing comparison between protected and unprotected conditions (IR drop) at nearly identical environmental states.

Coupons labeled as intact represent specimens with fully intact coatings and no intentional defects. Coupons designated H-S and H-L correspond to coatings with artificial holidays of 0.218 cm² and 0.507 cm², respectively, while H-XL denotes coupons with a much larger exposed area of approximately 25 cm². The Polarized coupons was anodically polarized to 2.0 V prior to measurement to initiate localized coating breakdown and pitting, after which ON potentials were recorded.
The table includes data for multiple coating systems, including coal tar (single- and double-coat systems, white pigment (4500)), fusion-bonded epoxy (FBE), and bare steel. The FBE coating thickness was approximately 25–30 mils, representative of typical field-applied FBE coatings.
Together, Tables 1 and 2 allow direct comparison of coupon behavior under protected and unprotected conditions, as well as assessment of the effects of coating type, defect size, and induced damage on measured electrochemical potentials.

Table 1. Coupon ON potential measurements with anode connected

Coating Type	Date of measurement (in volts) vs $Cu/CuSO_4$														
	2025-12-08					2025-12-16					2025-12-22				
	Intact	H-S	H-L	H-XL	Polarized	Intact	H-S	H-L	H-XL	Polarized	Intact	H-S	H-L	H-XL	Polarized
Coal Tar - 1Coat	-1.42	-1.42	-1.43			-1.46	-1.46	-1.46			-1.47	-1.47	-1.47		
Coal Tar - 2Coat	-1.42	-1.42	-1.43			-1.46	-1.46	-1.46			-1.47	-1.47	-1.47		
4500-25 mils	-1.42	-1.43	-1.43			-1.46	-1.46	-1.46			-1.47	-1.47	-1.47		
4500-45 mils	-1.42	-1.43	-1.43			-1.46	-1.46	-1.46			-1.47	-1.47	-1.47		
Bare Steel						-1.42					-1.43				
FBE						-1.46	-1.46	-1.46	-1.46	-1.46	-1.46	-1.46	-1.46	-1.46	-1.46

Table 2. Coupon ON potential measurements with anode disconnected

Coating Types	Date of measurement (in volts)														
	2025-12-08					2025-12-16					2025-12-22				
	Intact	H-S	H-L	H-XL	Polarized	Intact	H-S	H-L	H-XL	Polarized	Intact	H-S	H-L	H-XL	Polarized
Coal Tar - 1Coat	-1.06	-1.03	-1.02	-		-1.08	-1.07	-1.06			-1.08	-1.06	-1.05		
Coal Tar - 2Coat	-1.04	-1.03	-1.02			-1.08	-1.07	-1.06			-1.07	-1.06	-1.05		
4500-25 mils	-1.03	-1.03	-1.02			-1.08	-1.07	-1.06			-1.07	-1.06	-1.05		
4500-45 mils	-1.03	-1.02	-1.02			-1.07	-1.06	-1.05			-1.07	-1.06	-1.05		
Bare Steel						-1.02					-1.02				
FBE						-1.05	-1.05	-1.05	-1.04	-1.04	-1.05	-1.05	-1.05	-1.04	-1.04

Task 3: Validation of the *a priori* framework with experimental and field conditions for characterization/modeling and Evaluation/Validation

Multilevel Bayesian Modelling

During the previous quarter, we developed a Bayesian machine learning framework that integrates theoretical predictions, experimental findings, and field inspection data to quantify interactions within the pipeline–coating–soil–CP system. In the current quarter, we focused on a more efficient implementation using a multilevel modeling approach.

The Bayesian multilevel refinement model provides a computationally efficient way to estimate the underlying coating impedance along a pipeline while retaining full uncertainty quantification. At its core, the method couples a 1D physics-based Transmission Line Model (TLM) of cathodic protection with a hierarchical Bayesian formulation. The TLM describes how the pipe–soil potential responds to spatial variations in soil resistivity, coating condition, and anode locations, and is discretized into a linear system whose solution yields the potential field $\phi(x)$. The coating impedance $Z(x)$ is not treated as a fixed input; instead, it is inferred as a latent field from noisy close-interval potential surveys (CIPS), encoded through a finite number of parameters (e.g., lognormal coating resistivity segments) that control a smooth impedance profile along the route. A fully fine-resolution Bayesian inversion over an entire long pipeline would be prohibitively expensive: every additional degree of freedom in the impedance field increases the Bayesian updating parameter dimension, the cost of each forward solve, and the number of evaluations that NUTS algorithm needs to explore the posterior. At the same time, the field data (CIPS and soil resistivity) do not justify uniformly high resolution everywhere; many segments are relatively uniform or low-risk, while only certain regions (e.g., near anodes, suspected defects, or anomalous readings) truly demand fine detail. We observed that a multilevel refinement approach addresses this imbalance: it uses a coarse global model to capture large-scale behavior and then selectively refines only those segments where additional resolution actually adds information. Hence, the overall multilevel modelling consists of three units (Figure 5):

1. Segmentation Unit: A multilevel discretization module that first assigns coarse coating segments over the full pipeline and then defines refined windows with finer segments where more detail is needed. It controls the mapping from segment parameters to nodal quantities at both global and local scales, and it also governs the choice of Neumann vs. Dirichlet boundary treatments in the different stages.
2. Bayesian TLM: A physics-informed Bayesian Transmission Line Model that links coating impedance, soil resistivity, anode configuration, and boundary conditions to the pipe–soil potential. This unit encodes the forward model and likelihood and provides posterior estimates of potential and impedance at the chosen resolution. Computationally, we exploit the tridiagonal band structure of the TLM system using a custom banded solver, which significantly reduces the cost of each forward solve and thus accelerates sampling.
3. Posterior Blending: A synthesis step that merges the coarse global posterior with the refined local posteriors into a single multi-resolution field. Coarse results provide the backbone; refined windows overwrite or smoothly blend into this backbone in their respective regions, including overlap handling, to produce final means and credible intervals for impedance and potential along the entire route.

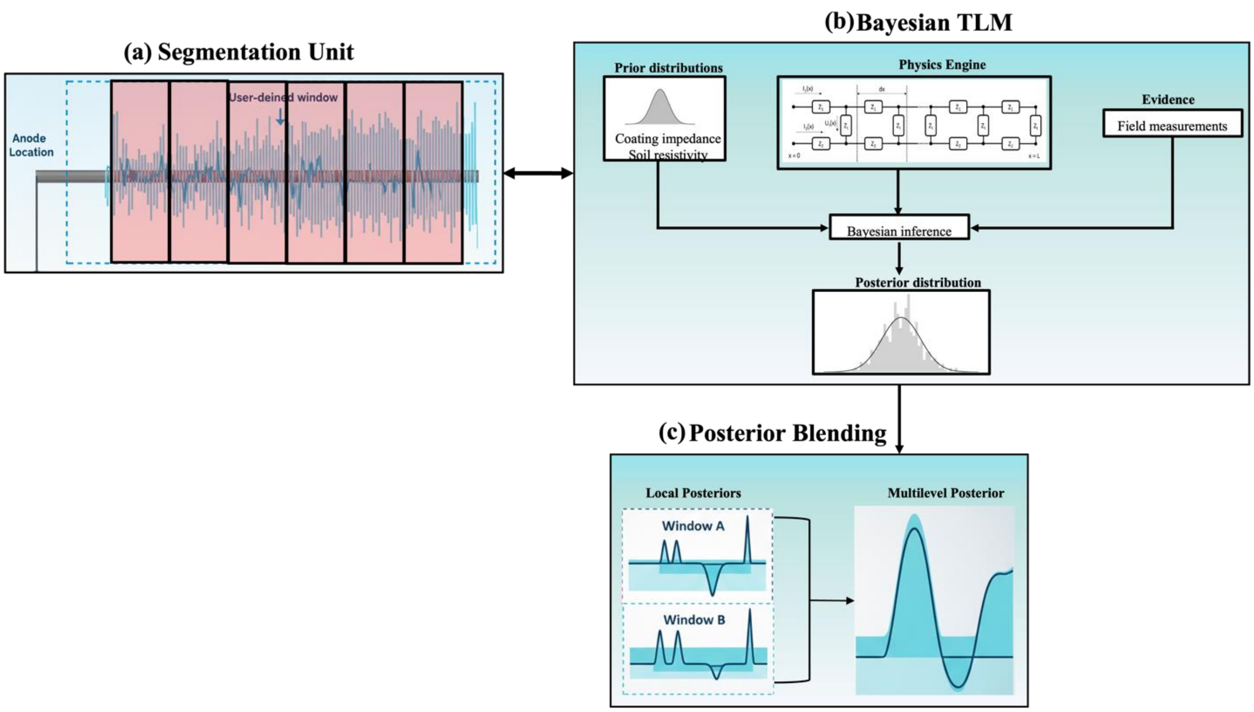

Figure 5: Multilevel Bayesian modelling

Methodology

The first step is a coarse-resolution Bayesian inversion across the full pipeline. The domain is divided into relatively large coating segments, each with a latent lognormal coating resistivity parameter that controls the local impedance via the dielectric coating model. This coarse

parameterization drastically reduces the dimensionality of the problem, making posterior sampling manageable while still allowing spatial variability in impedance at a large scale. These segment parameters are mapped to nodal impedances through the dielectric coating model and embedded into the TLM operator. Given observed CIPS data and an observation-noise model, NUTS sampling is used to draw from the joint posterior over the coarse coating parameters, the potential field, and the noise scale. This produces a global posterior estimate of potential and impedance that is fast to compute and already reflects the main spatial trends and data constraints. Figure 1 (b) illustrates the Bayesian Transmission Line Model framework.
In the global coarse run, Neumann boundary conditions are used at the ends of the modeled pipeline segment (a physically motivated approximate "natural" boundary condition consistent with the expected CP potential near -0.85 V). At this stage, endpoint potentials are not known, and imposing arbitrary fixed values would risk over-constraining the solution. A Neumann condition lets the global model find an internally consistent potential profile given the data, soil, and anodes.

Importantly, this coarse inversion is not just a computational convenience; it is also essential for well-posed refinement. When we later zoom into a subdomain for fine resolution, that subdomain is not physically isolated: currents and potentials are influenced by conditions outside the window. Running a highly resolved local model with arbitrary boundary conditions could yield refined solutions that look smooth locally but are globally inconsistent. The coarse model resolves this by providing physically grounded estimates of the potential at the boundaries of each refinement window, together with their uncertainty. These boundary values from the coarse posterior become the "anchors" that tie each refined inversion back to the overall system behavior.

The next stage introduces local refinement on selected subdomains where more resolution is desired for example, regions with suspected coating degradation. For each refinement window $[x_a, x_b]$, the model is restricted to this subdomain, and the TLM is re-discretized with a finer coating parameterization. Here we impose Dirichlet boundary conditions at x_a and x_b using coarse posterior summaries. This effectively conditions the refined model on the global solution: the fine model must match the coarse behavior at the boundaries but is allowed more flexibility inside the window via the finer parameterization. Within each window, a new Bayesian inversion is run, inferring a higher-resolution impedance profile that is consistent with both the local data and the global context provided by the coarse model.

Multiple refinement windows can be defined along the route. Windows may overlap, in that case, each window produces its own refined posterior over potential and impedance on the overlapping region. Finally, the refined windows are stitched back into a single global impedance and potential profile by blending their posteriors with the original coarse posterior always accompanied by uncertainty bounds that propagate through both levels of the modelling hierarchy.

Preliminary results of the proposed framework applied to a 50 km pipeline are shown in Figure 6. Figure 6(a) presents the close-interval potential survey (CIPS) data along the pipeline (black points), overlaid with the coarse global Bayesian TLM posterior mean (red dashed line) and the refined multilevel posterior mean (green line). The coarse model is applied with 1 km coating segments, so it uses a relatively small number of impedance parameters to capture the large-scale behavior. For refinement, the model uses higher-resolution coating segments of length 0.25 km along the entire pipeline as a proof of concept; in practice, this refinement would be applied only in selected regions. Figure 6(b,c) shows zoomed-in impedance posteriors for two representative segments. In each inset, the red band denotes the coarse-resolution posterior (mean and 95% credible interval) inherited from the global Neumann-BC run, while the blue band shows the locally refined posterior (mean and 95% credible interval) obtained from a Dirichlet-anchored subdomain inversion. Together, these panels illustrate the posterior blending step: the coarse results provide a globally consistent backbone, while the refined windows locally sharpen the impedance estimate and its uncertainty without re-meshing the entire pipeline. The refined model better matches the observed CIPS data in these regions and therefore yields a more informative inference of the underlying coating impedance.

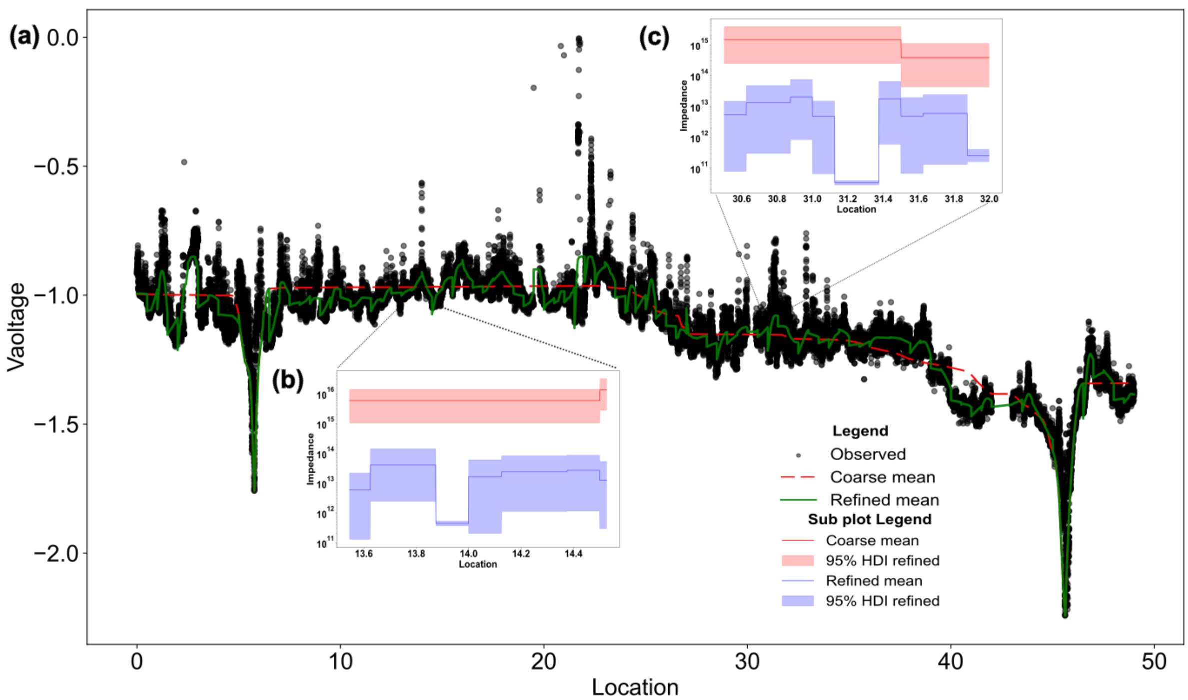

Figure 6: Bayesian multilevel refinement of pipe–soil potential and coating impedance on 50 km pipeline.

Overall, these results demonstrate that the Bayesian multilevel refinement framework can efficiently recover a spatially resolved, uncertainty-aware estimate of coating impedance by combining a coarse global backbone with targeted local refinement. By anchoring fine-scale inversions to a physically consistent global TLM solution, the method preserves computational tractability while enhancing sensitivity to localized coating degradation. The next critical step is model validation by comparing the inferred impedance profiles against the true underlying impedance. The Texas team has established a field testbed with ground-truth measurements, which will be used in the coming quarter to rigorously validate and further calibrate the proposed methodology.

Task 4: Procedure based on ECDA method.

External Corrosion Direct Assessment (ECDA), as described in NACE standard SP0502, is an organized process for characterizing and evaluating onshore steel pipeline systems. The methodology is proposed to manage the risk of external corrosion failures in steel pipelines, prioritize repair numbers and locations, and consequently maximize the integrity of the metallic pipeline. The ECDA comprises four steps, namely: (1) pre-assessment, (2) indirect assessment, (3) direct assessment, and (4) post-assessment.

The development of a field test to generate information to use for the developed algorithm and integrate into an ECDA methodology.

We have 50ft of 4-inch bare steel pipeline buried in the ground. The pipeline is used for water distribution, and the pipeline is located in Bryan, Texas. We design and set the conditions of the pipeline to have CP system via galvanic anodes and also impress current.
There were three different sites to set up different conditions of the pipeline simulating defects or heterogeneities at the soil/pipeline interface.

Once we collect the data, we will be able to run our current algorithm and establish more quantitative criteria during the ECDA methodology. For example, we will be able to add some quantitative characteristics for the first three steps.

Project Financial Activities Incurred during the Reporting Period:
Project Activities with Cost Share Partners:

During the ninth quarter of this project, we met several times (around seven) with the co-sharing partners; we will organize a meeting at the beginning of 2026 for feedback on the new field-controlled testing.

Financial Summary

- Federal Cost Activities:

Category	Amount spent during Year 2 2024-2025
Personnel Salaries	
Students (RA)	$10,557
Benefits	$1973
Tuition	$7,228
Operating Expenses	$1,171.00
Travel	NA
Materials and Supplies	NA
Miscellaneous	NA
Indirect costs	$6255
Total Costs	$27,185.00

- Cost Share Activities:

    - Cost share contribution:

- Heuristech has contributed $28,200.00 in technology training and/or company personnel hours for physical laboratory testing and mathematical tools.
- Integrity Solutions has contributed $86,000 in CP field data collection, technical staff resources to collect, collate, evaluate, screening, database development, attending workshops and training, analyzing Cathodic Protection (CP) data, contributing to computer algorithm development programming, and other program software/model components.

Project Activities with External Partners:

- We will organize a technical workshop with the team partners to get feedback on our proposal concept.
- We will organize different courses for pipeline companies, one of which will be integrity and risk.

Educational Activities:

- Student mentoring:

We organize weekly meetings in the corrosion group for research updates and activities performed. Each student is assigned a PhD student or a Postdoctoral Fellow to follow up on the activities and discuss the results obtained. The students participate in the laboratory activities and conferences (such as AMPP and TAMU internal conferences).

- Dissemination of Project Outcomes:

We submitted two abstracts to the AMPP 2026 annual conference, and they were accepted. We have one Research in Progress and one poster for the same conference.

Potential Project Risks:

Currently, there are no potential risks.

Future Project Work:

We anticipate following the proposed timeline with no current changes during the next months. We will follow the Gantt chart to track progress and plan.

During the next 30, 60, and 90 days, we will perform task 1 activities. Additionally, we will continue with Task 2,3, and 4 activities over the next 30, 60, and 90 days.

Theoretical work, field control work, and generated database analysis will be considered for the next quarter.

- Include different surveys of the field pipeline with anomalies, including coating defect activity and severity in the coating impedance model
- Continue validating the model with multiple sets of field data.

The timeline and schedule for the project are in the Gantt chart.

Task/Subtask	Fiscal Year											
	2023	2024				2025			2025	2026	2026	2026
	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Task 1: Designing and building the physical prototypes in laboratory conditions and deterministic modeling												
Task 2: Integrating field inspection, theoretical, with experimental data by applying pattern recognition techniques relating the pipeline-coating-soil system with CP												
Task 3: Validation of the *a priori* framework with experimental and field conditions for characterization/modeling and Evaluation/Validation												
Task 4: Development and validation of the methodology for ECDA based on CP levels												

Deliverable Milestones are indicated in black*, and in dark green is the extended activities.

Potential Impacts to Pipeline Safety:

During the pipeline survey and Transmission Line Modeling, we validated the algorithms used for Artificial Intelligence with the field database. The potential impact is the results generated for the AI algorithm; the TLM is based on a deterministic and fundamental approach. This can not only show different trends for a buried structure under cathodic protection but also include several features in the RoW, resistivity, rectifier location, coating anomalies, and soil characteristics. The rectifiers, anodic beds, soil compositions, current distribution, etc. The new field testbed will simulate different controlled environments, this latter will be validated with the theoretical algorithm based on TLM and Machine learning. Finally, the impact to Pipeline safety with the new test bed or field-controlled environment testing and validation will help in the sensitivity accuracy of the new developed methodology.

References

1. Huang, V.M.-W., et al., *The apparent constant-phase-element behavior of an ideally polarized blocking electrode: a global and local impedance analysis.* Journal of the Electrochemical Society, 2006. **154**(2): p. C81.
2. Brug, G., et al., *The analysis of electrode impedances complicated by the presence of a constant phase element.* Journal of electroanalytical chemistry and interfacial electrochemistry, 1984. **176**(1-2): p. 275-295.
3. Tsai, Y.-T. and D. Whitmore, *Nonlinear least-squares analyses of complex impedance and admittance data for solid electrolytes.* Solid state ionics, 1982. **7**(2): p. 129-139.

.