WHEN TRUST MATTERS

Reduction of Methane Leaks through Corrosion Mitigation Pre-treatments for Pipelines with Field Applied Coatings

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U.S. Department of Energy
National Energy Technology Laboratory
Resource Sustainability Project Review Meeting

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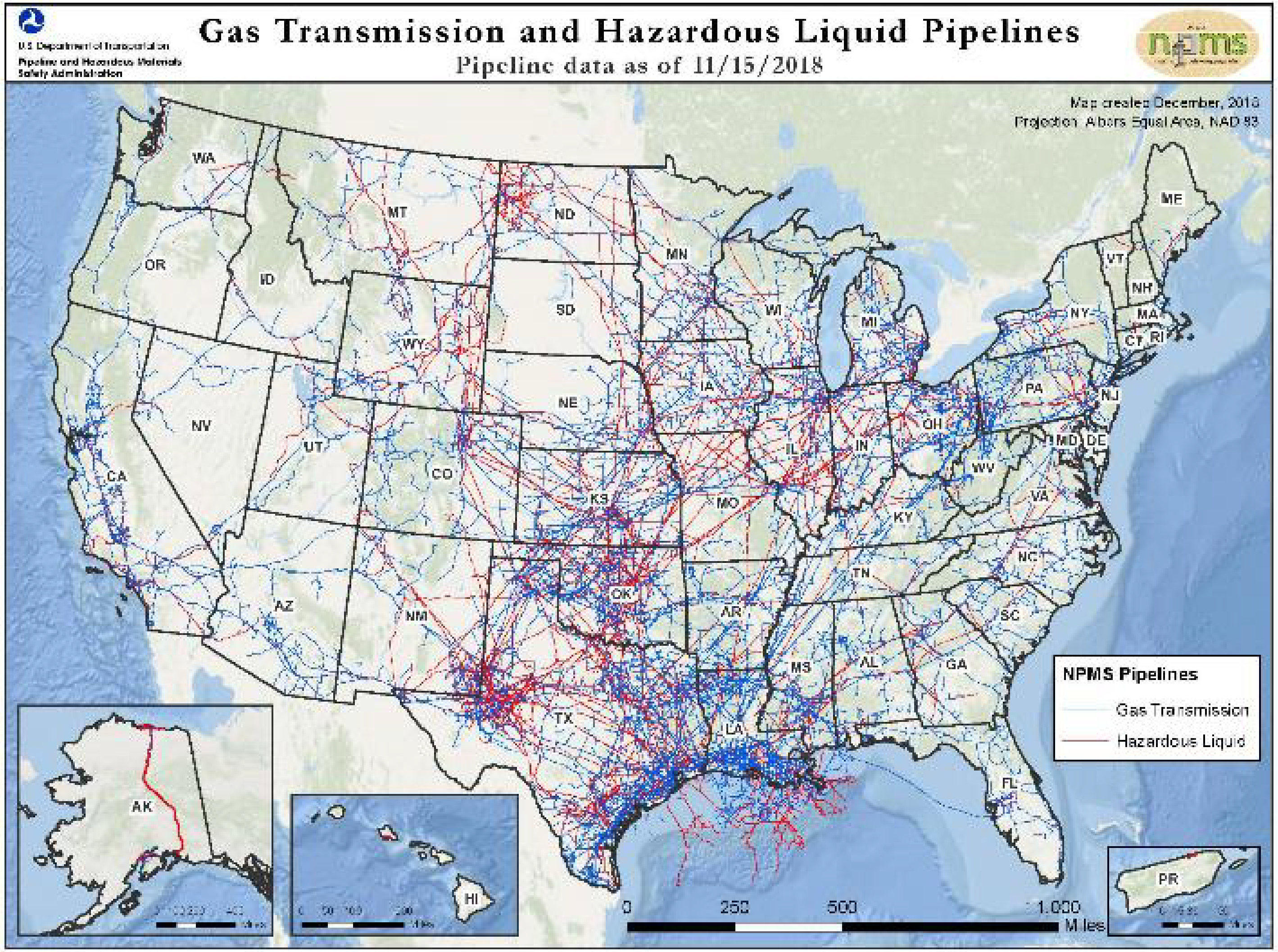
Pittsburgh, PA

Reducing Methane Emissions from Natural Gas Transmission Pipelines

- **300 thousand miles of natural gas transmission pipelines in U.S.** https://www.phmsa.dot.gov/data-and-statistics/pipeline/pipeline-mileage-and-facilities
- **Deliver 28 trillion cubic feet to annually to 75 million customers** (https://www.eia.gov/energyexplained/natural-gas/natural-gas-pipelines.php)
- **Natural gas (pipeline quality) is comprised of 70-90% methane by volume** http://naturalgas.org/overview/background/



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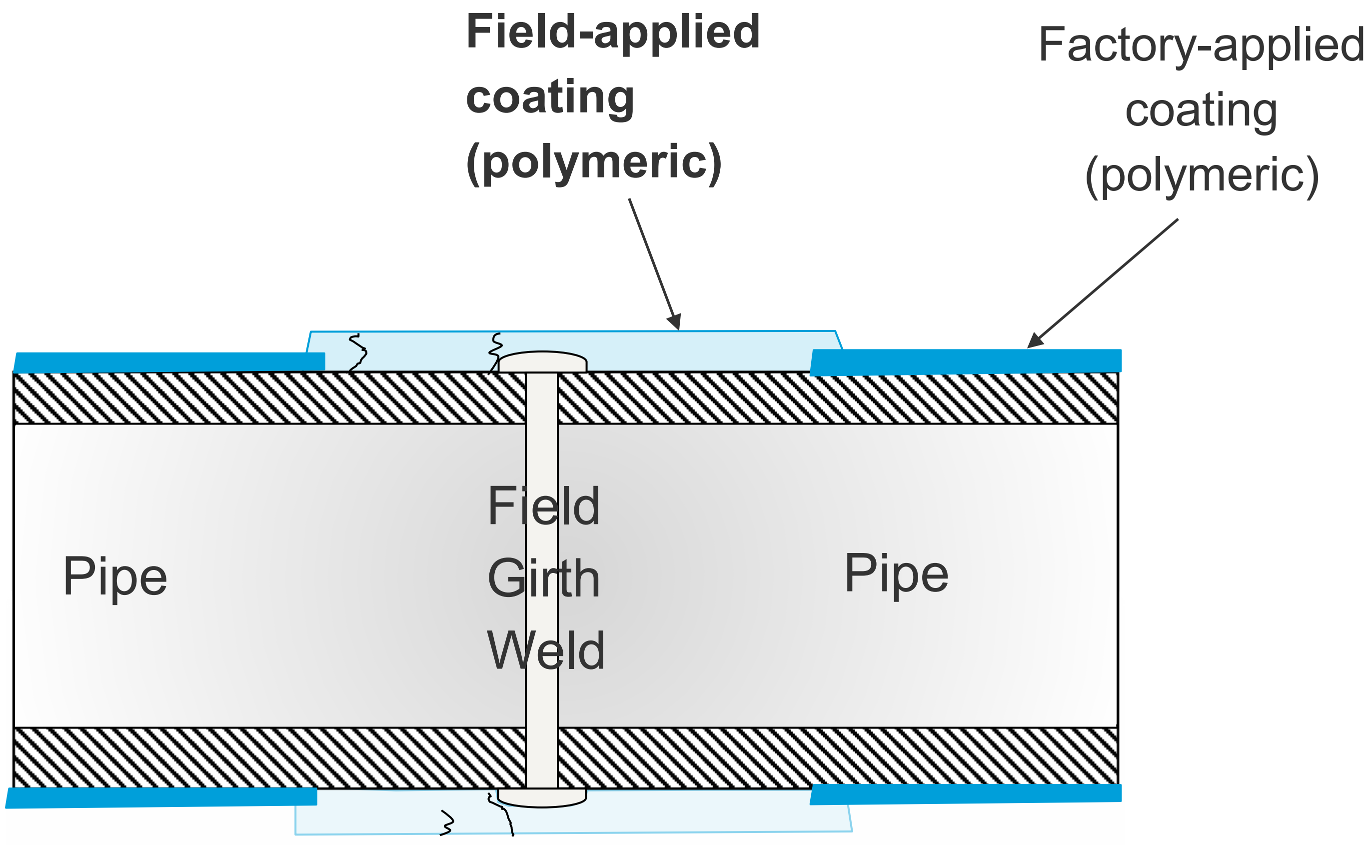
Problem: Lower Quality Field-Applied Coating

- Field-applied pipeline coatings over field girth welds are usually lower quality than factory-applied pipe coating
- Experience more frequent repairs and failures, which result in methane emissions



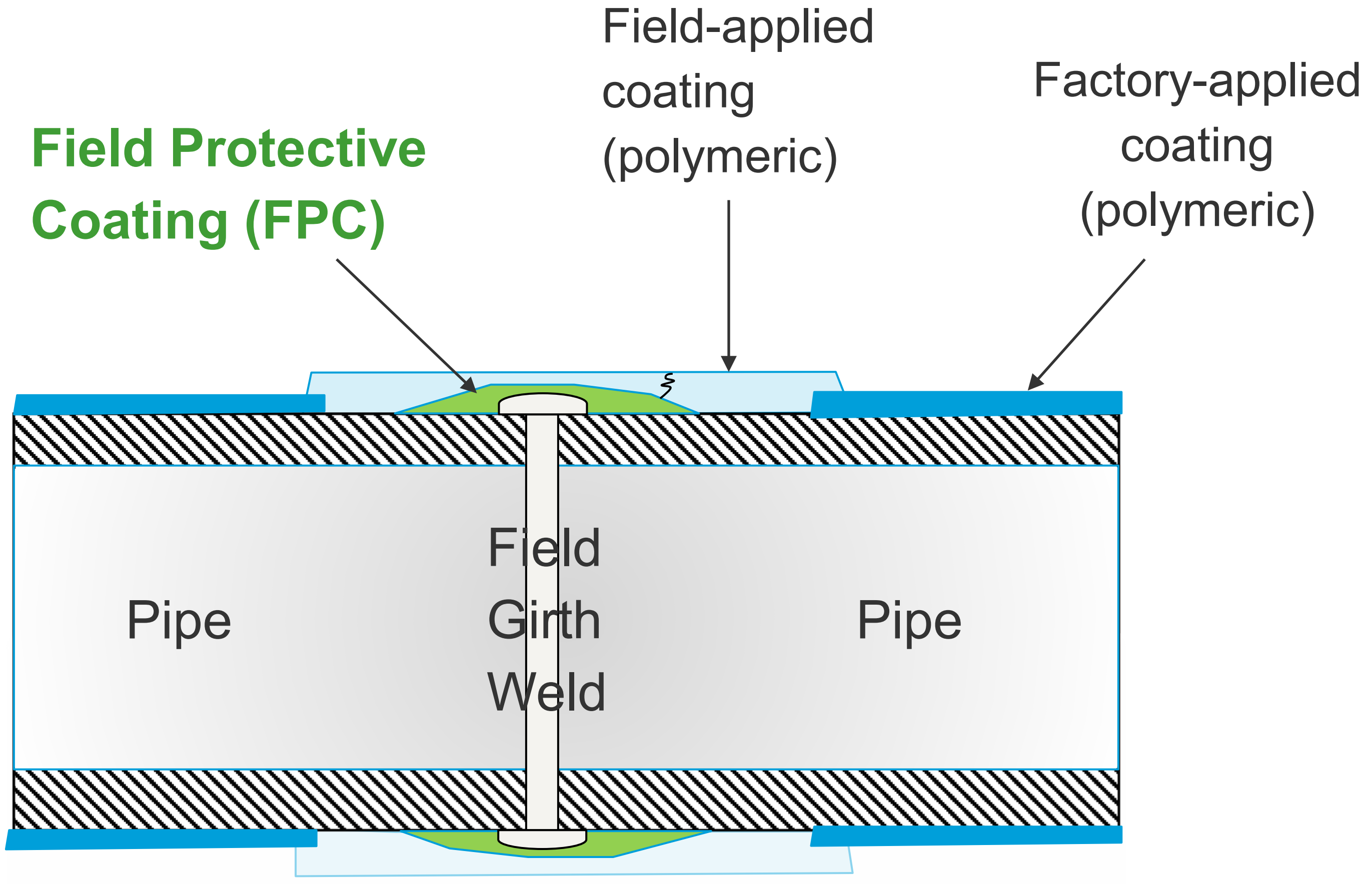
Axial cross-section of buried steel pipeline

Proposed Solution To Help Keep Methane in the Pipe

Field Protective Coating (FPC) provides extra alloy layer of corrosion protection in girth weld region.

May be desirable in pipeline locations where:

- Groundwater penetrates the field top coating
- Pipe is shielded from external cathodic protection
- Inaccessible locations for future repair



Axial cross-section of buried steel pipeline

Project Duration & Funding

- 4 years: September 1, 2020 to August 31, 2024

- Direct cost (77%)
  - **U.S. Department of Energy NETL**: $1,499,252
- Cost share (23%)
  - **Enbridge**: pipeline field testing $300,000
  - **Lincoln Electric**: coupon fabrication $75,008
  - **DNV**: technical advisor, software $57,488
  - **MC Consult**: technical advisor $16,000

Project Total: $1,947,748

Project Participant Organizations

Lead Organization

DNV (Dublin, OH): Leading independent expert in risk management and quality assurance, including leading pipeline corrosion and welding expertise. Global HQ in Norway with 12,000 employees worldwide in 100+ countries.

Cost Share Partner

Lincoln Electric (Cleveland, OH): Leading world manufacturer of welding, brazing, and soldering alloys and robotic welding and cutting equipment, with 11,000 employees and 60 manufacturing locations worldwide

Cost Share Partner

Enbridge (Houston, TX): Leading operator of oil and natural gas pipelines in North America, headquartered in Calgary, Canada. US operations has 23k miles of gas transmission and midstream pipelines in 30 states, transporting 19% of the natural gas consumed in the US (18 billion cubic feet per day).

Project Objectives

1. Develop field applied alloy coating over girth welds to mitigate corrosion under field applied coatings
2. Detail field applicability of coating system
3. Develop guidance for application and technology transfer to industry

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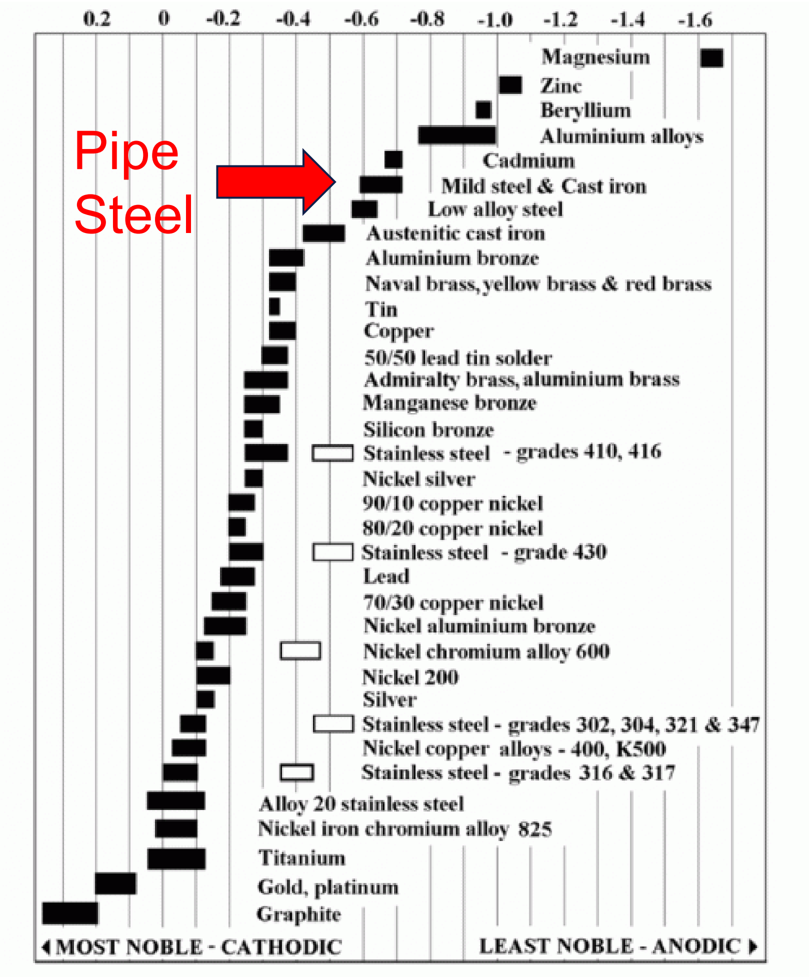
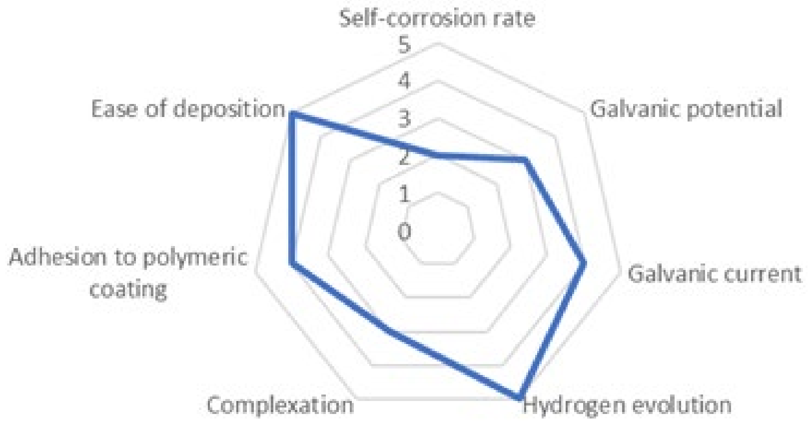
Project Approach

- Optimize and select alloy(s) for field protective coating, using models and experiments
- Consider:
  - Sacrificial alloys (less noble than steel) and
  - Corrosion resistant alloys (more noble than steel)
- Generate alloy coated pipe steel coupons for corrosion testing in:
  - Laboratory and
  - Pipeline field sites
- Document performance and draft guidance for field protective coating

BP1: Metal Alloys Review and Selection



Galvanic series of metals



- Selection Criteria for an effective field protective coating:
  - Minimal self-corrosion
  - Optimized galvanic potential and current
  - Mitigate hydrogen evolution
  - Avoid complexation
  - Adhesion to field applied polymeric coating
  - Weldability

Alloy Coating Types Considered

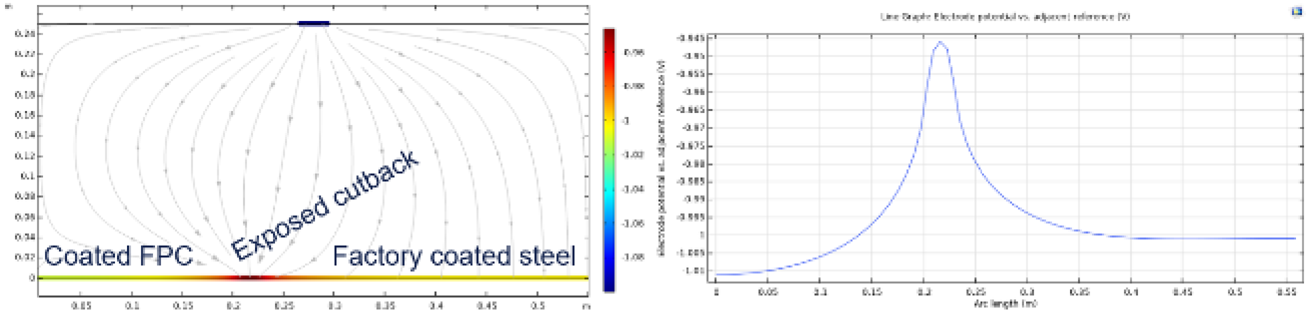
- Sacrificial alloy: Aluminum
  - 4043 with ~5% of Si
  - 5356 with ~5% of Mg
- Corrosion resistant alloy: Low alloy steel (welding electrode compositions)
  - ER80S-**B2** (1.25% Cr)
  - ER90S-**B3** (2.25% Cr)
  - ER90S-**B9** (9% Cr)
- Selection was based on:
  - Commercial availability
  - Suitability for field coating
  - Performance in environmental conditions, galvanic potential, corrosion rates

Electrochemical Modeling

- **Two density functional theory (DFT) models were developed** for estimating corrosion resistance of the proposed alloys
  - Model estimating the work function of the material, from tabulated experimental and computed work function data
  - Model using Corrosion Susceptibility Index (CSI), based on a database of DFT computed adsorption energies for oxygen vs chloride on alloy surfaces
- **Two finite element codes were used, Beasy and COMSOL**, to model system where galvanic (sacrificial) field coating is applied across the joint region, to show the electrochemical protection provided by the coating maintains pipeline steel below corrosion potential of -770 mV.
- **Additional COMSOL scenarios** were set up using the data from X52 and the conductivity of the NS4 electrolyte environment.

Electrochemical Testing in NS4 Solution

- A representative soil simulant solution NS4 was used to mimic the aqueous environment in which corrosion could occur in the field.

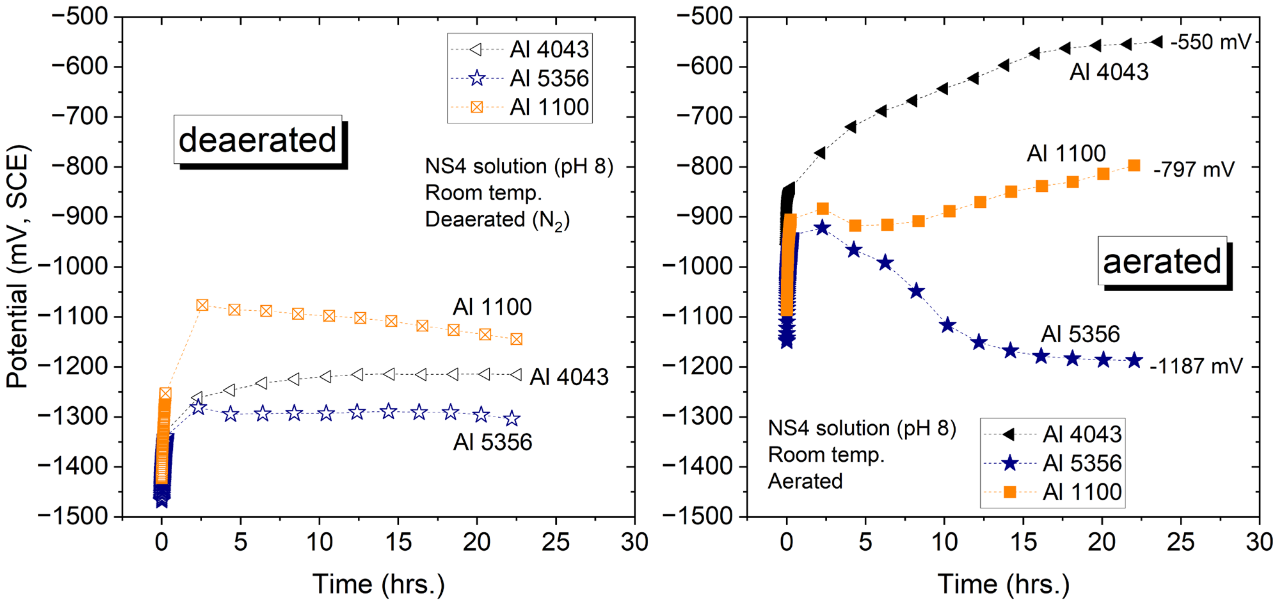


COMSOL simulations of 5356 Coated FPC region showing potential, current flow and profile along the coated pipe, cutback and factory coated steel (deaerated).

Solution composition of NS4

Reagent	g/L
KCl	0.122
$NaHCO_3$	0.483
$CaCl_2.2H_2O$	0.181
$MgSO_4.7H_2O$	0.131

- pH ~ 8
- Solution resistivity = 950 Ω·cm
- Deaerated and aerated conditions

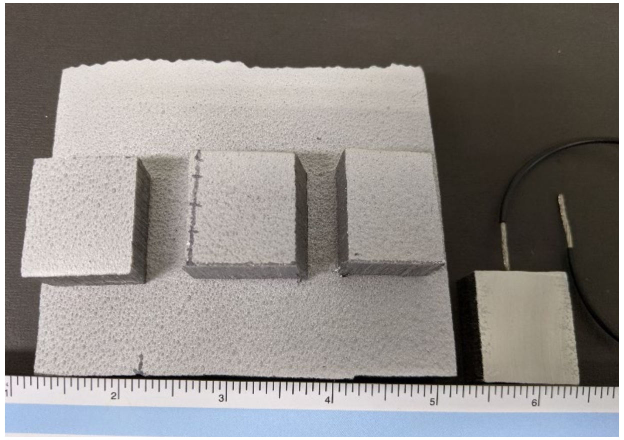


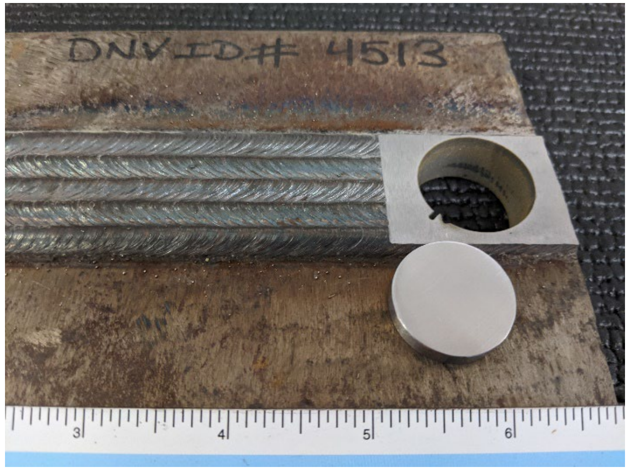
Selected Alloy Coatings

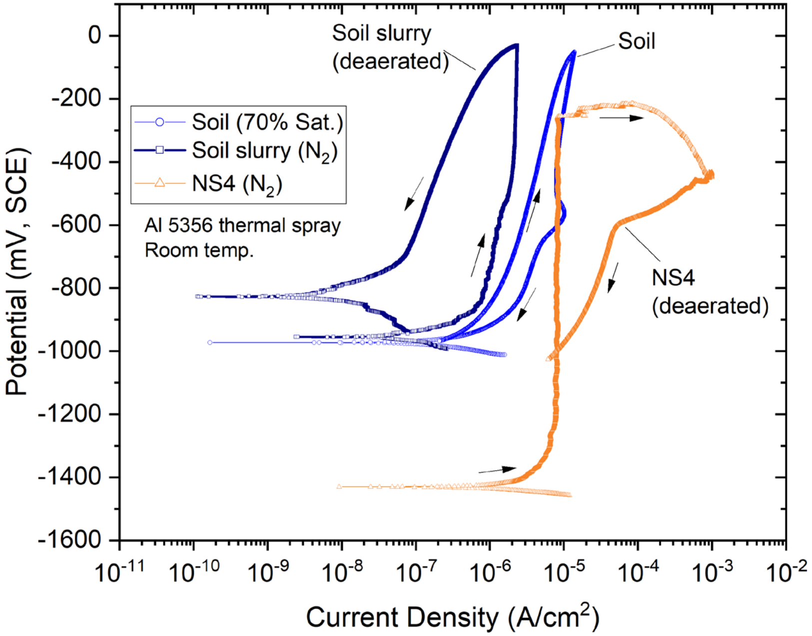
- Baseline electrochemical curves were produced to characterize the underlying pipeline steel (X52) in both aerated and deaerated soil simulant solutions
- Based on electrochemical test results, two alloys were selected for further evaluation:
  - Sacrificial alloy: **Aluminum 5356** (Al-Mg alloy) with:
    - 4.5-5.5% Mg
  - Corrosion resistant alloy: **Steel B9** (Fe-Cr-Mo-Ni-V alloy) with:
    - 8.5-9.5% Cr
    - 0.85-1.10% Mo
    - 0.40-0.80% Ni
    - 0.15-0.25% V

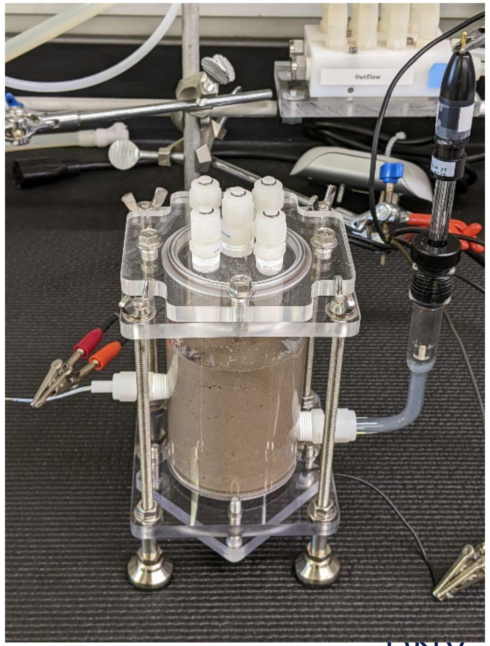
Laboratory Testing of Coated Coupons

- Steel samples were coated by:
  - Lincoln Electric: Gas metal arc welding (GMAW) of steel alloy B9 (no PWHT)
  - Flame-Spray Industries: Flame spray of aluminum alloy 5356 (Unweldable to steel, due to brittle intermetallics)
- Laboratory tests on flat disc coupons for:
  - Corrosion rate and open circuit potential in aerated and deaerated NS4 solution
  - Electrochemical tests in Enbridge provided soil



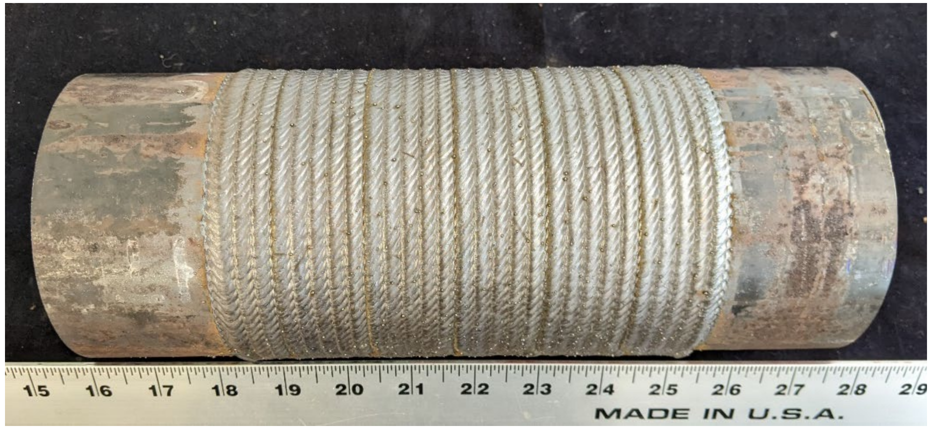


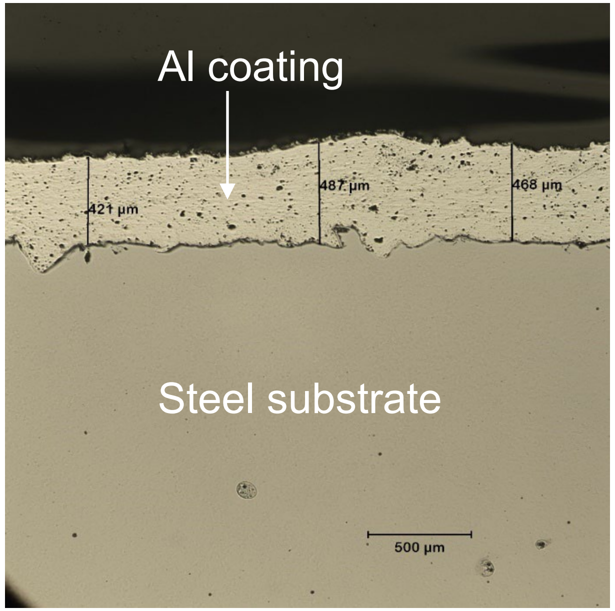


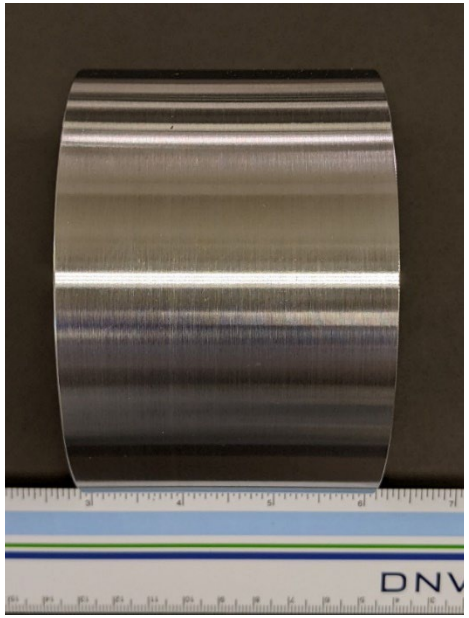


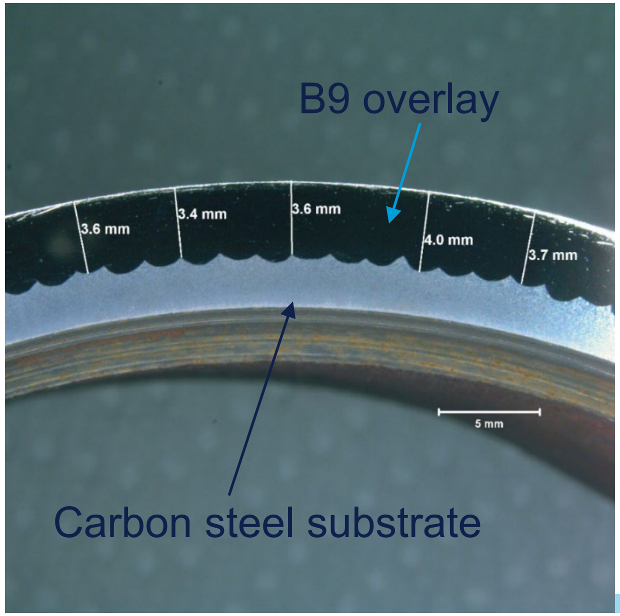
BP2: Fabrication of coated pipe coupons

- 4.5" diameter X42 steel pipe coupons were coated by:
  - Flame sprayed aluminum 5356 (~450 µm)
  - GMAW steel B9 & machined smooth (4 mm)



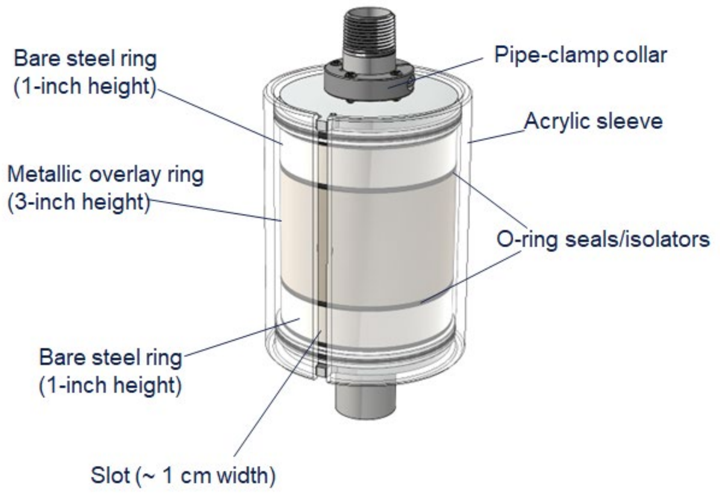


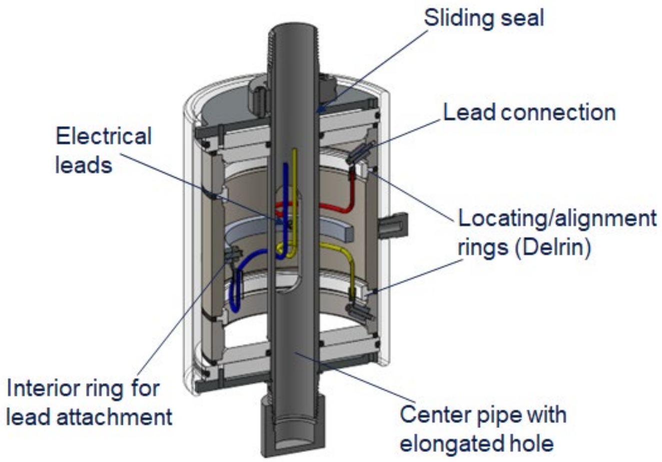


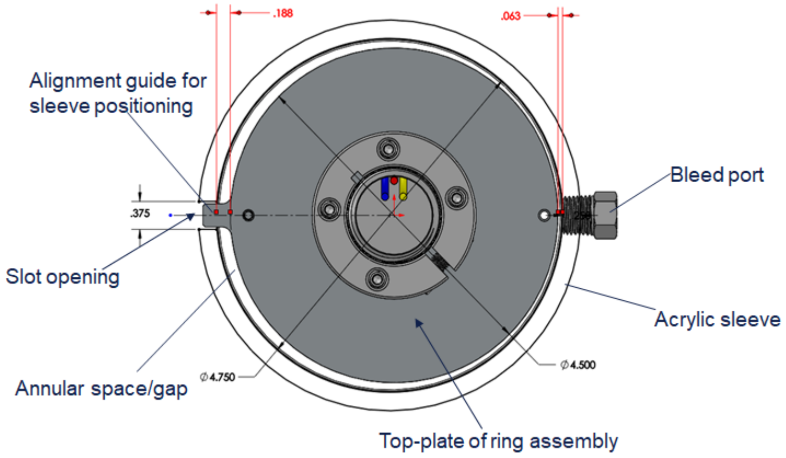


Design & Fabrication of Field Coupon Assembly

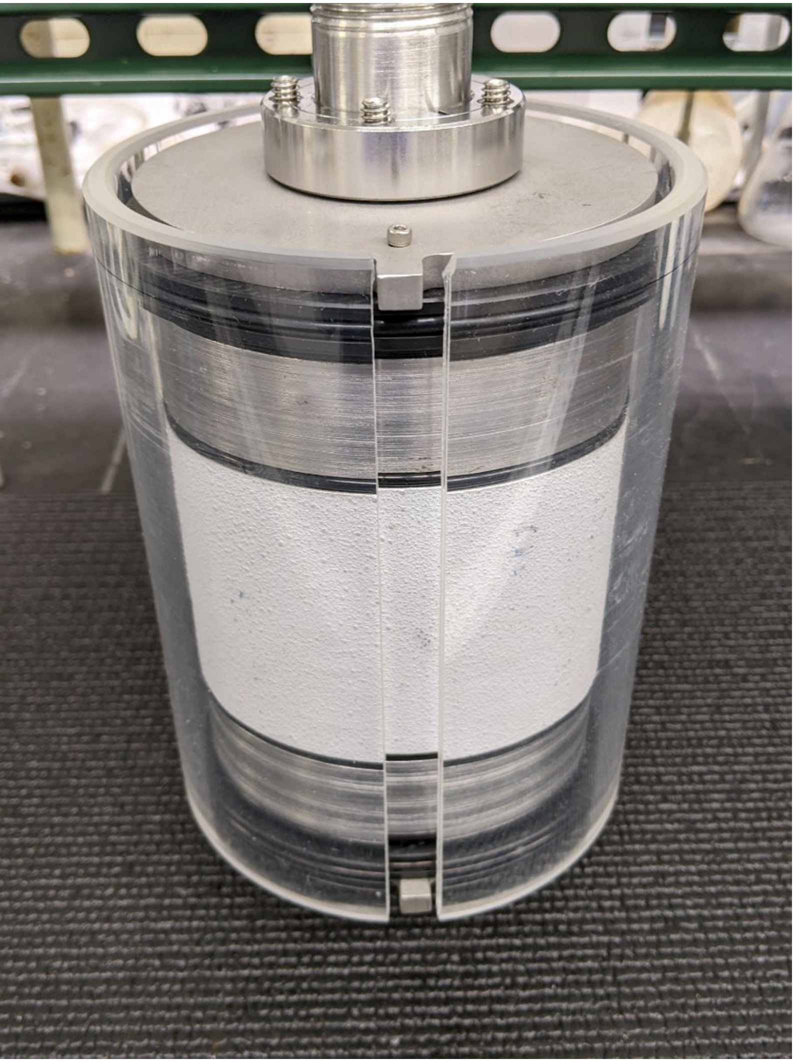
- Two bare steel rings at each end with coated ring in the center
- Rings are isolated, wired, and sealed
- Clear acrylic sleeve with slot simulates pipe coating disbondment
- Sleeve is eccentrically positioned to simulate variable disbondment gap of 0.063” to 0.188”

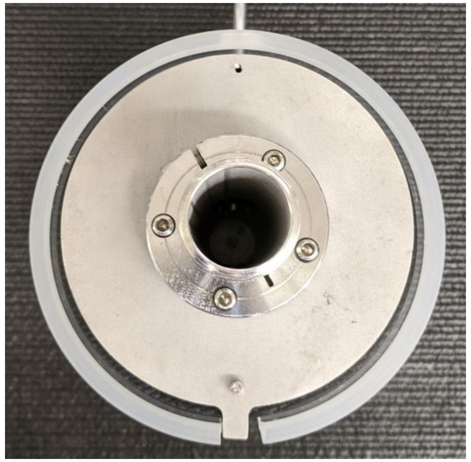


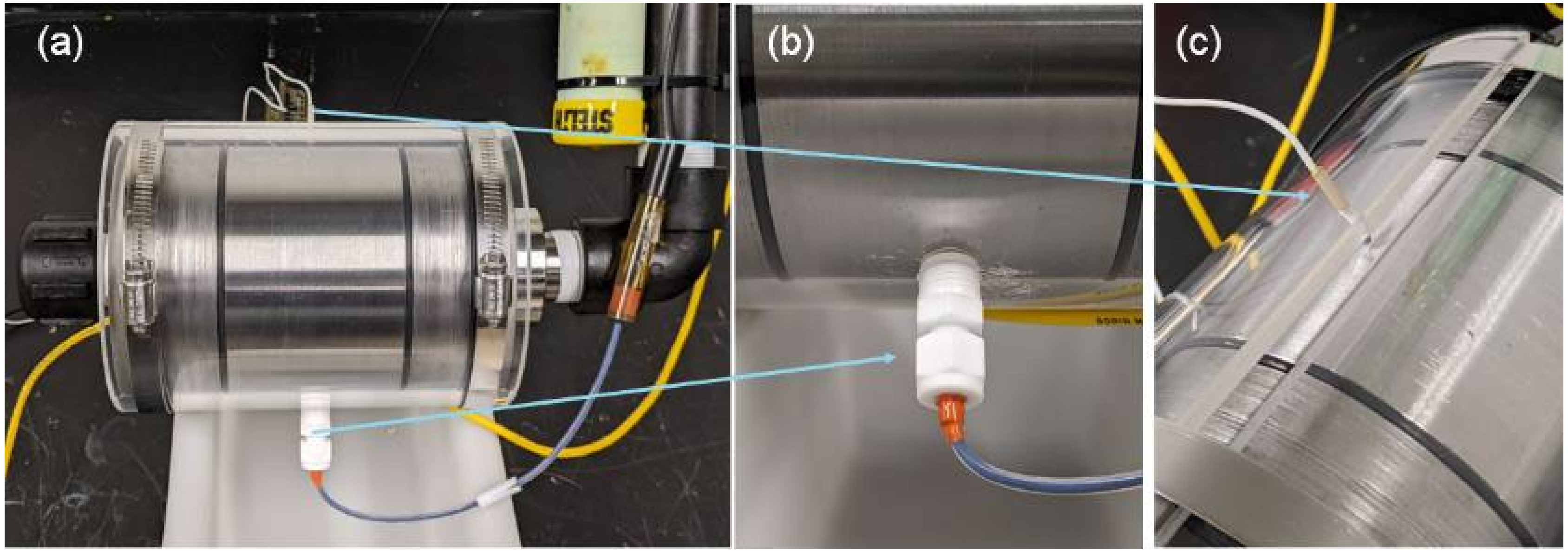




Coupon Assembly

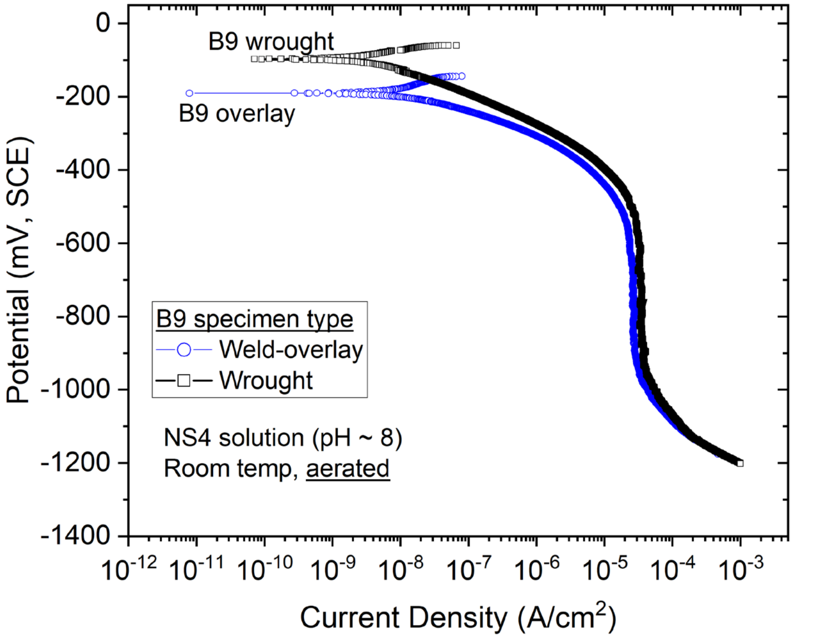


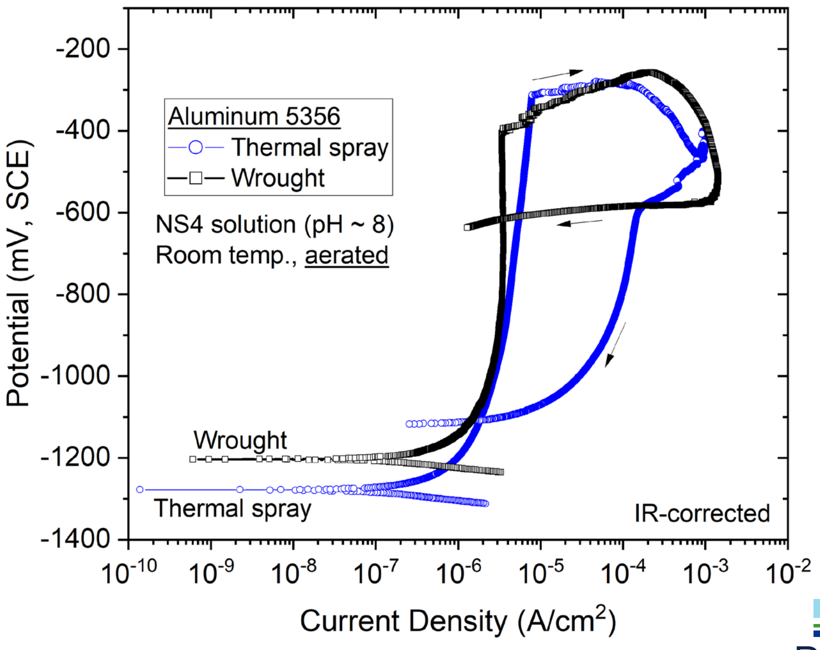




Initial Laboratory Test Results

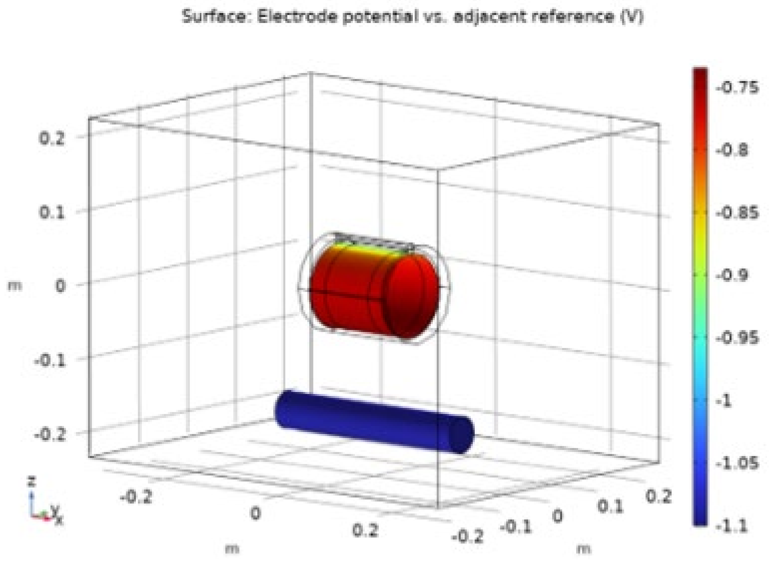
- Test results of aluminum 5356 and steel B9 samples were very similar to previous tests of the original wrought alloys
- Both coatings provided protection over a range of simulated soil conditions
  - Aluminum 5356 exhibited low corrosion rates in simulated soil conditions from pH 5 to pH 11, with breakdown of semi-protective film observed at pH 12.
  - Steel B9 coating exhibited low corrosion rates in aerated conditions as well as soil environments ranging from pH 5 to pH 8.

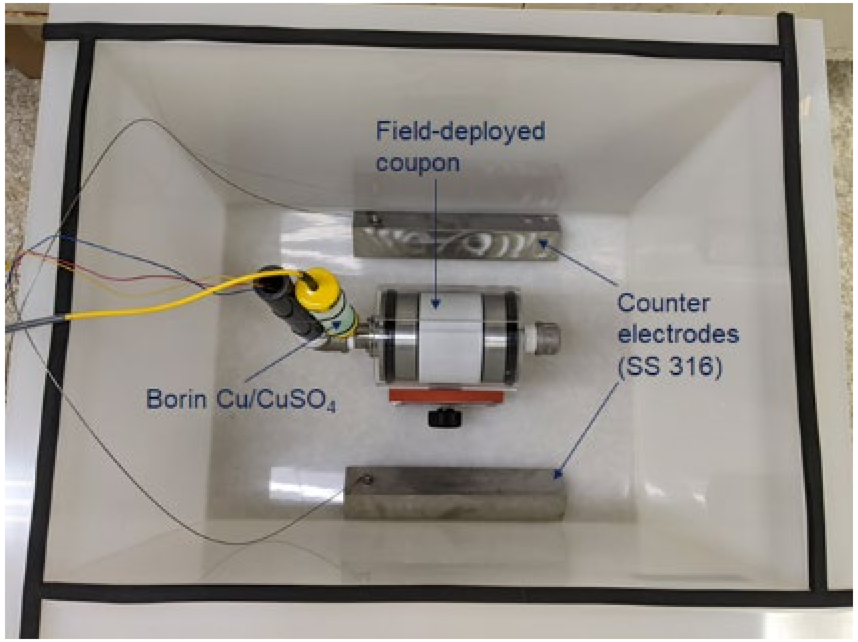


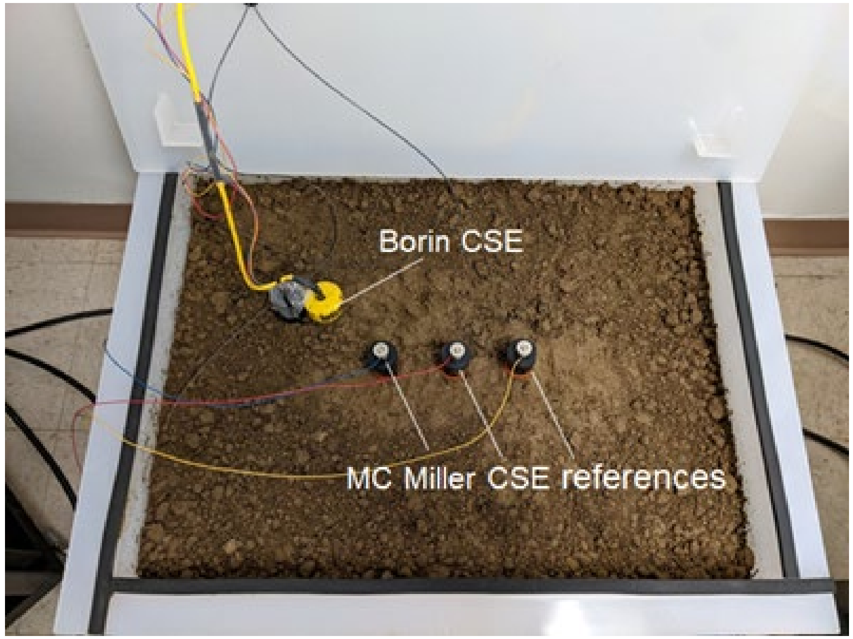


Soil Box Testing

- Primary objectives are to test design of coupon assembly (sealing, sleeve function, electrochemical response, etc.) and optimize procedures for field tests
- Measured corrosion rates, galvanic corrosion, and effects of CP on coupon behavior

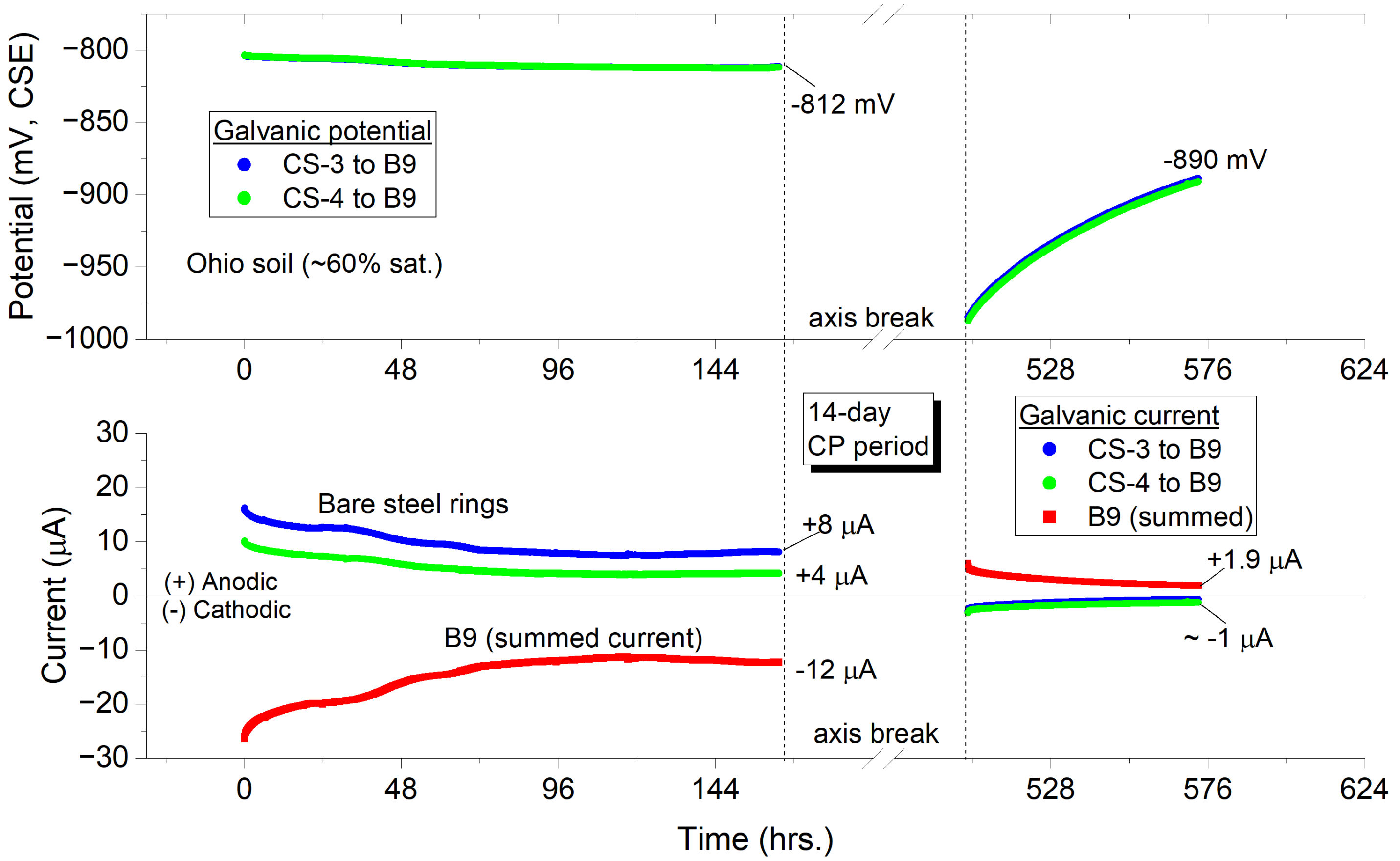






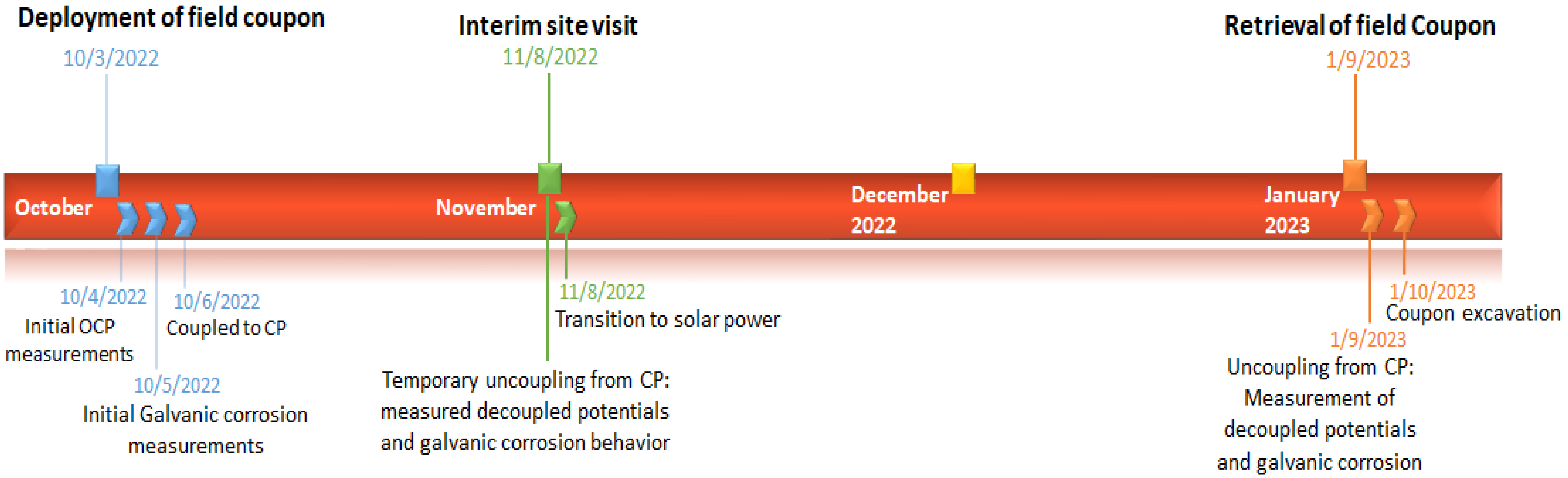
Soil Box Test Results

- Test coupon design was successful in capturing the complex conditions created by a disbonded coating
- Provided useful results to validate the fitness of the coupon design for field testing
- Demonstrated functionality and correlation with prior lab tests
- Cathodic protection (CP) did not worsen galvanic interactions in 14-day CP period

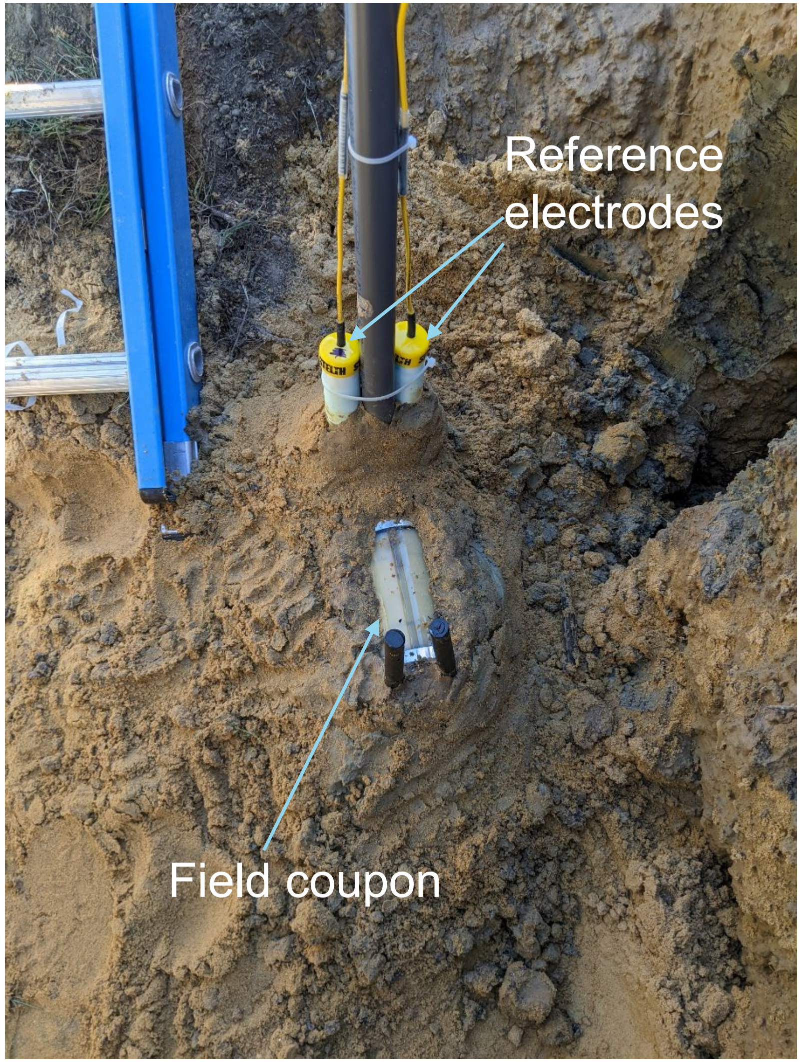


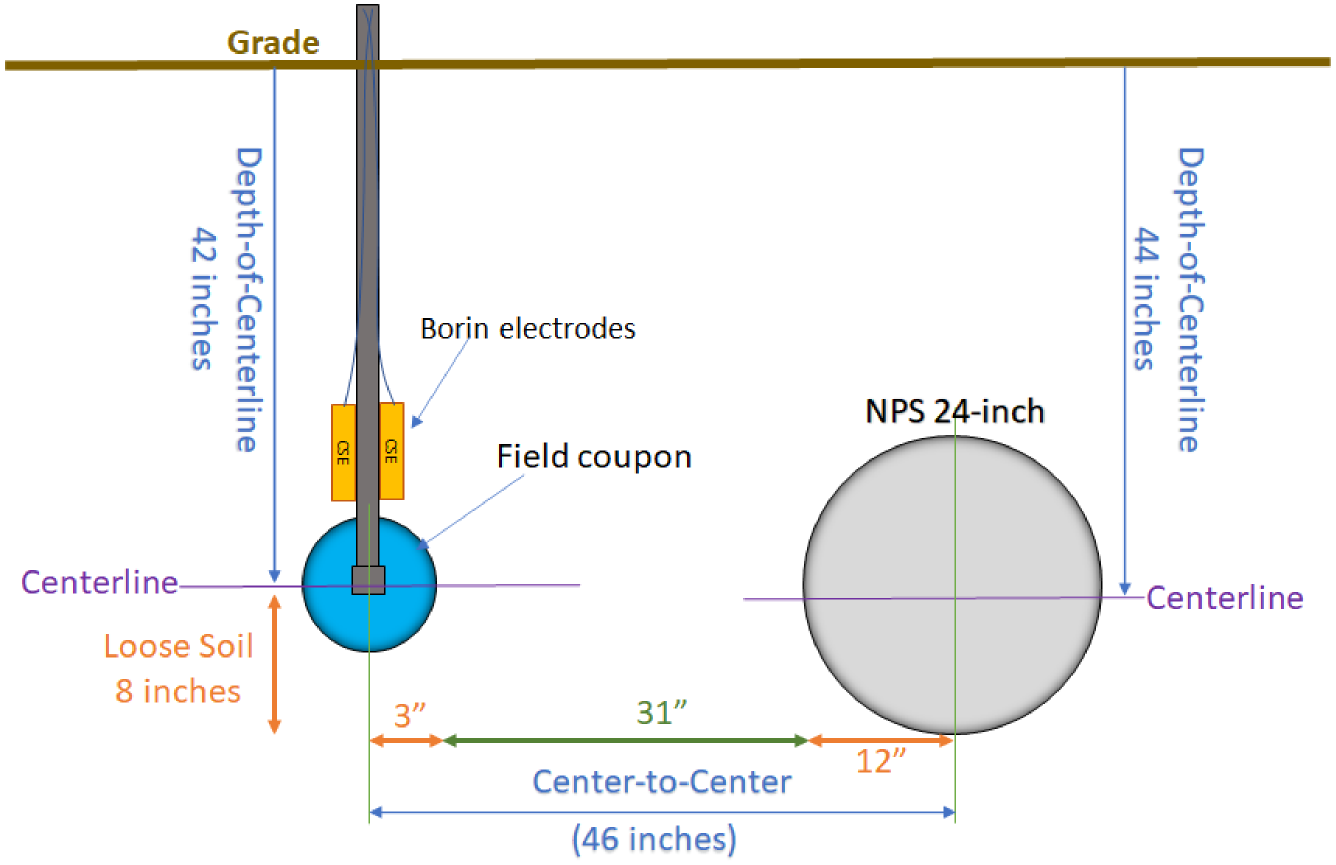
3-Month Pipeline Field Test

- Enbridge Huntsville Compressor Station, San Jacinto County, TX (70 miles North of Houston)
- Solar power installed at site initially resulted in inconsistent DC voltage supply



3-Month Field Test in Huntsville, TX





3-Month Field Test Results

- Overall results correlated with previous lab tests. Field variability in weather, soil, and CP conditions introduced additional factors to consider in the interpretation of the results.
- OCP data and initial galvanic current measurements were consistent with lab results obtained in Enbridge supplied soil.
- Heavy rains filling the coupon disbondment cavity and high CP levels may have raised the local pH around the coupons, which is being reviewed.

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Metric 1

FPC mitigates corrosion of steel under open circuit conditions (equivalent to cathodic protection shielded conditions)

Aluminum 5356: Yes	Coating provided anodic protection according to galvanic current measurements.
Steel B9: Yes	Coating exhibited very low corrosion rates and also acted as weak anode after CP was removed.

Metric 2

Good adhesion of FPC and the polymer top coating before and after exposure to soil conditions:

a) FPC has good adhesion, before and after exposure to soil conditions

FPC: Yes	Aluminum 5356: Flame-Spray Technologies successfully applied thermal spray coating to steel pipe sections Steel B9: Lincoln Electric successfully applied weld coating to pipe sections
Polymer Top Coating: Yes	Project team discussed and initial observations support coating has good adhesion. Tests to confirm are planned for BP3

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Metric 3

The monitoring electrodes have satisfactory performance for over 3 months

Yes	Field monitoring was successful for the 3- month test. Custom zero-resistance ammeter (ZRA) equipment was constructed for field use, Electrical box panel was created for configuring coupons with measuring and data recording equipment.

Metric 4

Complete laboratory and 3-month field tests and report results

Task 3: Yes	Laboratory electrochemical testing of alloy candidates (sacrificial - aluminum 4043 & 5356, corrosion resistant – steel B2, B3, B9) were completed, where 5356 & B9 were selected
Task 4: Yes	3-month testing of field coupon in laboratory soil box & pipeline compressor station field site were completed

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Metric 5

Select pipeline field site & install field-deployed coupon

Yes	Field deployed coupon was successfully installed and tested for 3 months at Enbridge compressor station site in Huntsville, Texas. Installation included electrical box panel, wiring, monitoring devices, and solar power.

6-Month Pipeline Field Tests

- Started November 2023 at Enbridge pipeline sites in:
  - Huntsville, San Jacinto County, TX (70 miles North of Houston)
  - Gladeville, TN (30 miles east of Nashville)
- Aluminum 5356 and steel B9 test coupons
  - Segmented (same as 3-month test)
  - Unsegmented coupons (2-part epoxy, polyethylene tape) w/coating defects
- Improve power reliability for field measurements
- Measurements: Open circuit potential, on-potential, and galvanic corrosion using dual ZRA configuration

Test Coupons for 6-Month Pipeline Field Tests

Coupon external coating	FPC alloy	Cathodic Protection	Test Location	
			Texas	Tennessee
1. Segmented with acrylic sleeve	Al	Yes	X	
2. Segmented with acrylic sleeve	B9	Yes	X	
3. Polyethylene tape coating	Al	Yes	X	X
4. Polyethylene tape coating	B9	Yes	X	X
5. 2-part epoxy	Al	Yes	X	X
6. 2-part epoxy	B9	Yes	X	X
7. 2-part epoxy	Al	No	X	X
8. 2-part epoxy	B9	No	X	X

6-Month Test Installation at Pipeline Field Sites

TX

TX

TN

Future Project Plans

- Complete 6-month field tests in TN, TX. Analyze and report results.
- Complete coating disbondment tests
- Draft Guidance Report for application and technology transfer to industry
- Presentation at International Pipeline Conference (ASME), Calgary 9/2024
- Project close 8/31/2024

Questions?

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Appendix

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Project Organizational Chart

Cost Share Partners:
Enbridge
Lincoln Electric

Lead Organization:
DNV
Principal Investigator:
Kenneth Lee

Project Advisors:
Neil Thompson, Ph.D.
Narasi Sridhar, Ph.D.
(MC Consult LLC)

Task 1
Project Management
Lead
Kenneth Lee

Task 2
Optimization of Coating Composition
Lead
Chris Taylor, Ph.D.

Task 3
Laboratory Testing of Coated Samples
Lead
Ken Evans

Task 4
3-month Lab & Field Coupon Testing
Lead
Jason Land & Ken Evans

Task 5
6-month Field Coupon Testing
Lead
Jason Land

Task 6
Guidance Document
Lead
Kenneth Lee

BUDGET PERIOD 1 (Tasks 1–2) BUDGET PERIOD 2 (Tasks 3–4) BUDGET PERIOD 3 (Tasks 5–6)

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Project Schedule

	9/1/2021				9/1/2022				3/1/2023			
	Budget Period 1				**Budget Period 2**				**Budget Period 3**			
Task	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7-8**	**Q9-10**	**Q11-12**	**Q13-14**	**Q15**	**Q16**
Task 1.0 Project management & planning							6-mo. NCTE		6-mo. NCTE			
1.1 Project management plan												
1.2 Technology maturation plan												
Task 2.0 Optimization of coating composition												
2.1 Modeling of FPC alloy corrosion												
2.2 Testing of alloy compositions												
Task 3.0 Lab testing of coated samples												
Task 4.0 Fabricate & 3-mo. test of FPC coupons												
Task 5.0 Field test 6-mo. of FPC coupons at 2 sites												
Task 6.0 Guidance Report												

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