Pipeline Materials Technologies for Mitigating Corrosion, Methane Emissions, and Hydrogen Embrittlement

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Acknowledgements

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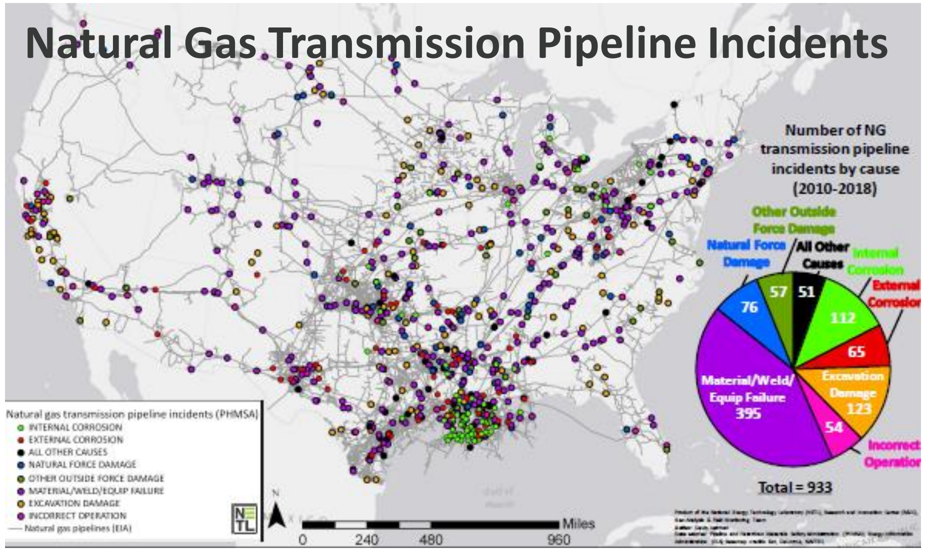
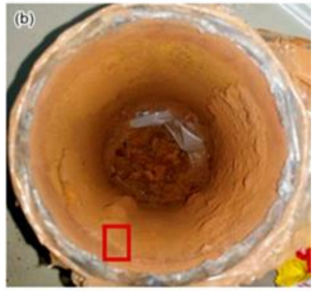
Disclaimer

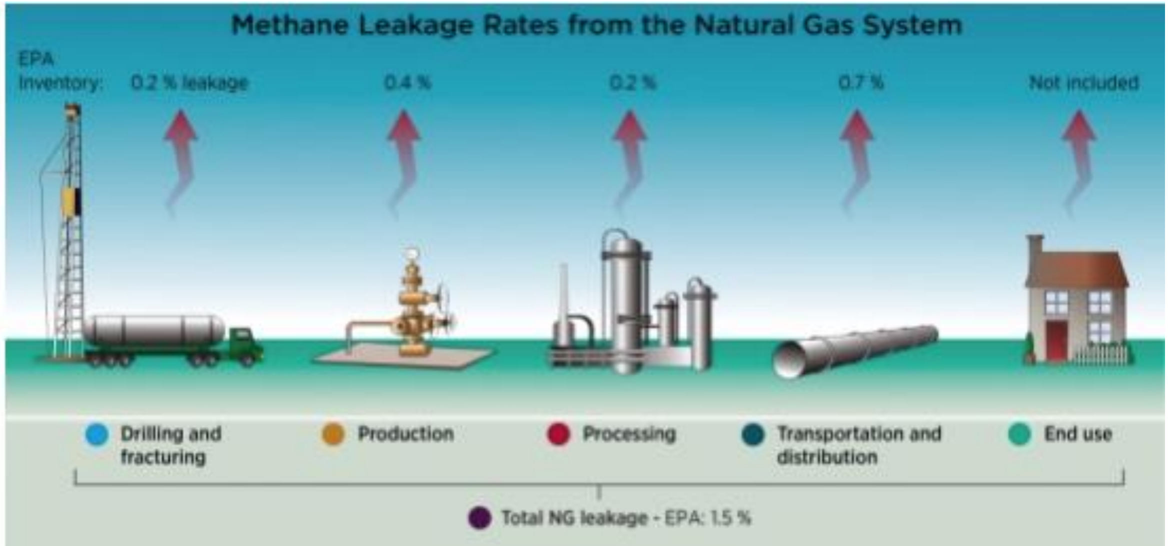
Natural Gas Infrastructure – Materials Challenges



Justman, Rose & Bauer, NETL, 2017. Data analyzed from U.S. DOT PHMSA incident data

Internal corrosion





https://www.news.ucsb.edu/2014/013953/americas-leaky-natural-gas-system-needs-fix

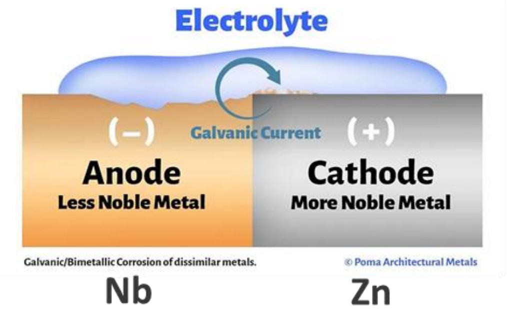
- **Methane emissions**
- **Internal corrosion**

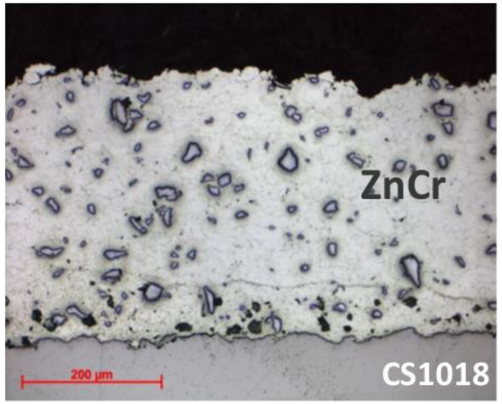
- **Cost-effective refurbishment of in-service pipes**

- **Hydrogen compatibility**
- **Remote monitoring**

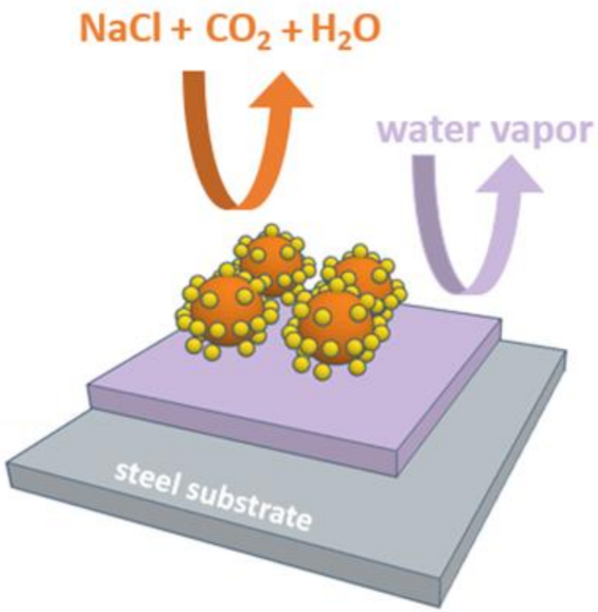
Mitigation – NETL Approach

Self-Healing Metallic Coatings

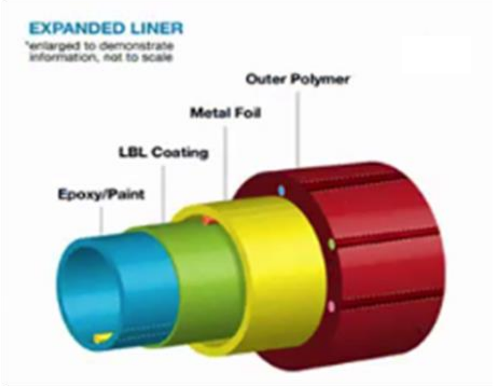


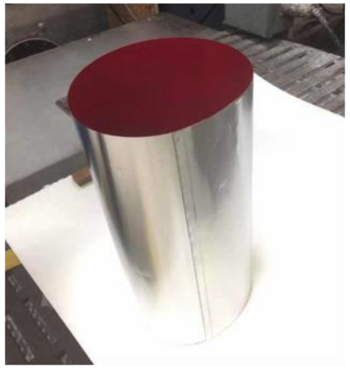


Superhydrophobic Anti-Corrosion Coatings



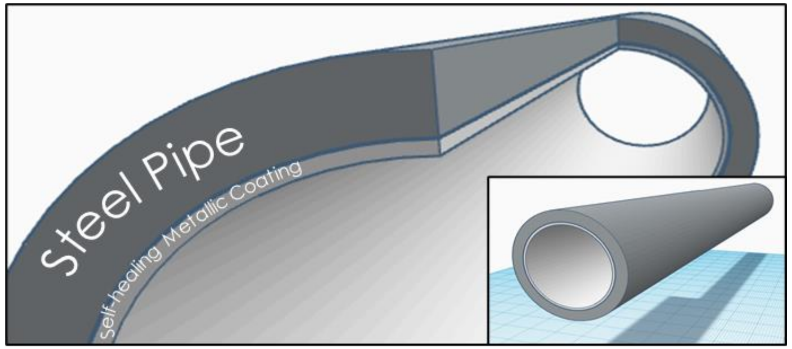
Composite Liners

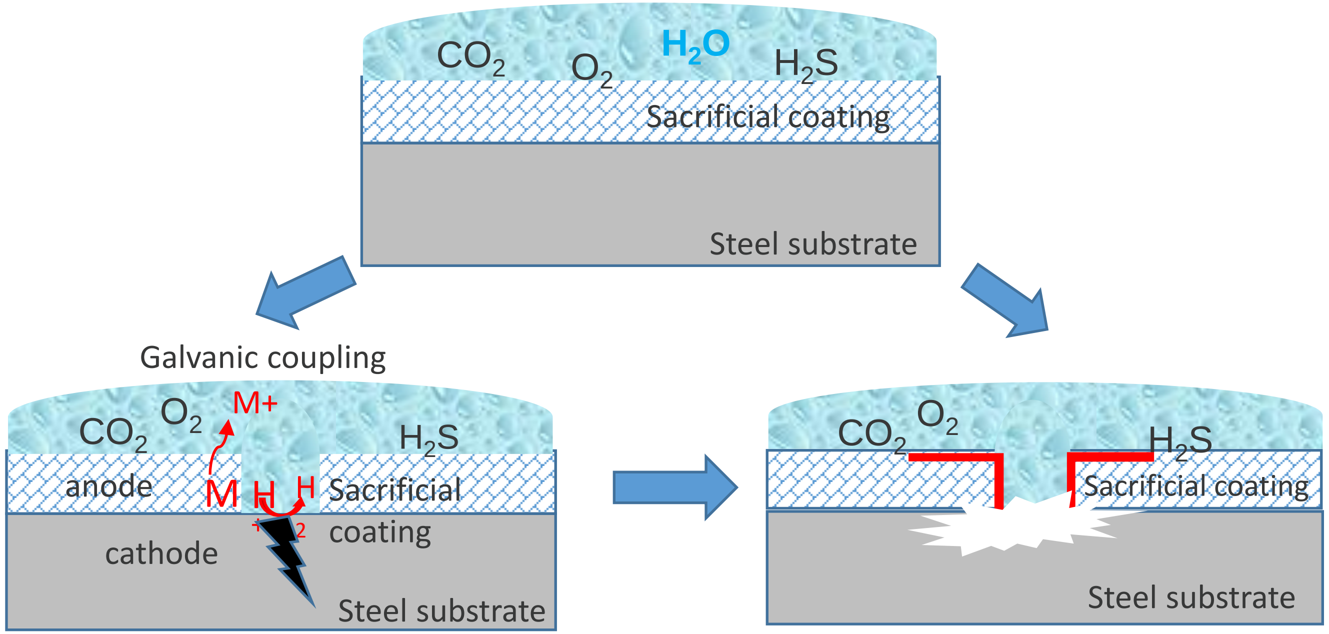




Self-Healing Metallic Coatings

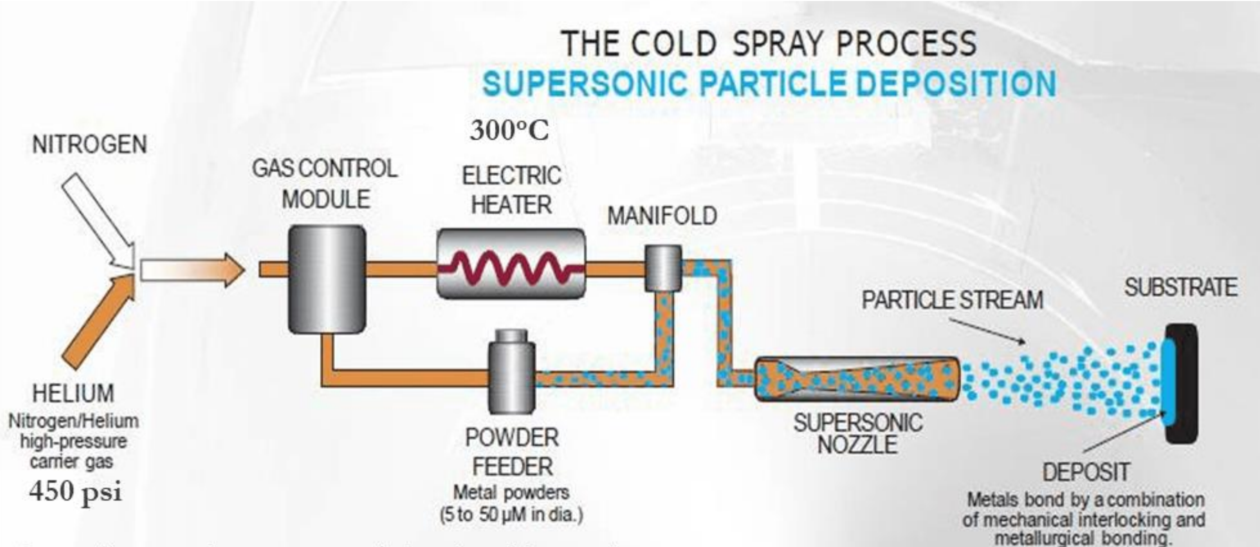
- Sacrificial coatings are used for corrosion protection.
- Zinc is a common sacrificial coating.
- However, Zn corrodes too fast in NG pipeline conditions.
- Can we slow Zn corrosion inside NG pipelines?
- Can we form *micro galvanic cells* to control Zn corrosion?



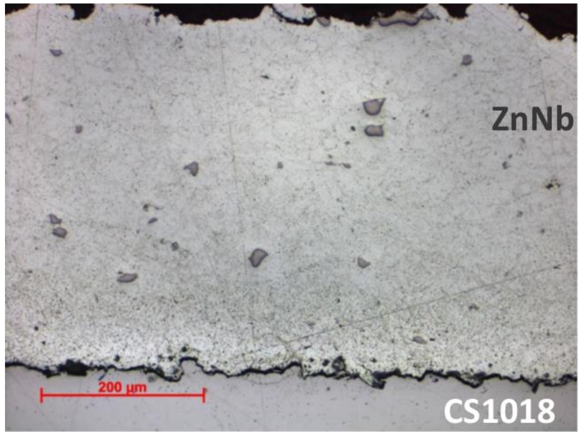


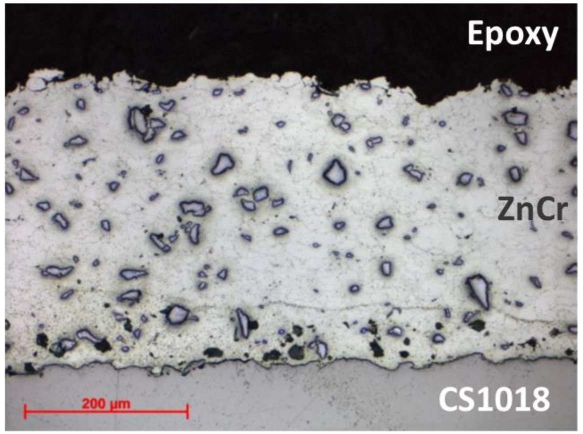
Self-Healing Metallic Coatings

Cold Spray Coating Technology



https://vrcmetalsystems.com/what-is-cold-spray/





Coatings	Thickness (µm)	Porosity (%)
ZnNb	428 ± 5.1	≈ 0.32 ± 0.13
ZnCr	304 ± 7.0	≈ 0.5 ± 0.28

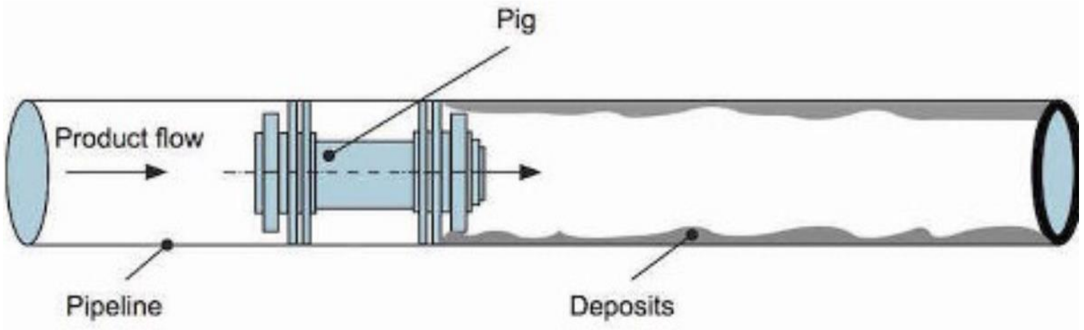
Self-Healing Metallic Coatings - Mechanical Testing

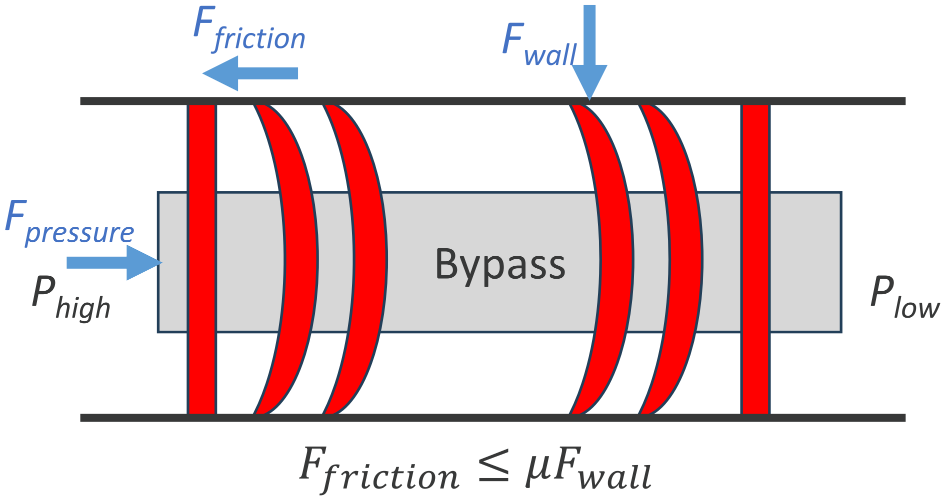
Forces imparted by pigging on cold-sprayed self-healing coatings

- Most forces on coatings during the pigging process will be:
  - Wall (compressive)
  - Friction (shear)
- Testing for shear adhesion and wear properties will determine the viability of these coatings to mechanical pigging.

$$\tau = \frac{P_{max}}{A}\ [MPa]\ \text{(PSI)}$$

$$\text{wear} = \frac{CW_x}{\rho S_x}\left[{mm^3}/{Nm}\right]$$

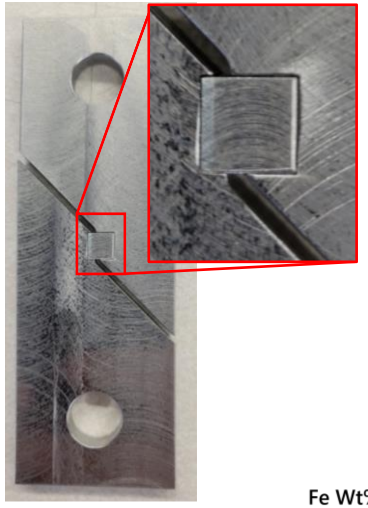


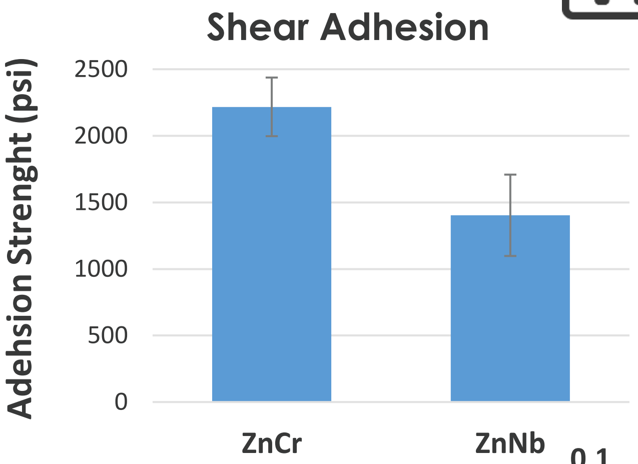


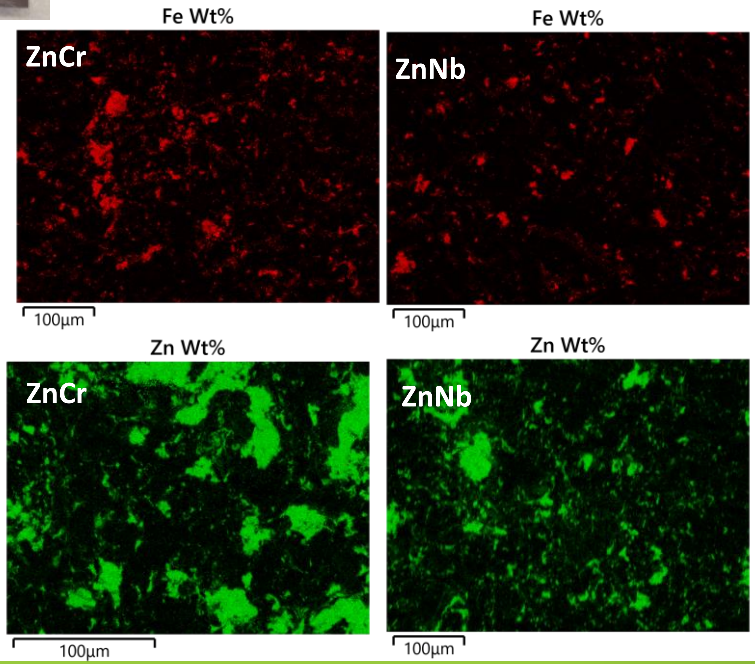
Self-Healing Metallic Coatings

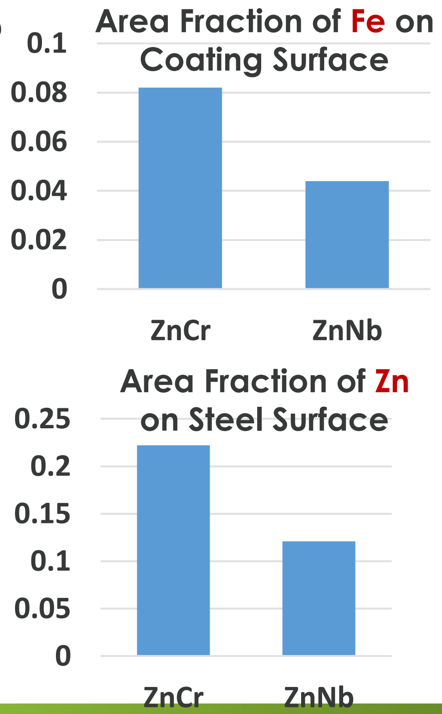
Shear Adhesion Testing

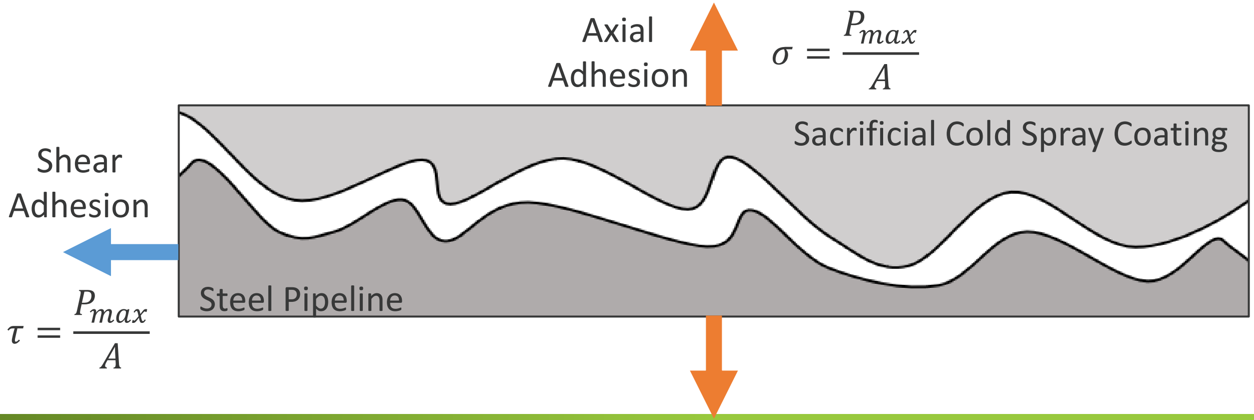
- Most forces on coatings during the pigging process will be friction (shear).
- Shear testing clevises were fabricated, and results were tabulated for both maximum shear strength (modified ASTM B 831).
- Fracture surfaces were imaged for elemental composition on both fracture surfaces.
- Shear adhesion appears to correlate with area fraction of elements left on opposing surfaces.
- Shear adhesion and axial adhesion measurements were not correlated.











$$\sigma = \frac{P_{max}}{A}$$

$$\tau = \frac{P_{max}}{A}$$

Self-Healing Metallic Coatings

NATIONAL ENERGY TECHNOLOGY LABORATORY

Pin-on-Drum Wear Test

- Wear properties of the zinc cold spray coatings is similar though slightly higher than pure zinc.
- The wear rate of zinc and the zinc cold spray coatings is approximately three times that of the underlying X65 pipeline material.

$$\text{wear} = \frac{CW_x}{\rho S_x}\left[{}^{mm^3}/_{Nm}\right]$$

where:

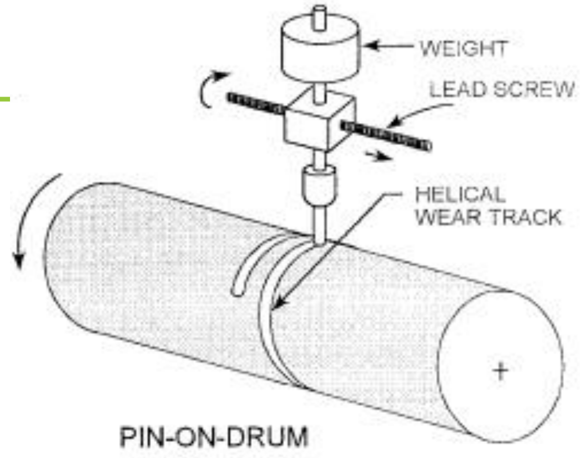
$W_x =$ mass loss of the test specimen

$S_x =$ mass loss of the reference specimen

$\rho =$ density of the test specimen, known or measured to three sig figs g/cm^3 (mg/mm^3)

$C =$ reference constant equal to the mean mass loss (mg) of the reference pin per unit track length (m) per unit load (N), for the abrasive type and test parameters used. (The ratio C:S_x functions as a normalizing factor).

The value of the constant C for a given reference material and abrasive is determined from a large number of tests, preferably in several machines and/or locations

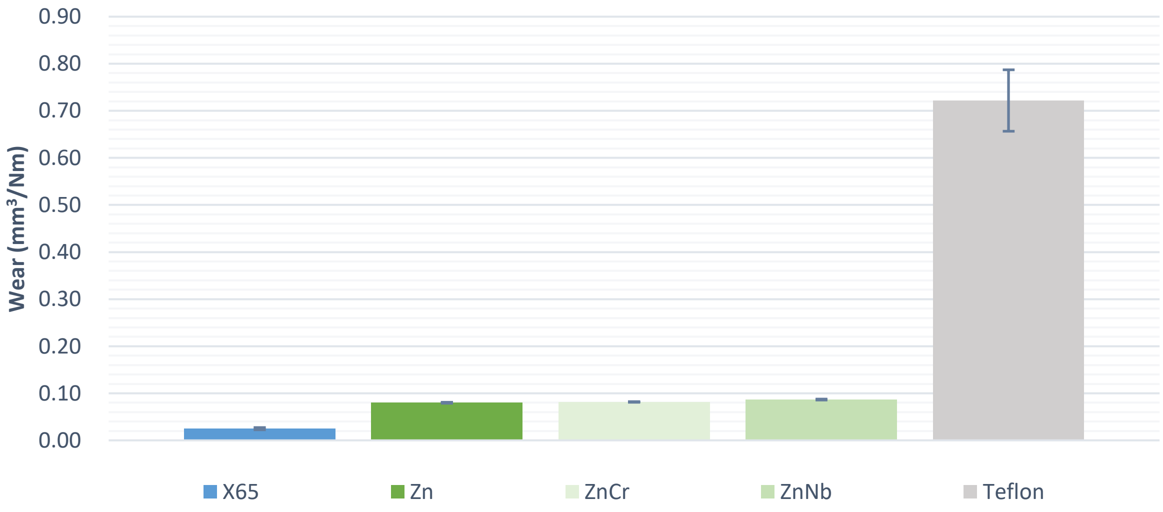


PIN-ON-DRUM

ASTM G 132

Testing Conditions

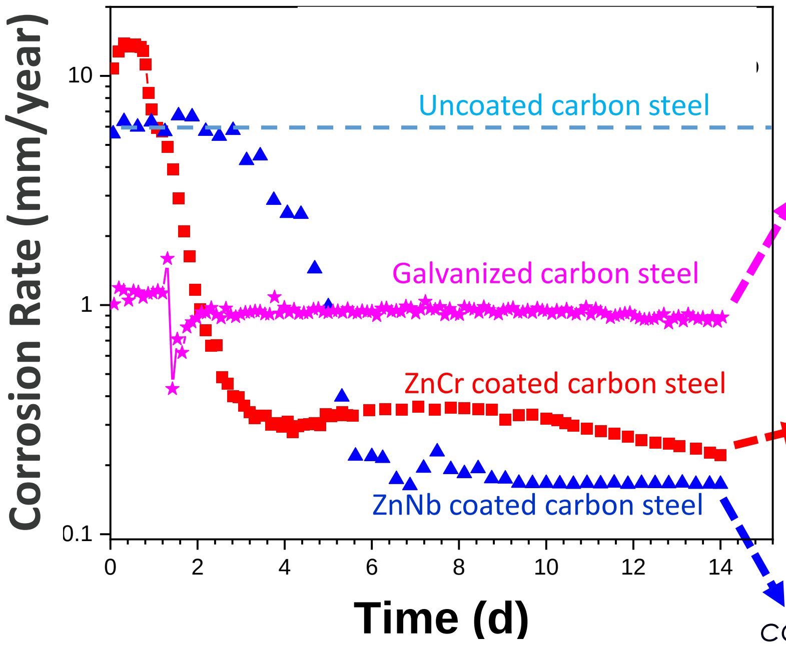
Abrasive	Force, N	distance, m
150 grit SiC	65.47	3.2



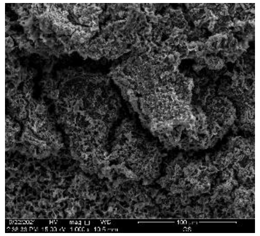
Self-Healing Metallic Coatings

✓ *Laboratory corrosion test*

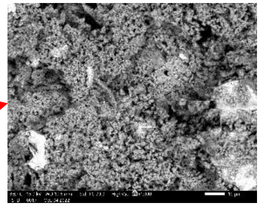
p_{CO2} = 4 bar, T=40 °C, 3.5 wt% NaCl



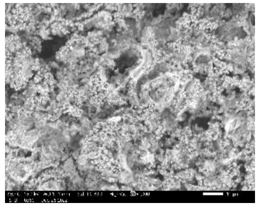
Galvanized steel



Carbon steel coated with ZnCr

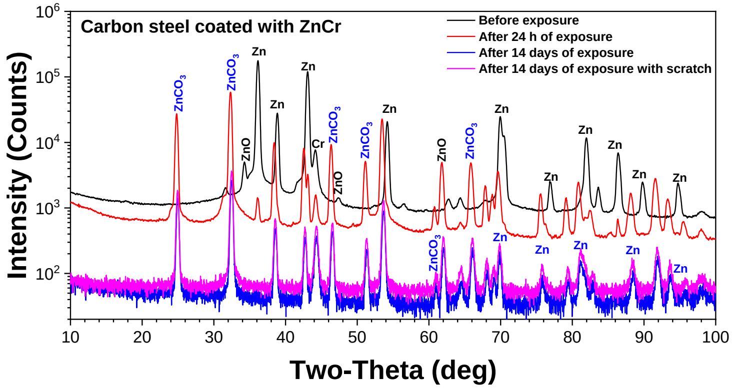


Carbon steel coated with ZnNb

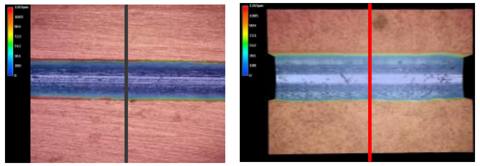


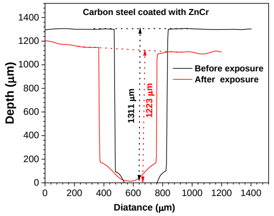
Z. Belarbi et al., , "Binary Sacrificial Coatings for Internal Corrosion Protection of Natural Gas Transmission Pipelines,," in ECS Meeting Abstracts MA2022-01-0686. , 2022.

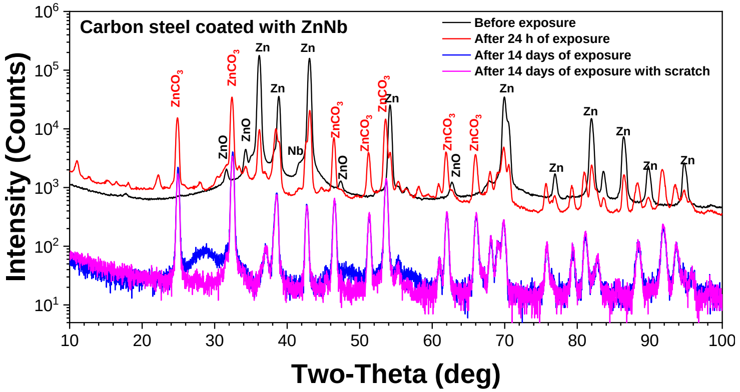
✓ *Self-healing properties*



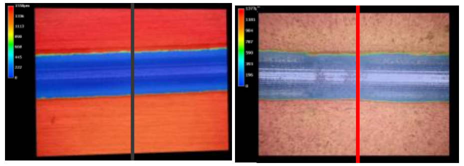
Before exposure | After 14 days of exposure

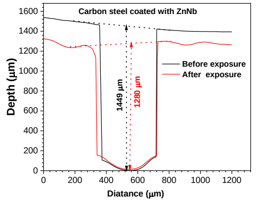






Before exposure | After 14 days of exposure

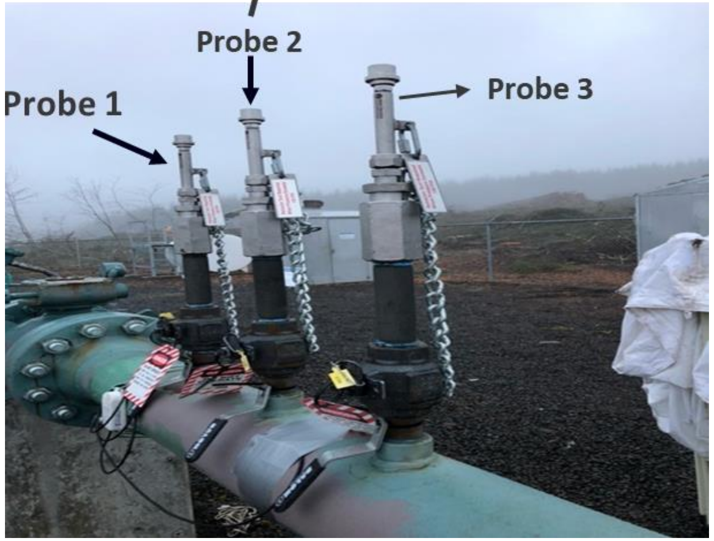


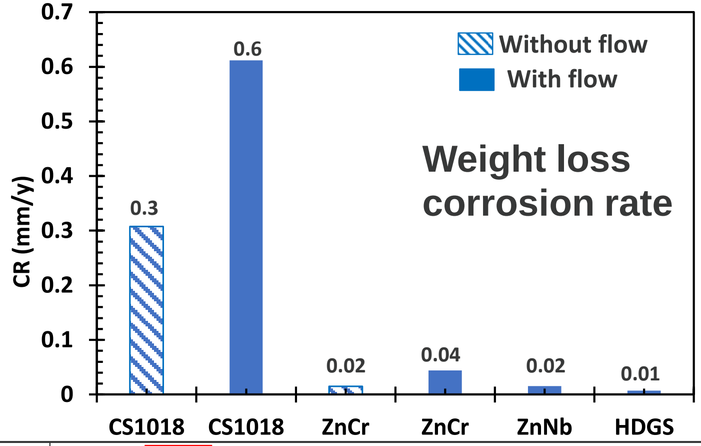


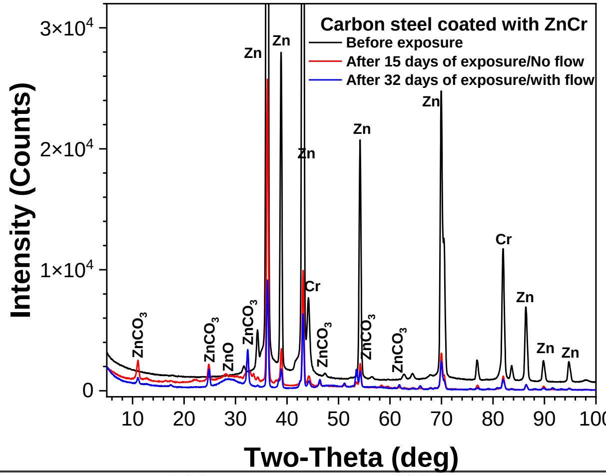
Self-Healing Metallic Coatings – Coated Coupons in Pipeline

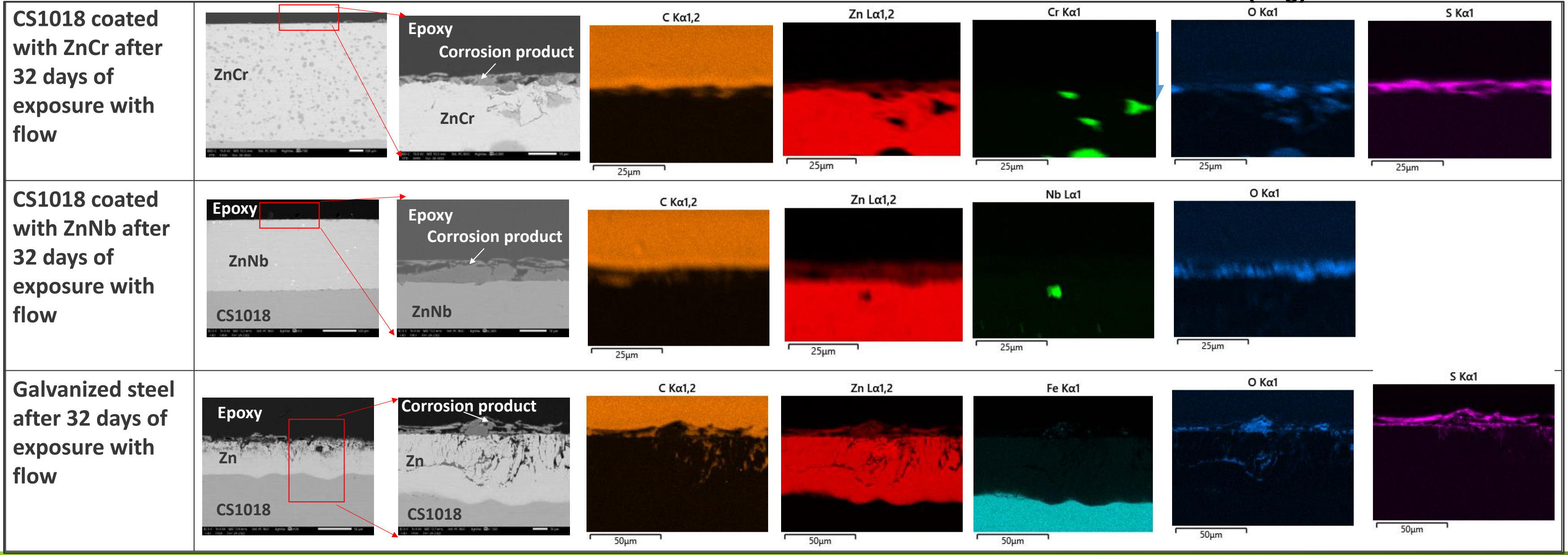
Field Test at NW Natural Gas Storage Facility - TRL 5

Probes removed after 32 days of exposure to natural gas under flow





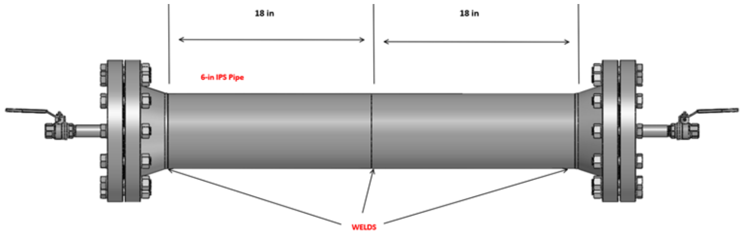




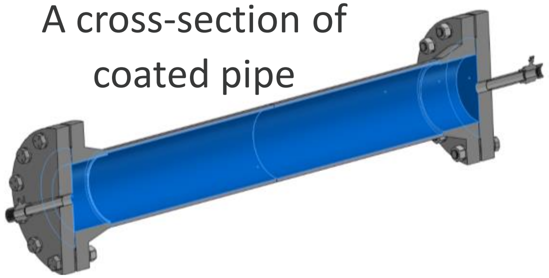
Z. Belarbi, et al., "Field Testing of Self-Healing Metallic Coatings for Internal Corrosion Protection of Natural Gas Pipelines," in AMPP 2023, paper no 18857.

Self-Healing Metallic Coatings – Coated Pipe Test (TRL 6)

A test section of uncoated pipe



A cross-section of coated pipe

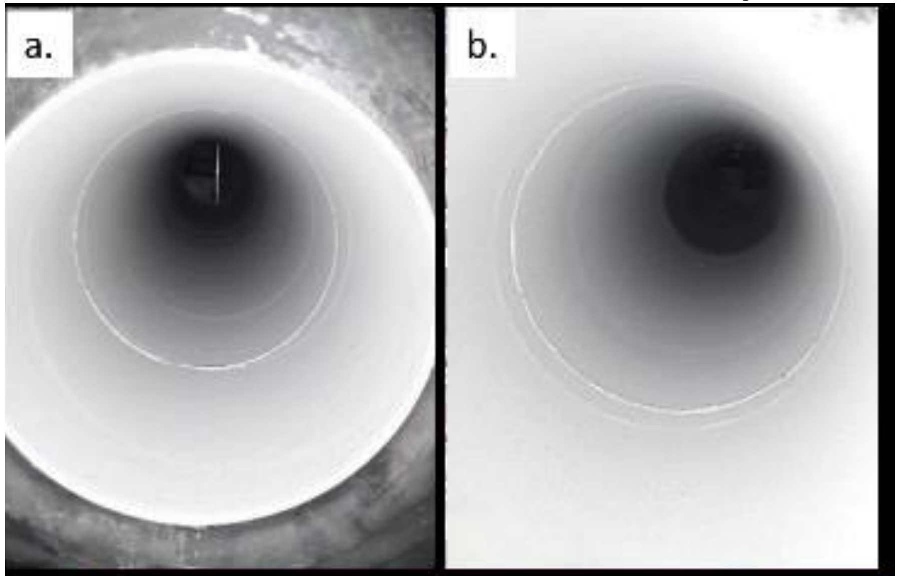


Field Test Parameters	Specification
Line pressure	500 psi to 1000 psi*
Flow Rate	Stagnant condition
Natural Gas Characteristics	Untreated (corrosive)
Test duration	90 days
Pipe diameter	6 inches
Pipe length	3 feet

Cold spray setup at VRC Metal Systems

Pipe inner surface with Zn-Cr top-coat

Pipe inner surface with Zn-Nb top-coat



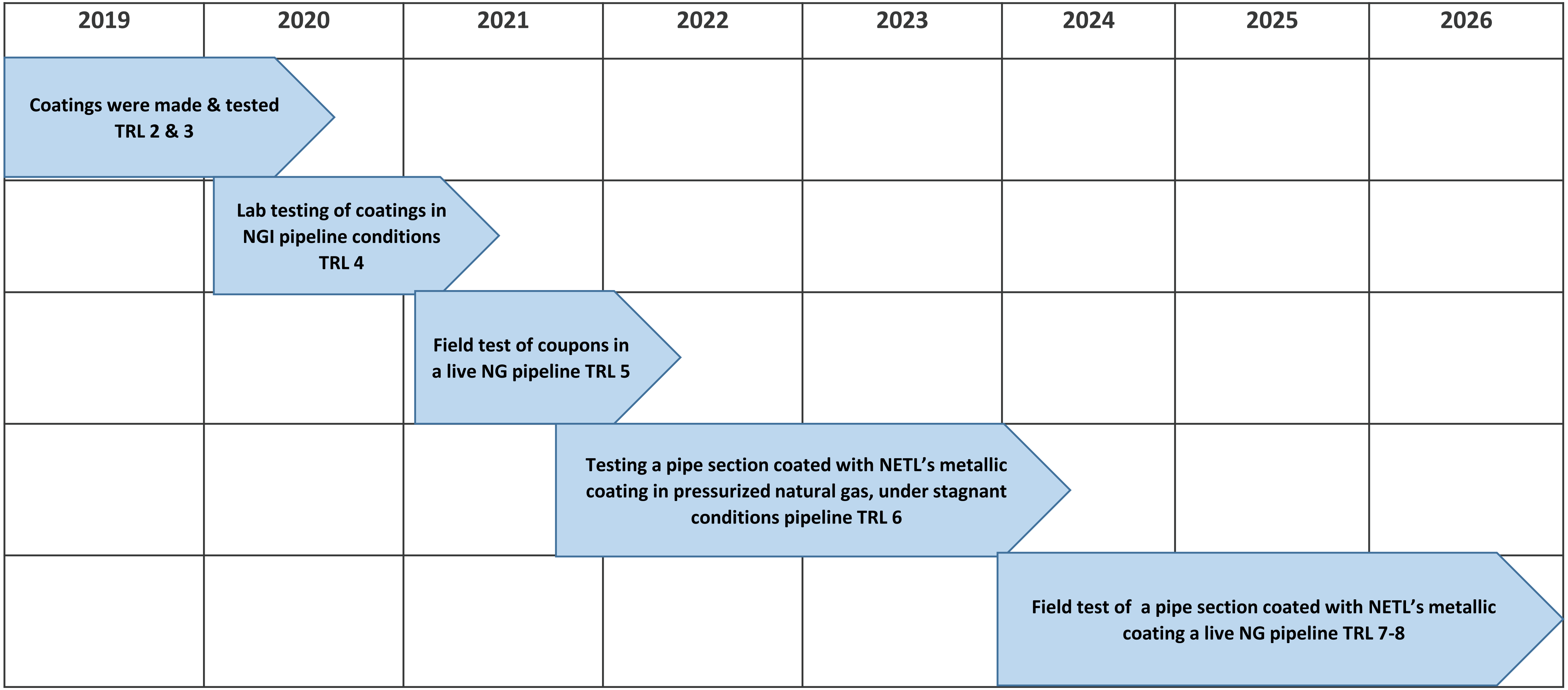
c.

Initial Diameter (In.)	Final Diamter (In.)	Deposition/ Layer (In.)	Total Deposition (In.)	Target Deposition (In.)
6.048	5.998	0.0017	0.025	0.012-0.016
6.048	6.02	0.0016	0.014	0.012-0.016

Field Test at NW Natural Gas Company:
Gas Being Injected Into Test Sample Pipe (right of pipe - Red Hose) to Purge of Air. Verification of 100% Gas on Vertical Vent Pipe with Gas Detector (left of pipe), Indicating Air Purged.

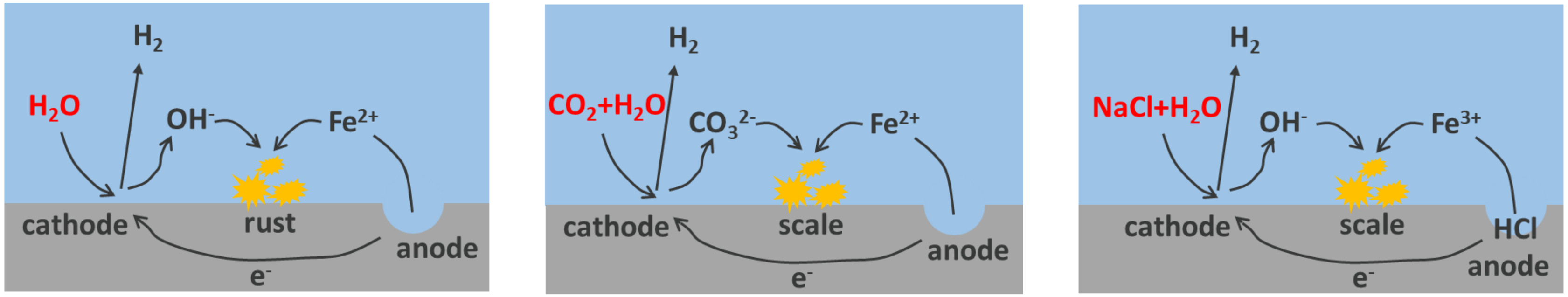
Self-Healing Metallic Coatings

TRL Evaluation & Timeline



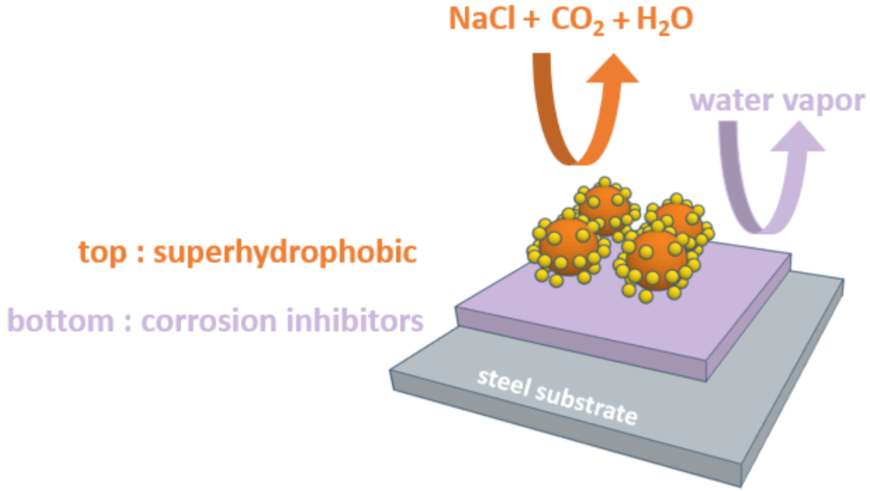
Superhydrophobic Anti-Corrosion Coatings

Three major corrosive species: H_2O, CO_2, and NaCl



To the best of our knowledge, no existing material can handle all three corrosive species at once.

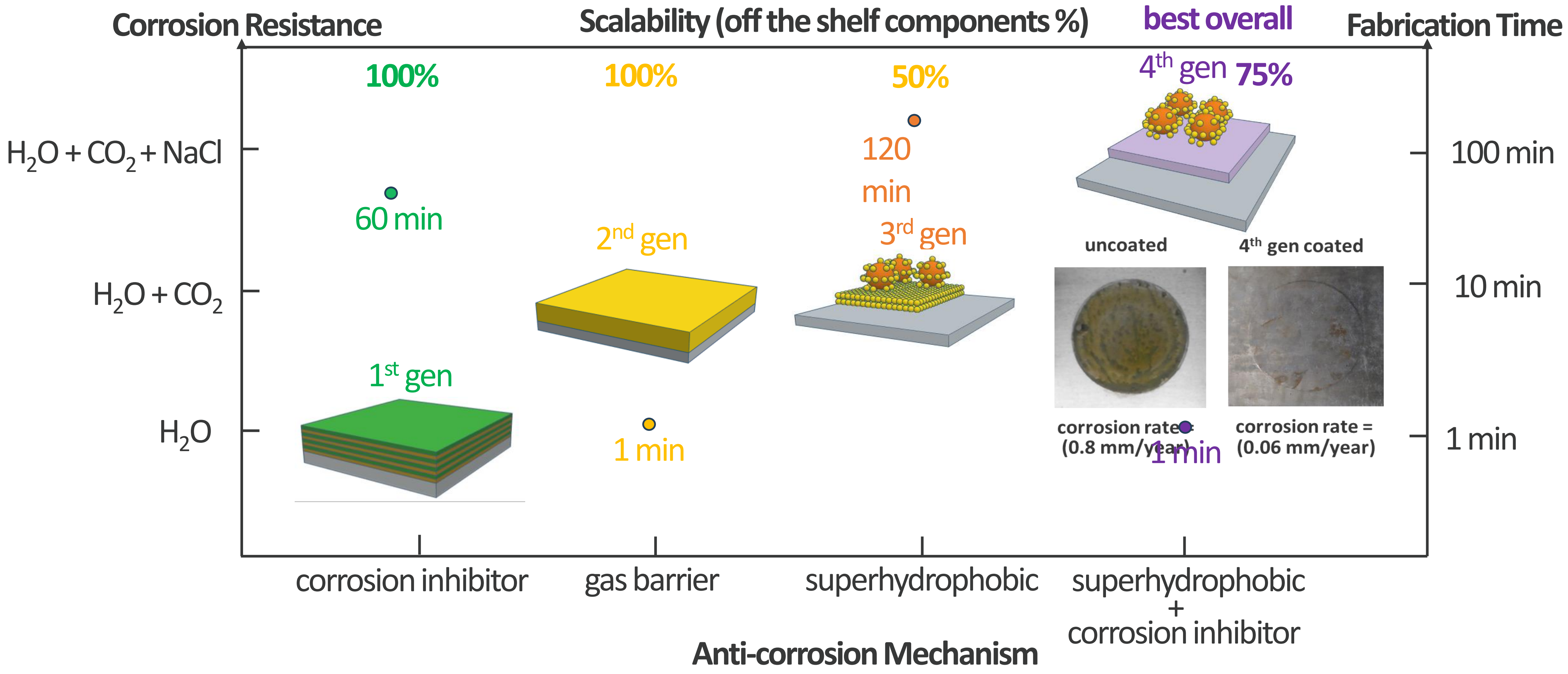
A multilayer coating was developed, with each layer tackling a specific set of corrosive species.



Superhydrophobic Anti-Corrosion Coatings

NATIONAL ENERGY TECHNOLOGY LABORATORY

Evolution of anti-corrosion coatings developed by NETL

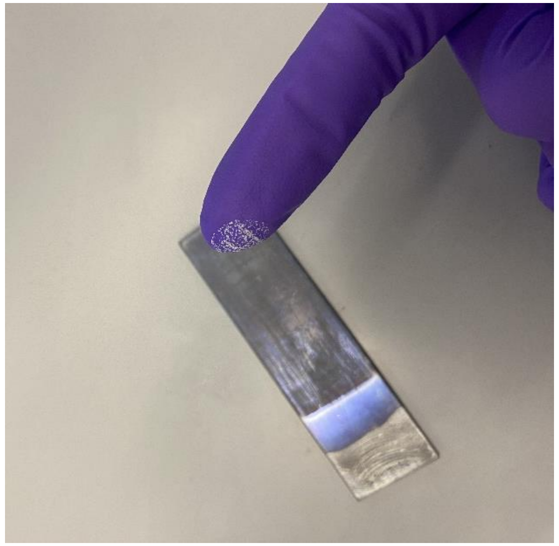


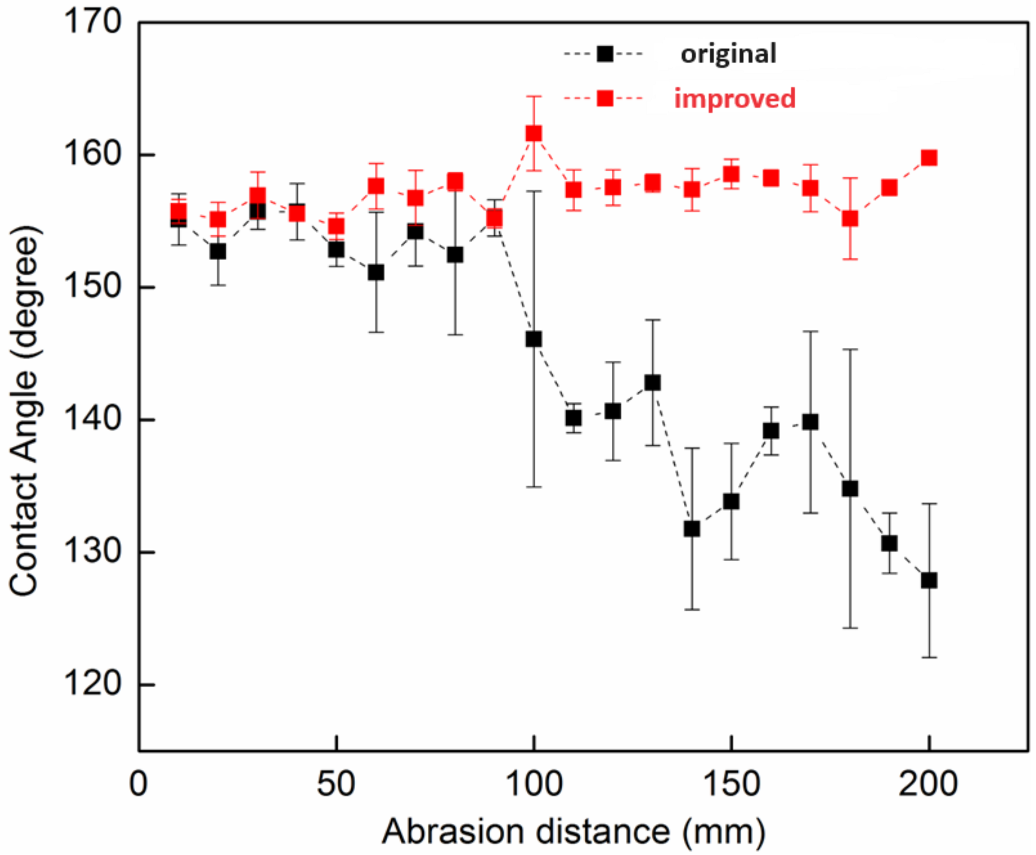
Superhydrophobic Anti-Corrosion Coatings

Improve mechanical property

Improving mechanical property without lowering hydrophobicity (contact angle), which can be critical for surviving the field test.

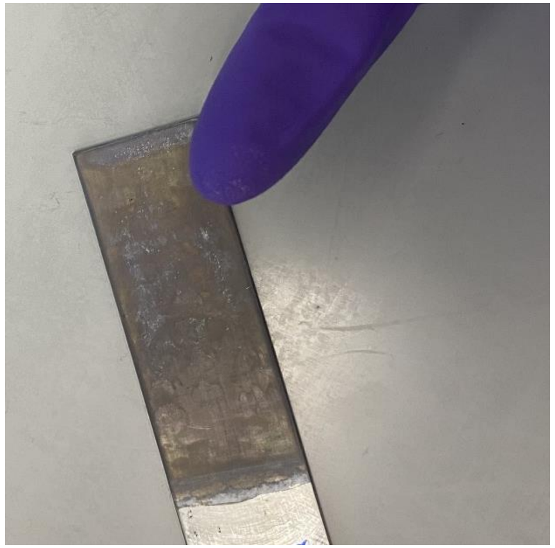
original





dragged across a 600 grit sand paper over different distance

improved

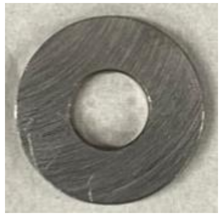


Superhydrophobic Anti-Corrosion Coatings

Field test sample preparation and installation

X65 steel washers were prepared using the new recipe with improved mechanical property.

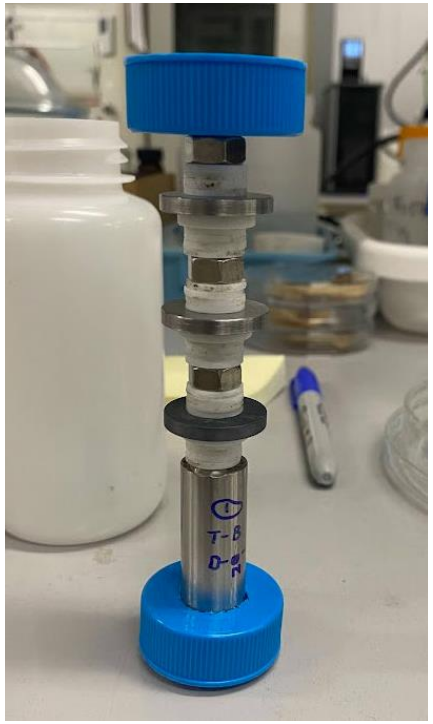
bare steel



primed

coated

load on sample holder



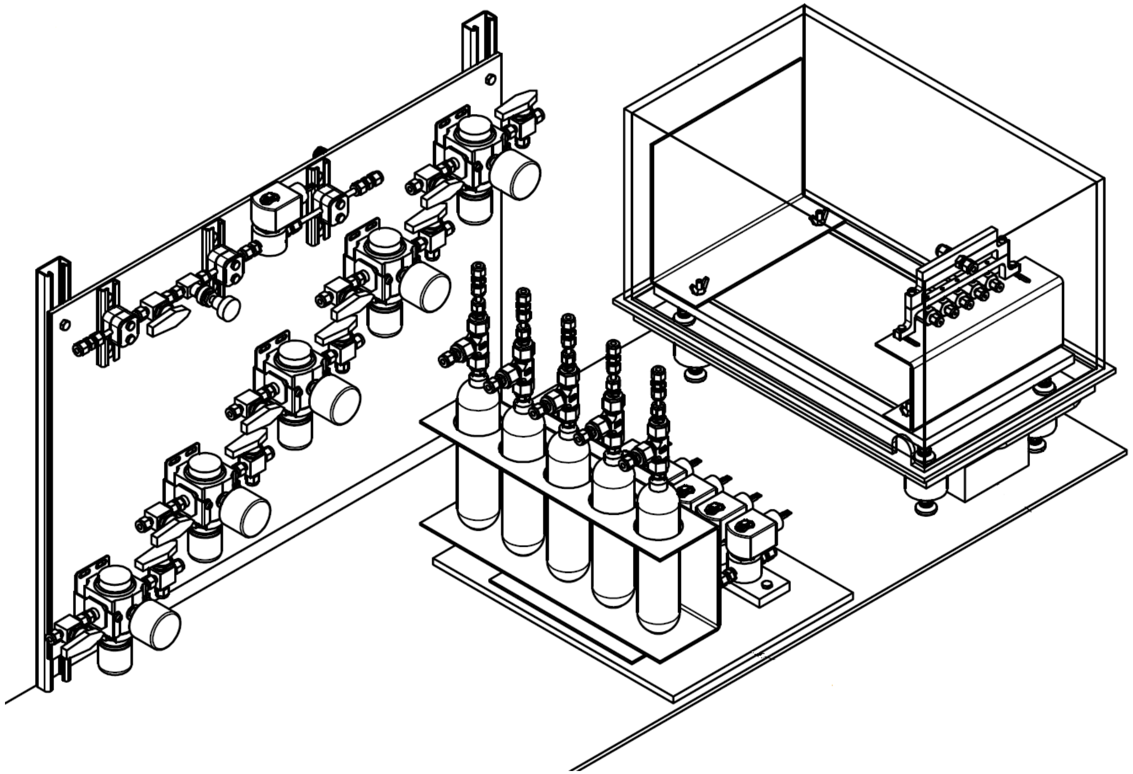
installation

NW Natural Gas Company

Superhydrophobic Anti-Corrosion Coatings

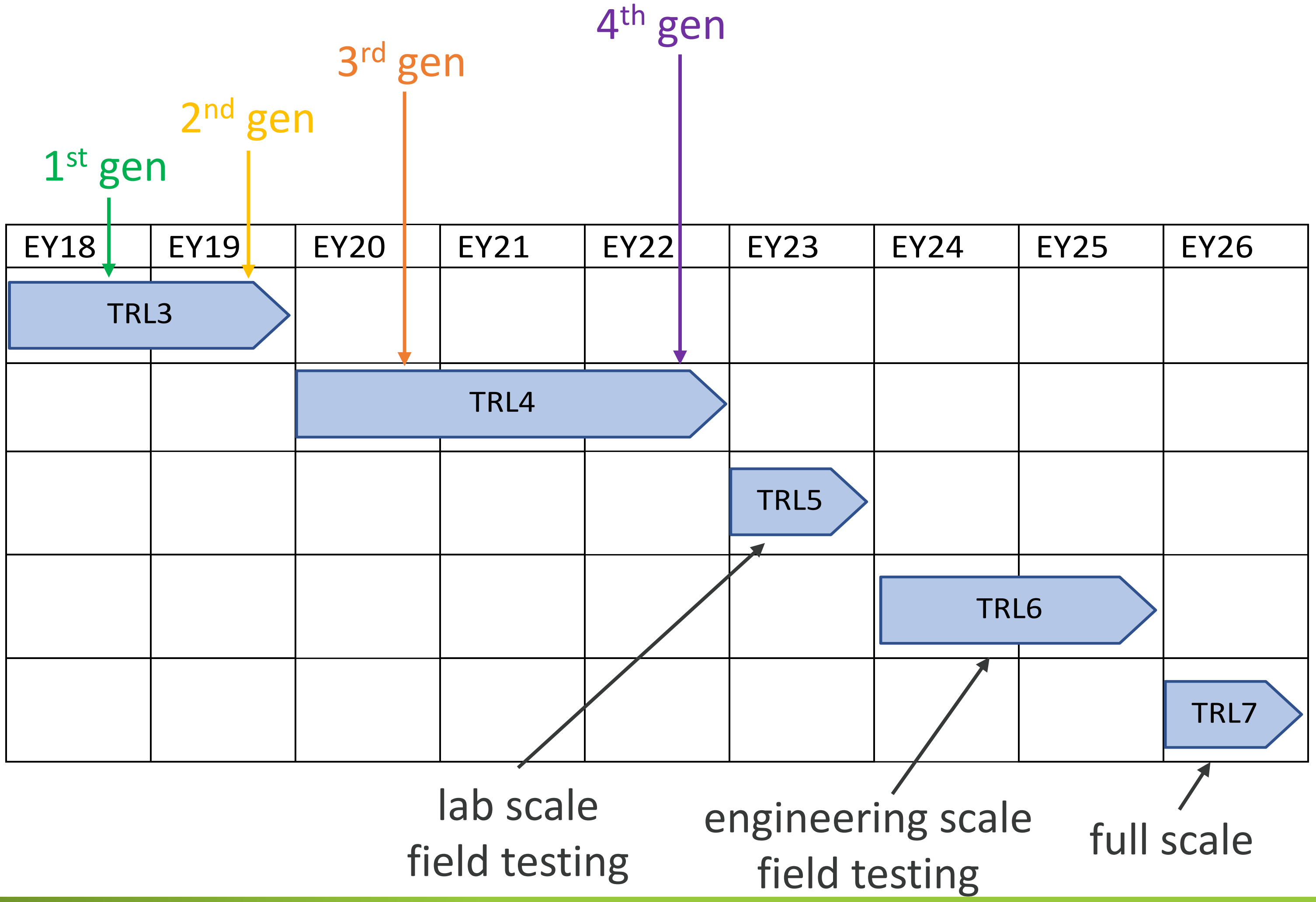
Automation

A multi-head spraying system was commissioned to automate the fabrication process and improve reproducibility.



The development in coating composition and fabrication process could further improve scalability.

Conclusions and future plan



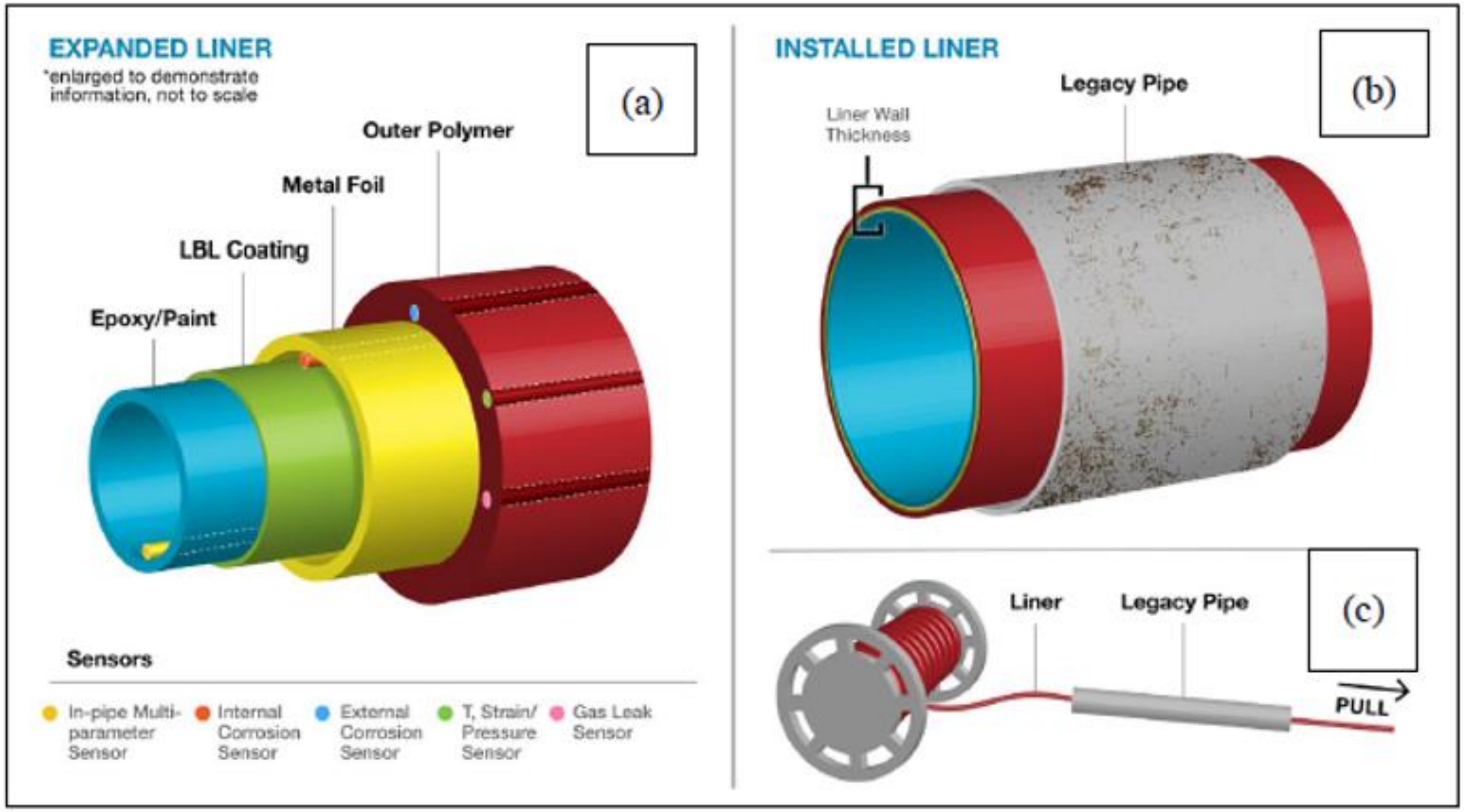
Expected Completion Date	Milestone Description
09/30/2020	Complete fabrication and corrosion testing of at least two steel coupons with defect-free multilayer coatings.
03/31/2021	Demonstrate a defect-free, corrosion resistant multilayer coating under continuous CO_2 bubbling.
03/31/2022	Demonstrate a multilayer superhydrophobic corrosion-protective coating that can reduce the corrosion rate of carbon steel (API 5L X65 grade) to < 0.1 mm/year under realistic conditions in the laboratory .
09/30/2024	Demonstrate a coated sample that can reduce the corrosion rate of carbon steel (API 5L X65 grade) to < 0.01 mm/year in a live natural gas pipeline.

Passed the internal invention review board; filing a patent application

Goal: simple, scalable, strong, and cost effective

Composite liner for mitigating pipeline corrosion and gas permeation

Liner prototype development with collaborators – Progress and ongoing efforts

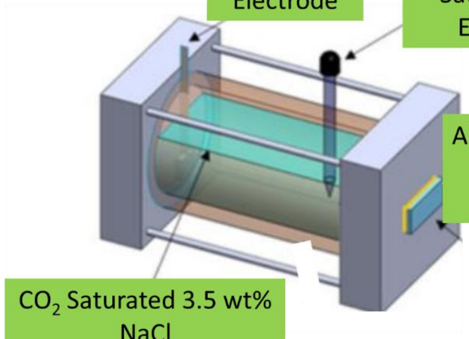


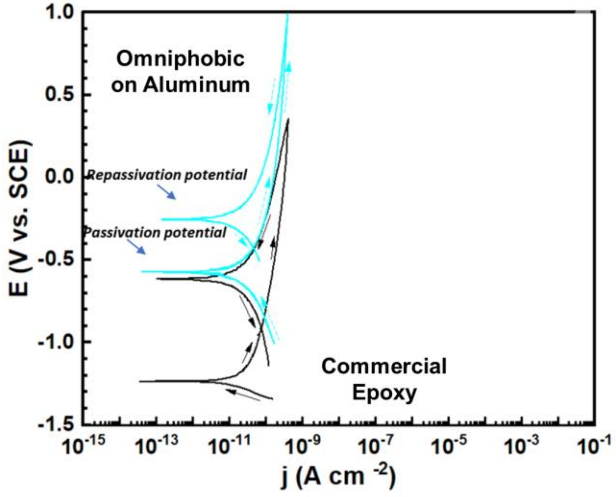
An illustration of sensor-embedded composite liner.
(a) Expanded view showing the individual layers of the liner.
(b) The liner is shown in the existing pipe after installation. (c) Installation process.

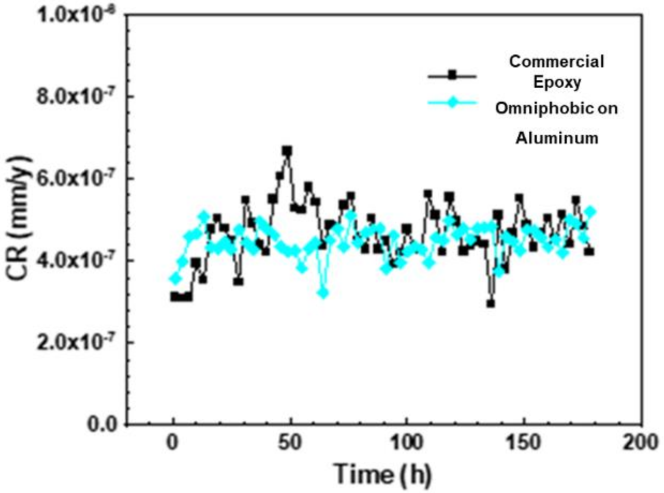
Composite liner for mitigating pipeline corrosion and gas permeation

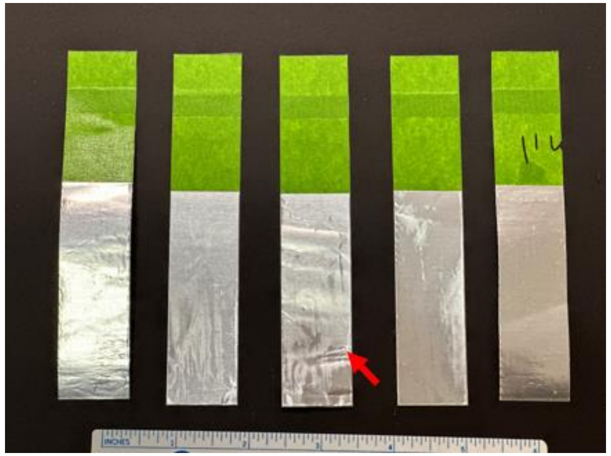
Inner layer development with collaborators – Progress and ongoing efforts

- Collaborating with Oceanit to develop inner polymer layer for corrosion resistance
- Polyurethane-based “Oceanit A” coating outperformed alternative coatings
  - Lower corrosion rate
  - Higher bonding strength
- Oceanit A coating of 16 – 20 µm thickness selected as inner layer material

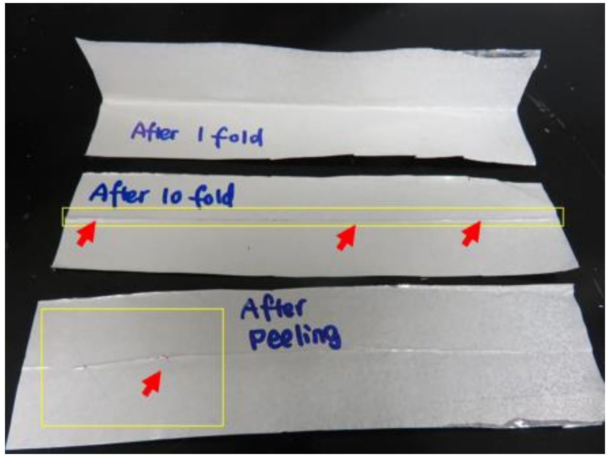








Minimal delamination observed on Oceanit A coating after peel test



Significant delamination observed on BarRust 236 commercial epoxy coating after peel test

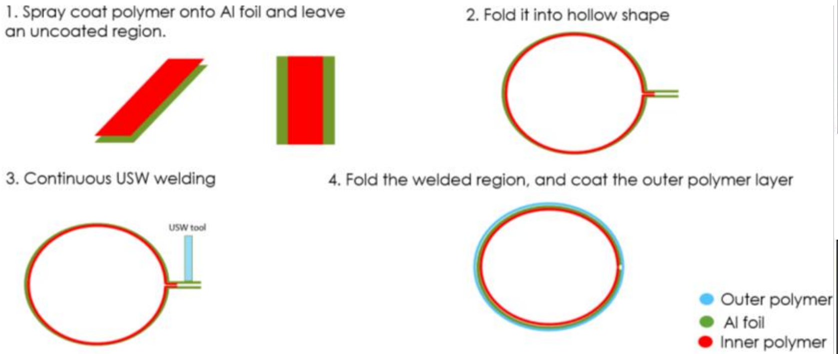
Composite liner for mitigating pipeline corrosion and gas permeation

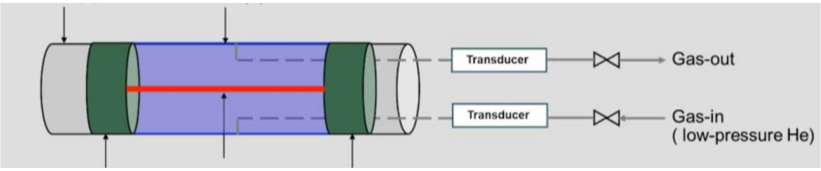
Middle layer development with collaborators – Progress and ongoing efforts

- Collaboration with ORNL
  - Improve scalability of Al foil ultrasonic welding to form liner with pipe geometry
  - Pressure testing of liner prototype

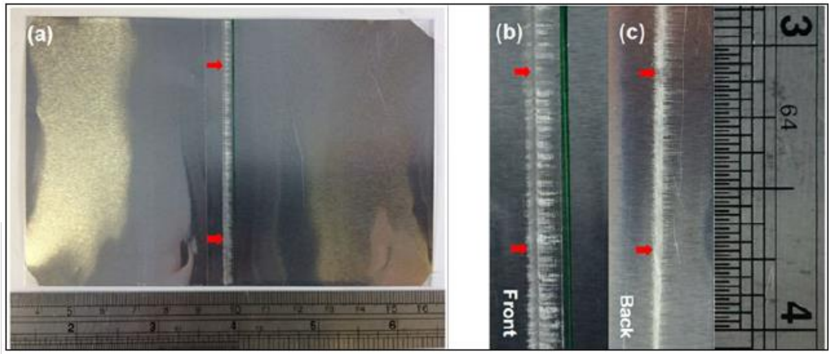
- Welding tests ongoing to improve flexibility of joined Al layer using thinner/softer foil

- Experimental rig suitable for pressure testing liner prototype ETA Q3 2024

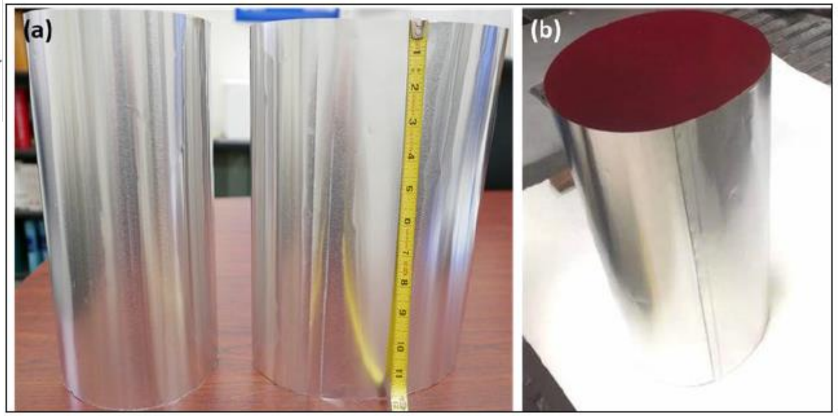




Schematic of pressure test setup



(a) Overview of the ultrasonic welding joint.
(b) Front view of the joint.
(c) Back view of the joint.



(a) A 1-foot long, 6-inch and 8-inch diameter pipe-shaped liner prototype.
(b) A liner prototype with the inner polymer layer integrated.

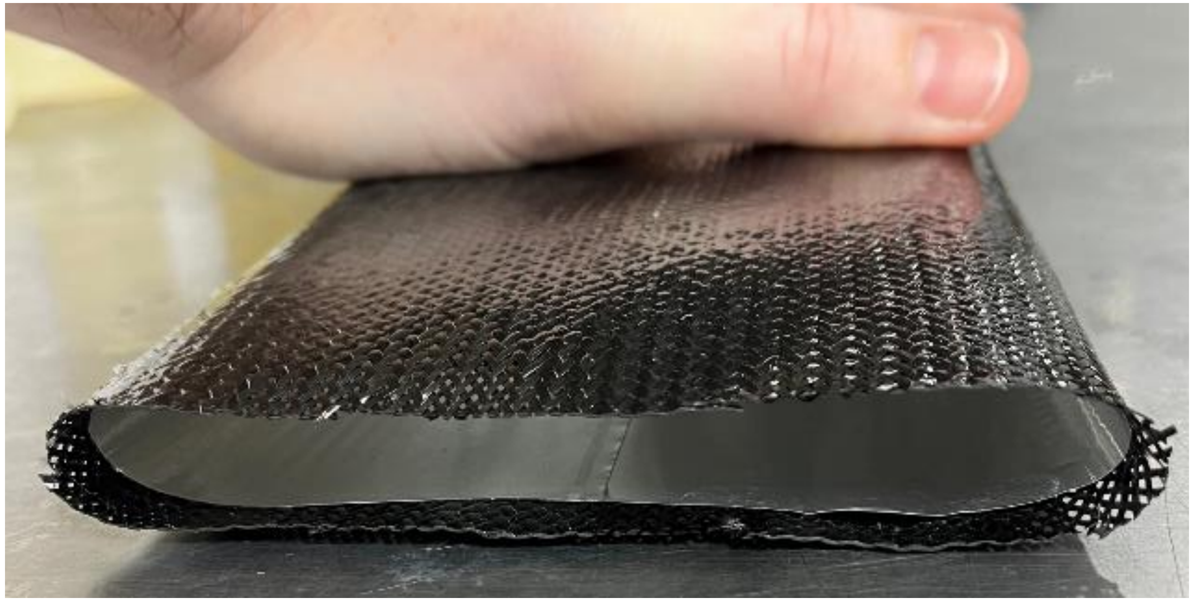
Composite liner for mitigating pipeline corrosion and gas permeation

NATIONAL ENERGY TECHNOLOGY LABORATORY

Outer layer development with collaborators – Progress and ongoing efforts

- Collaborating with DBTech to develop outer polymer layer for mechanical strength
- Evaluating feasibility of two elastomeric resin-infused carbon fiber composite layer designs
  - Pre-cured (cured at plant)
  - Prepreg (cured in field via steam treatment)
- Demonstrated resin adherence to Al foil layer prevents creasing when folded

Resin-infused biaxial carbon fiber composite layer



Adherence of resin to middle Al foil layer imparts minimum bending radius, preventing creasing when folded

U.S. DEPARTMENT OF ENERGY

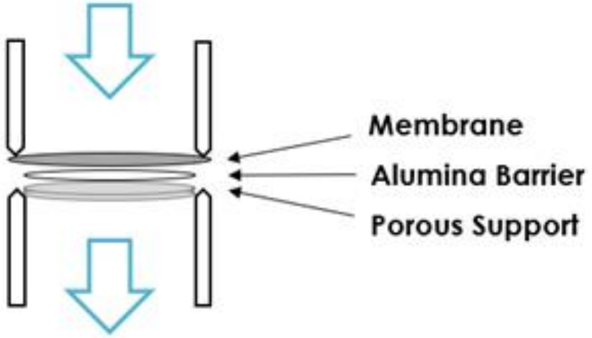
Composite liner for mitigating pipeline corrosion and gas permeation

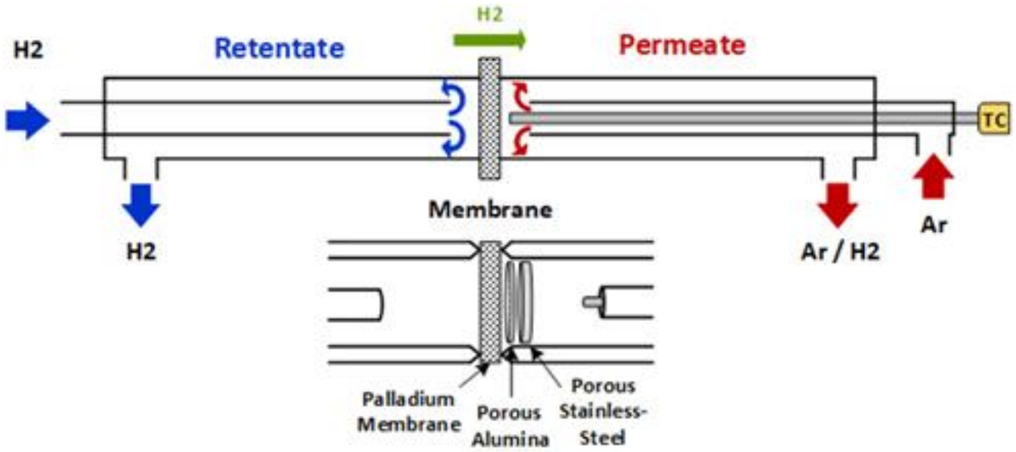
Hydrogen permeation testing of liner materials – Progress and ongoing efforts

- No hydrogen permeation through welded foil detected at pressures up to 145 PSIG

- Seamless and welded foils had comparable rates of pressure increase

- Future efforts will focus on permeation testing of welded foils and foils with omniphobic coating at higher pressures (1000 psig)





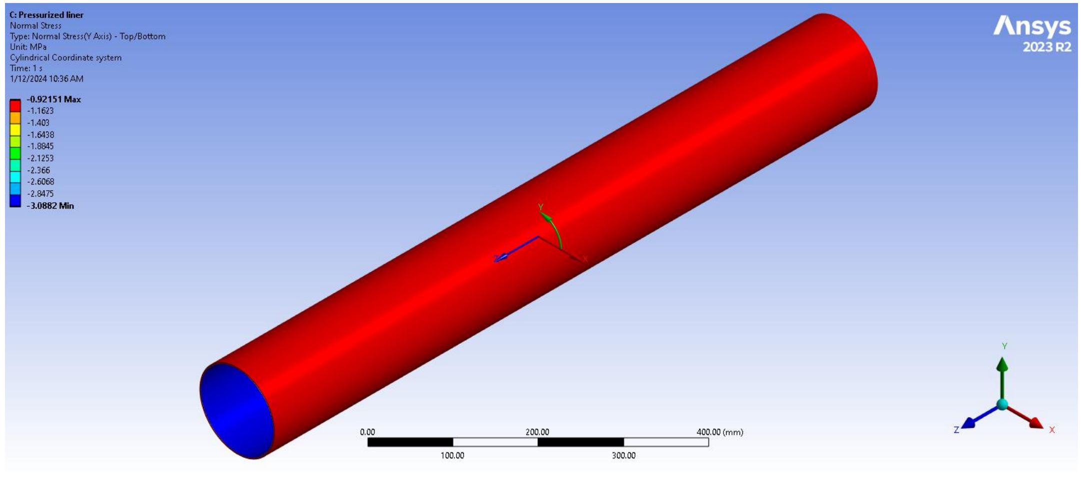
Composite liner for mitigating pipeline corrosion and gas permeation

FEA simulation of liner stress/strain state during operation – Progress and ongoing efforts

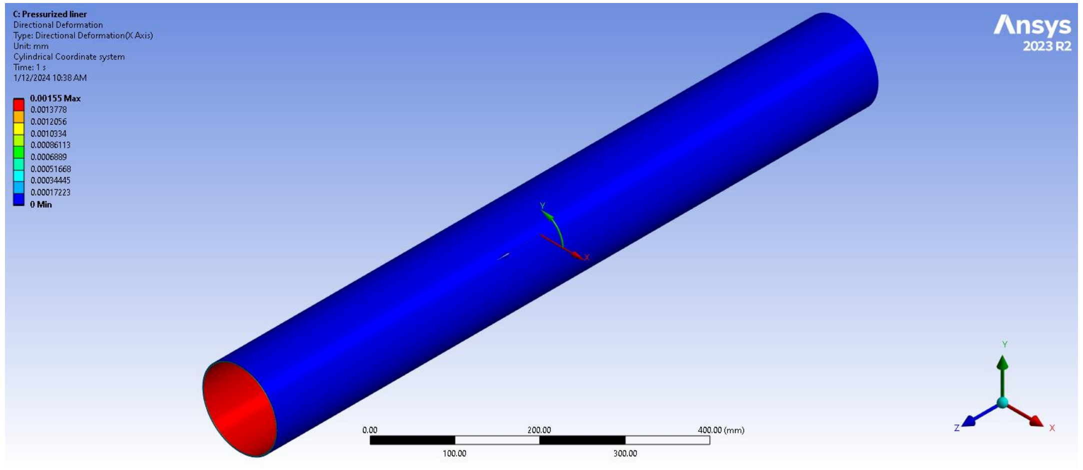
- Preliminary Ansys simulation results predict stress/strain of pressurized liner

- Future efforts will characterize performance of liner under different operating conditions and stresses associated with storage, installation, etc.

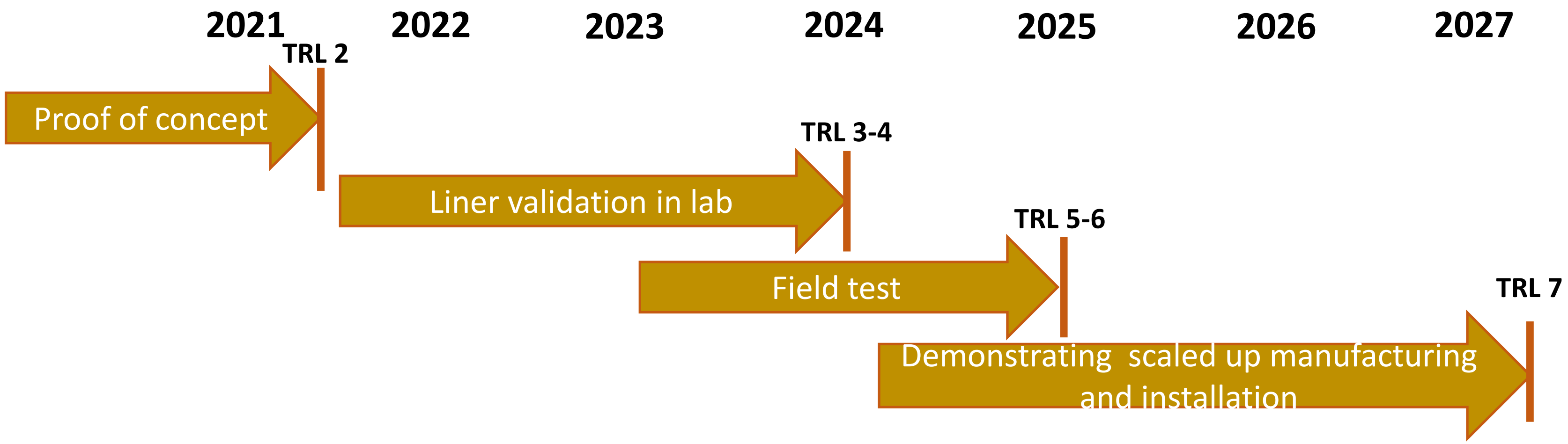
Axial stress in 3D



Hoop stress in 3D

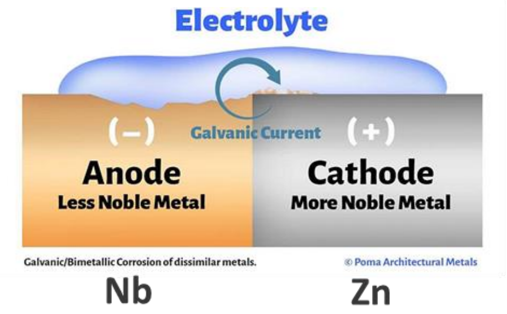


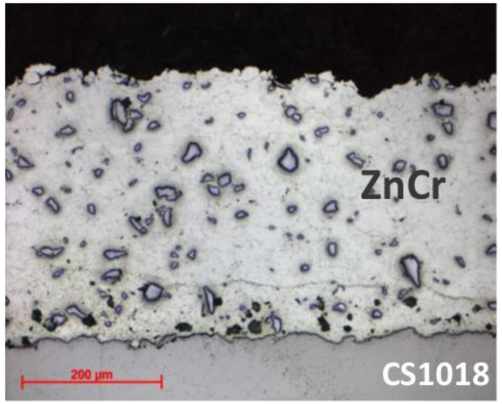
Composite liner technology maturation



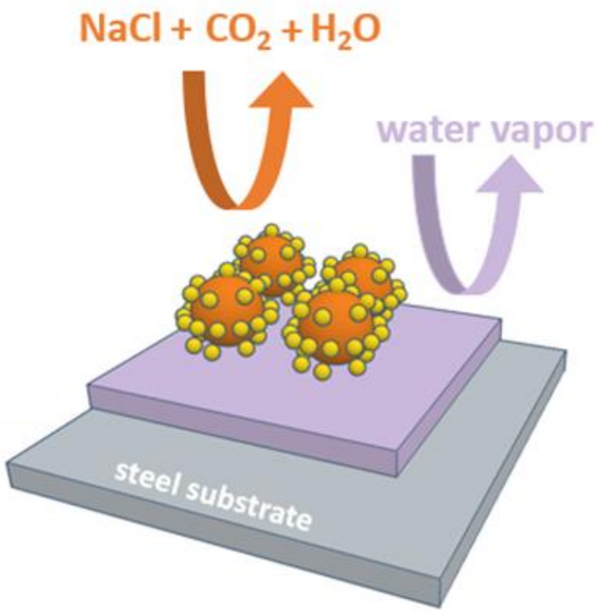
NETL's Coating and Liner Technologies for Pipelines

Self-Healing Metallic Coatings

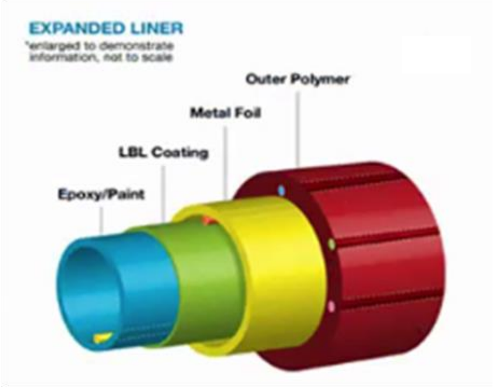


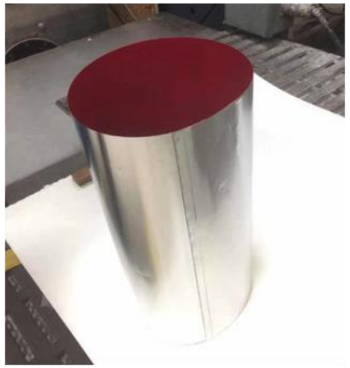


Superhydrophobic Anti-Corrosion Coatings



Composite Liners





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