Development of Advanced Pipeline Materials: Metallic Coatings and Composite Liners

Task 3 Natural Gas Infrastructure FWP 1022424

Program: 1611133 – Emissions Mitigation

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Ömer Doğan (PI), Kyle Rozman, Lucas Teeter, Kaimiao Liu, Fangming Xiang

U.S. Department of Energy/National Energy Technology Laboratory, Research & Innovation Center

U.S. Department of Energy

National Energy Technology Laboratory

2021 Carbon Management and Oil and Gas Research Project Review Meeting

August 2021

Presentation Outline

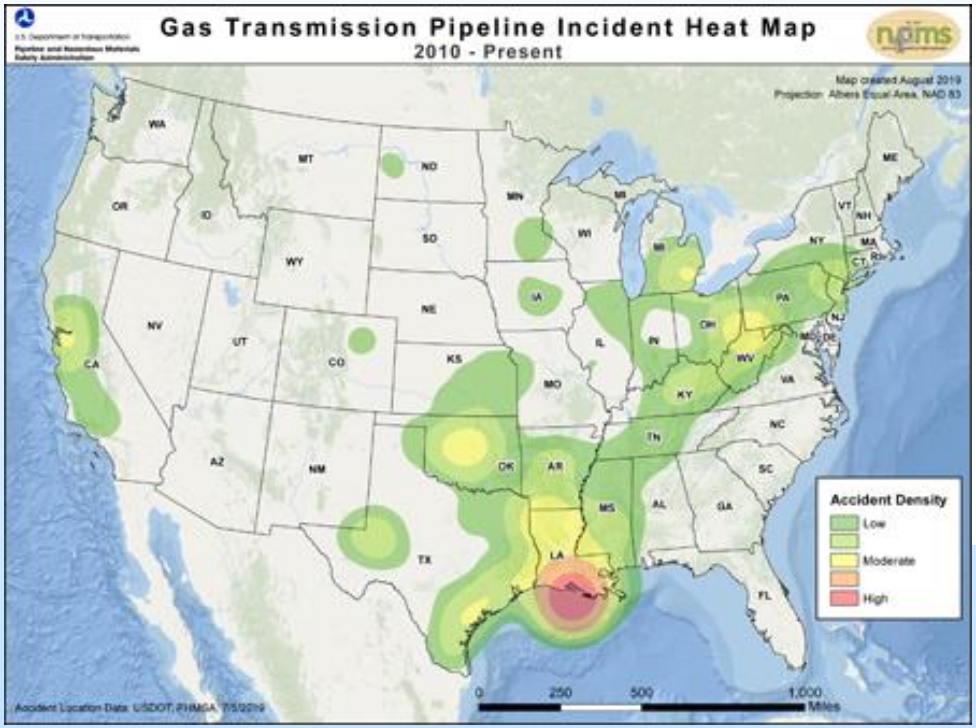
- Overview of Advanced Pipeline Materials Project
- Background & Objectives
- Approach to Mitigate Internal Corrosion & Methane emission: Coating and Liners
- Pipeline Material Technology: Summary

Overview of Advanced Pipeline Materials Project

- Project Funding: EY21: $882K
- Overall Project Performance Dates: April 1, 2021-March 31, 2024
- Project Participants: NETL/ Research & Innovation Center (RIC), DNV-GL, Oak Ridge National Laboratory (ORNL), Oregon State University (OSU), South Dakota School of Mines and Technology

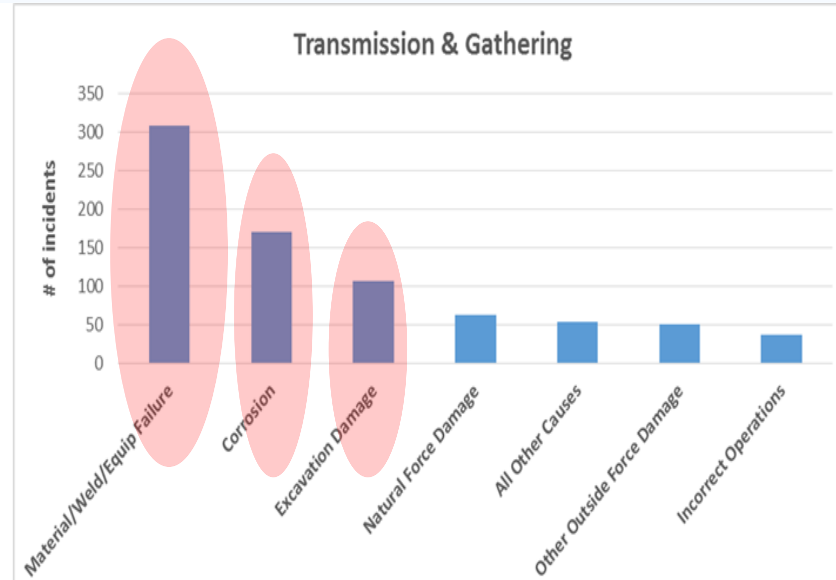
Overview: Advanced Pipeline Materials, Continued

The U.S. Department of Transportation reported numerous case histories of corrosion problems and failures in wet in gas pipelines.

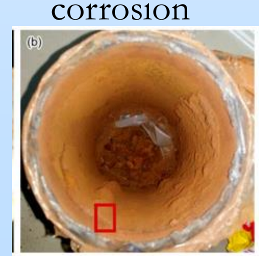


Incident Density of Gas Transmission Pipeline Incidents*

Top three incident causes in transmission & gathering system (1998-2017)**



Internal corrosion



External corrosion

Excavation damage

*https://www.phmsa.dot.gov/incident-reporting/accident-investigation-division/accident-maps

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

Objectives: Advanced Pipeline Materials

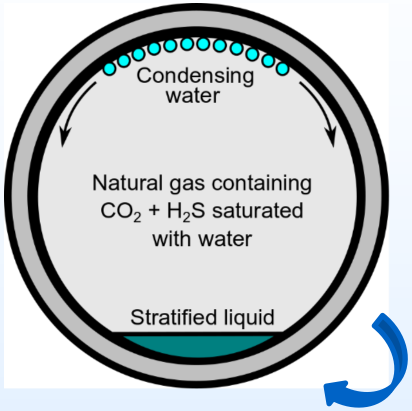
Overall Project Objectives

Develop **removable liners** and easy-to-deposit **long-lasting, self-healing, affordable coatings** for natural gas, hydrogen/ natural gas blends, and hydrogen transport, capable of:

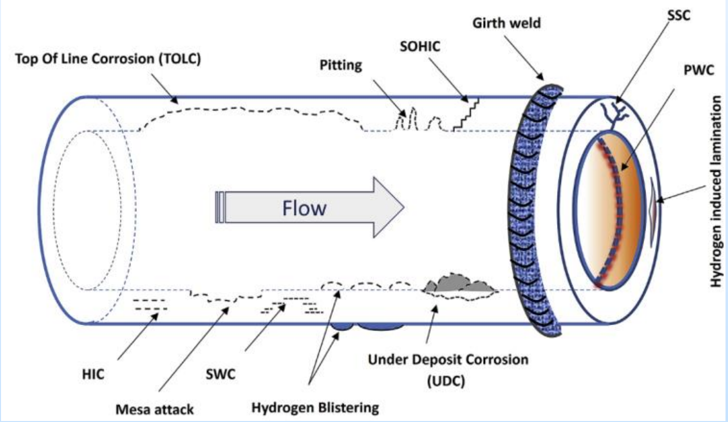
- Preventing corrosion in metal pipelines
  - Reducing corrosion rate of pipelines below 0.1 mm/ year to be monitored by advanced sensors
- Preventing methane emissions
- Identifying an alloy/pipeline material with suitable mechanical and corrosion properties for transporting natural gas, H_2, and CO_2

Background: Advanced Pipeline Materials

- Water is the primary actor in causing corrosion inside the gas pipelines
- CO_2 is the second most important contributor to corrosion
  - A natural gas transmission pipeline might be expected to have a partial pressure of 310 kPa (45psig) of CO_2



Heavy black powder deposits*



Different form of internal corrosion in natural gas pipeline **

- Solution to this problem: **Coatings & liners** to protect internal surface of pipeline against corrosion

*https://www.rosen-group.com/global/solutions/industry-case-studies/oil-gas/Case-Study-Black-is-Black.html
**M. Askari et al., Journal of Natural Gas Science and Engineering, 71, November 2019, 102971

Approach to Mitigating Internal Pipeline Corrosion & Methane Emission: Coatings and Liners

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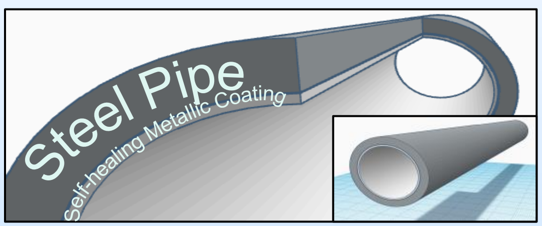
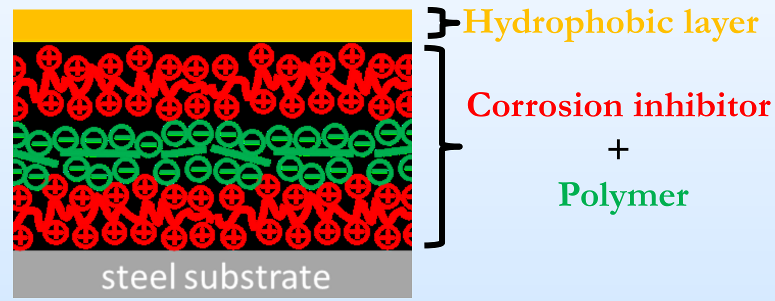
Corrosion Protection through Internal Pipeline Coatings (Subtask 3.1)

- Corrosion Protection through Zn-metal binary materials

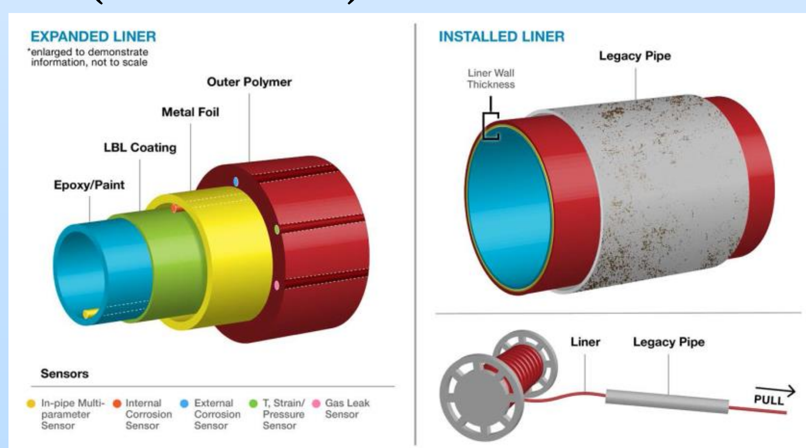


- Corrosion Protection through polymer -Based multilayer coatings



Corrosion Protection through Liners (Subtask 3.2)

Developing and Demonstrating Multi-Layered Composite Liners for Insertion into Pipe



Technical Approach: Task 3.1-Corrosion Protective Metallic Coatings Development

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Date	Milestone
3/31/2022	Identify at least one binary metal binary coatings with the reliable self-healing properties.
3/31/2022	Demonstrate a corrosion-protective coating that can reduce the corrosion rate of carbon steel (API 5L X65 grade) to < 0.1 mm/ year under simulated pipeline test conditions in the laboratory.
3/31/2022	Demonstrate level of risk for H_2 embrittlement and level of uptake of H_2 for binary metallic coated alloys.
3/31/2022	Identify at least one promising alloy for a multi-purpose pipe transporting natural gas, H_2, and CO_2.
3/31/2022	Successful evaluation of the selected binary coating in the field.
3/31/2023	Demonstrate a coated natural gas pipeline that features a low corrosion rate (< 0.01 mm/year) under actual field conditions.
09/31/2024	Technical support for successful demonstration of a coated natural gas pipeline that features a low corrosion rate (< 0.1 mm/ year) under actual field conditions as part of Subtask 7.4.

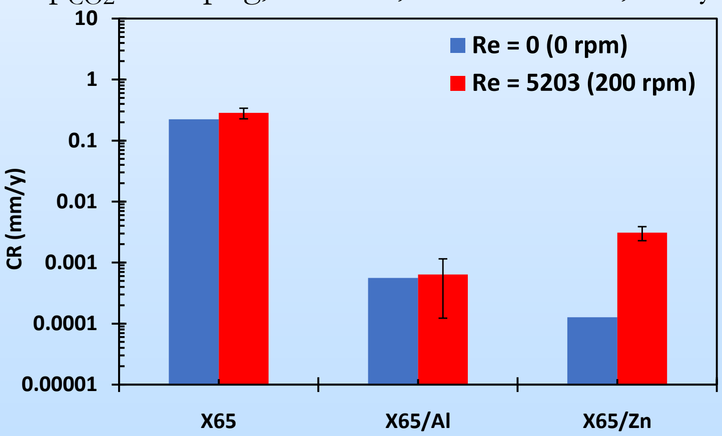
Metric Coated	State of Art	Project Target
Coated Steel Corrosion Rate	0.1 mm/y	<0.01 mm/y

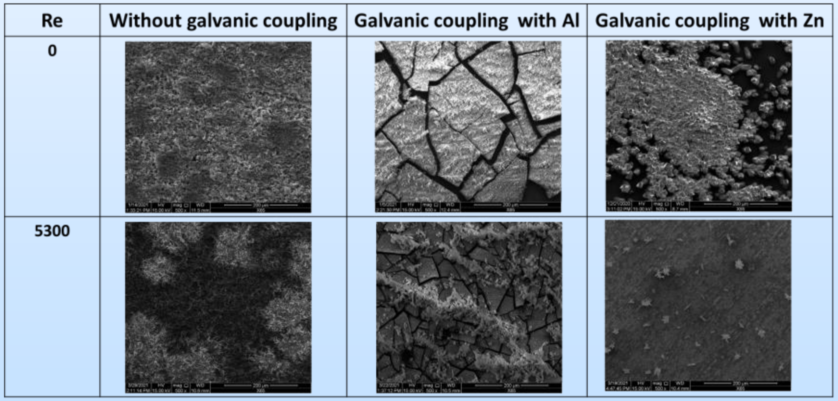
Metallic Coatings: Progress

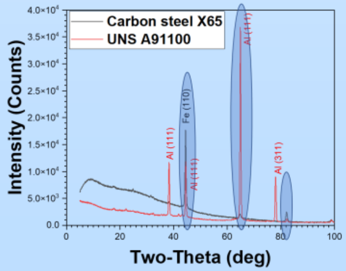
Key Accomplishment

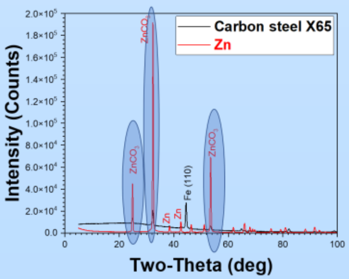
- Demonstrated the effectiveness of Zn and Al as sacrificial anode to protect API 5L X-65 steel in simulated NG pipeline environment

p_{CO2} = 45 psig, T=40°C, 3.5 wt% NaCl, 7 days







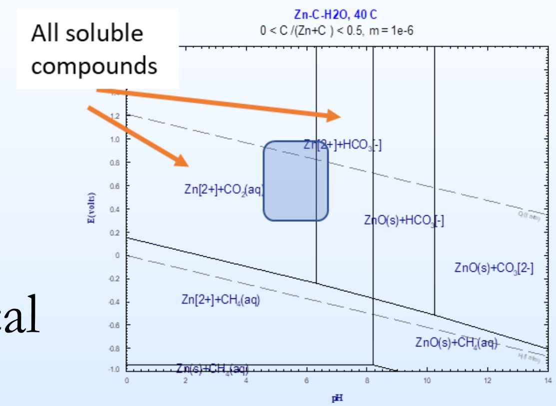


Metallic Coatings: Progress, Continued

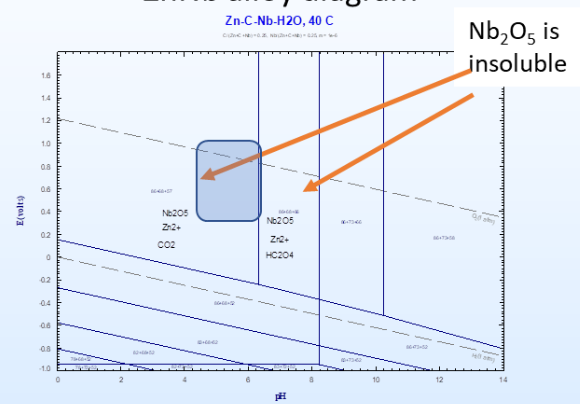
Key Accomplishment

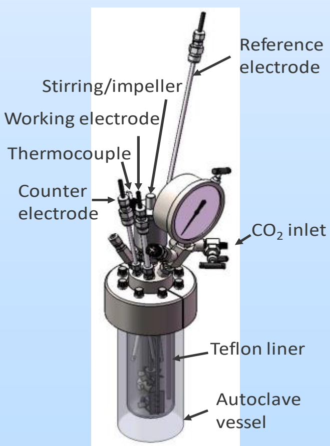
- Designed a zinc-based alloys with better corrosion performance than pure Zinc
  - Corrosion performance confirmed by electrochemical corrosion screening test

Zn alloy diagram



ZnNb alloy diagram





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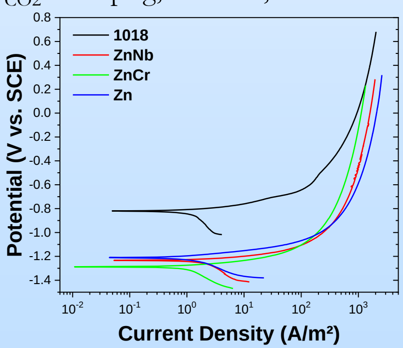

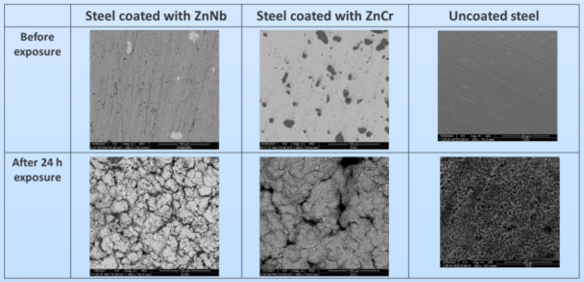

Polymer-Based Multilayer Coatings: Progress, Continued

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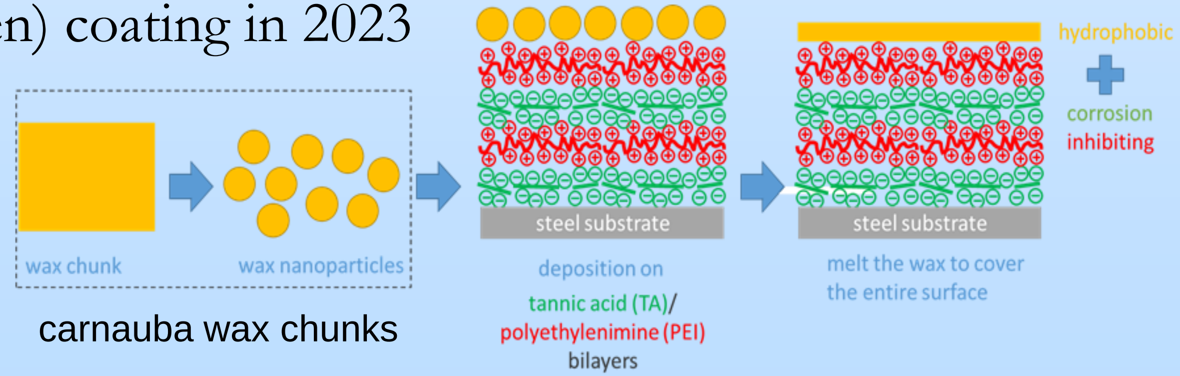
Key Accomplishment

A new multilayer coating that combines corrosion inhibition and hydrophobicity was developed and tested:

- ✓ Wax top layer allows the multilayer coating to be hydrophobic and resistant against CO_2-caused corrosion
- ✓ A low material cost of ~ \$0.3/ft^2
- ✓ Currently at TRL 3, expecting a field test of the next generation (4th gen) coating in 2023

CO_2 + water

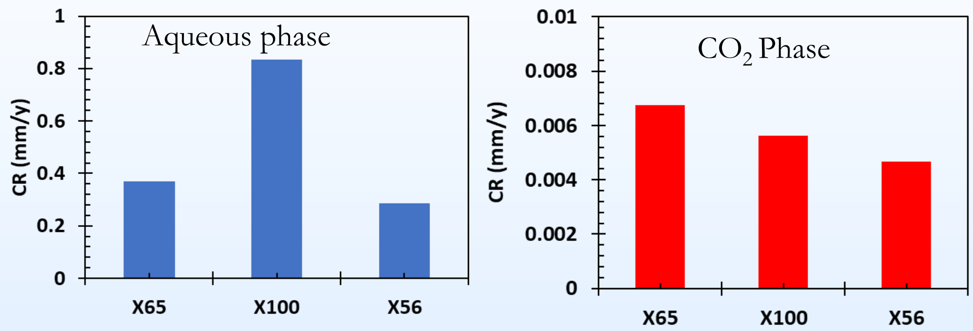


Alloy for Multi-Purpose Pipe Transporting Natural Gas, H_2, and CO_2

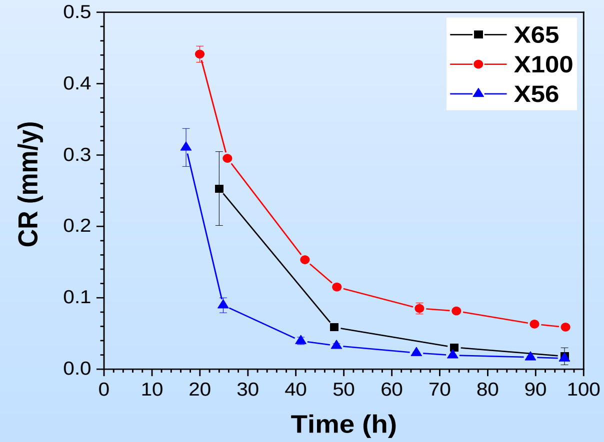
- **Key finding**:

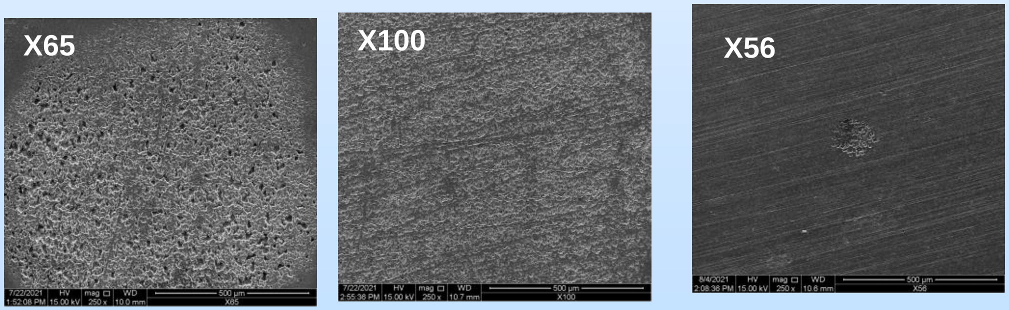
➢ Tested multiple steel pipelines exposed to supercritical CO_2 environment : Carbon steel X56 showed low corrosion rates

100 barg, 30°C



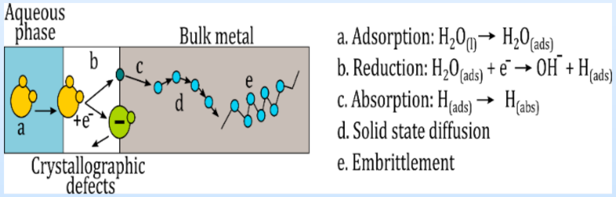
In-situ corrosion measurements

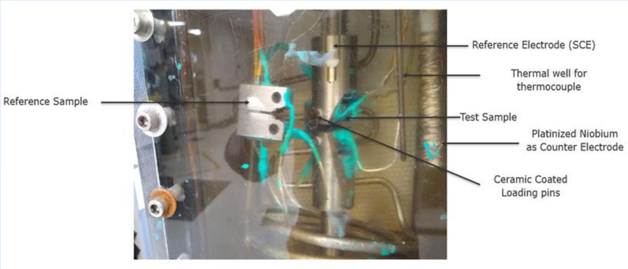


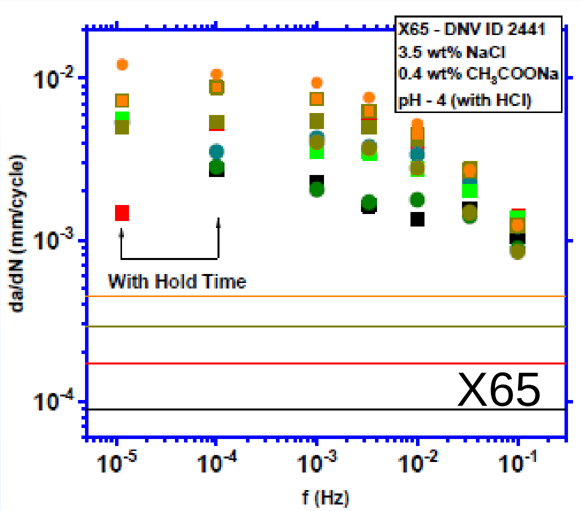


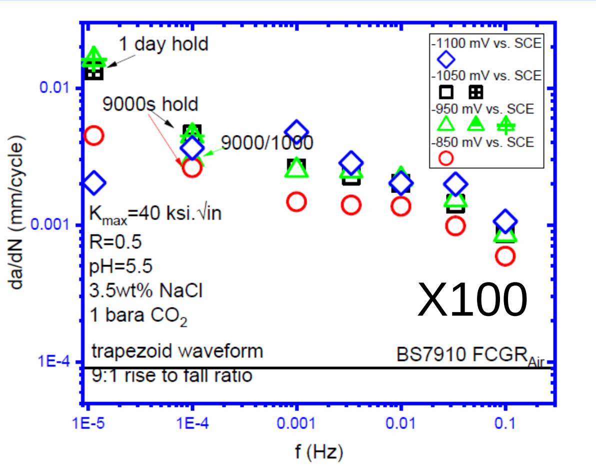
Steel for Multi-Purpose Pipe Transporting Natural Gas, H_2, and CO_2

- **Hydrogen Embrittlement Challenge:** Atomic hydrogen generated during dissolution (corrosion) of pipeline steel and dissociation of hydrogen present in natural gas can cause hydrogen embrittlement that can result in catastrophic failures of pipelines









Key finding:

➢<u>Fatigue crack growth rate (FCGR)</u>: Both X65 and X100 showed a significant increase in FCGR under cathodic polarization conditions compared to in air testing.

➢ Both steels also showed an increase in FCGR with decreasing frequency.

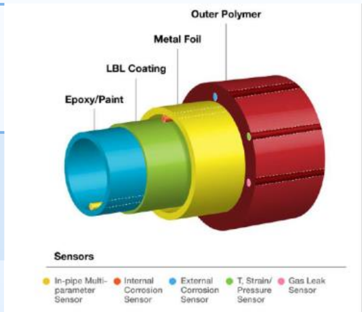
➢These observations suggest that these steels are susceptible to environmentally assisted cracking

Technical Approach: Subtask 3.2 Composite Liners Development

NATIONAL ENERGY TECHNOLOGY LABORATORY

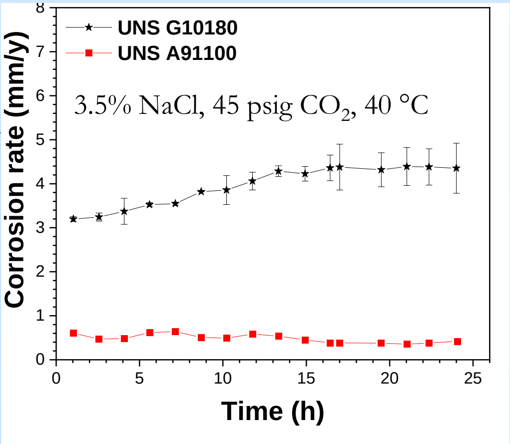
Milestones

03/31/2022	Manufacture a prototype metal liner for a natural gas pipeline
3/31/2022	Successful pressure testing (no leaks) of a 1-foot section of a 6-inch diameter composite liner.
3/31/2023	Present a detailed description of the composite liner installation technology.
03/31/2024	Manufacture a prototype composite liner that can be installed and tested in the field.



Metrics / Success Criteria

Metric	State of the Art	Proposed
Corrosion rate	0.01 mm/year	<0.001 mm/year
Coating integrity and pipeline heath monitoring	Point sensors, Costly, Infrequent inspection	Real-time distributed monitoring for >100km with <1m spatial resolution, 5-fold cost reduction
Hydrogen permeability	10^{-10} mols/m $Pa^{0.5}$ s	$<10^{-14}$ mols/m $Pa^{0.5}$ s
Cost	$1M-$10M per mile	$0.73M per mile ($0.41M per mile)



Technical Approach: Subtask 3.2 Composite Liners Development

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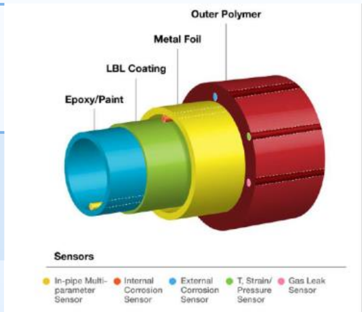

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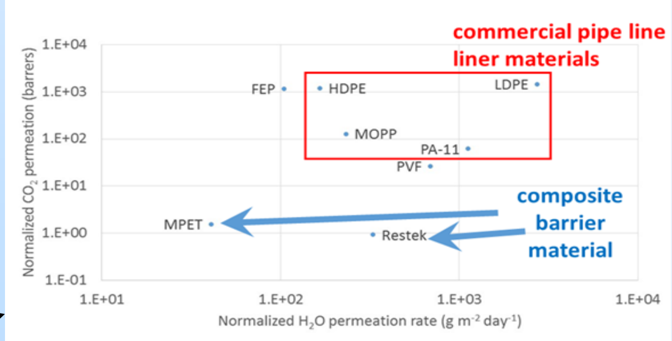
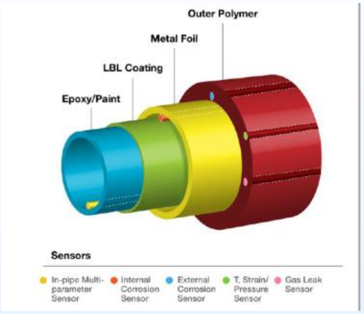
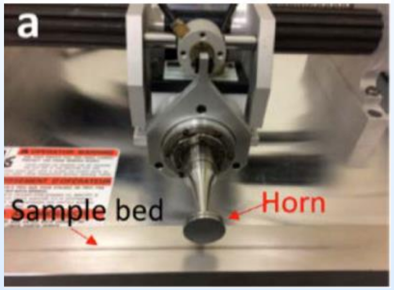


Challenge: Manufacturing Metal Foil "Pipe" Solution: Joining



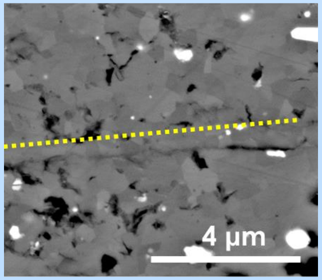
Ultrasonic welding techniques were investigated to join aluminum foils in collaboration with ORNL



- No clamping system required for this setup, minimize foil wrinkle caused by clamping

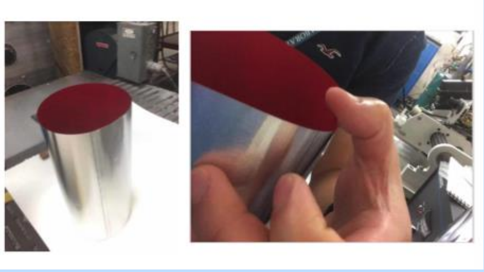
Key accomplishment:

✓ Demonstrated that thin metal foils can be joined without defects



✓ Aluminum foil only liner prototype welded with ultrasonic welding

✓ Liner prototype with interior coated with corrosion resistant polymer

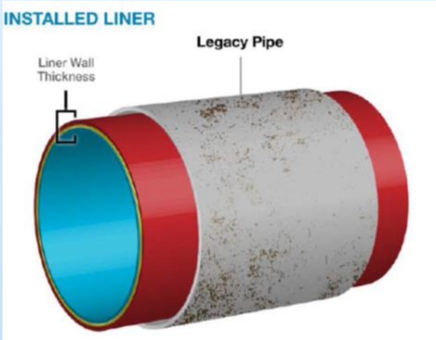


Pipeline Material Technology: Summary

- ✓ **Sacrificial metal coatings of interior of line pipe**
  - Demonstrated that metallic coatings with self-healing properties will protect pipeline steel in a pipeline environment in the laboratory
  - Developed metallic coatings that show superior performance in the laboratory on-going testing
- ✓ **Alloy for multi-purpose pipe transporting natural gas, H_2, and CO_2**
  - Caron steel X56 shows good resistance for supercritical CO_2 corrosion. However, in order to use carbon steel X56 for a multi-purpose pipe transporting naturalgas, H_2, and $CO_{2,}$ the level of risk for H_2 embrittlement and level of uptake of H_2 for X56 needs to be investigated
- ✓ **Composite Liners**
  - Demonstrated that addition of a metal layer in a polymer matrix is responsible for this improved performance
  - Demonstrated that thin metal foils can be joined without defects
  - Demonstrated that inclusion free Al can be resistant to localized corrosion in chlorides that are pitting agents

Pipeline Material Technology: Summary, Continued

- **Expected project outcomes upon completion** :
  - Material technologies that mitigate methane leakage through reliable pipeline corrosion protection
  - Enabling flexible pipeline corrosion protection
  - Materials and processes for pipeline manufactures



Publication list: 12 papers, 18 presentations, 1 patent application

Plans for Future Testing

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Corrosion Protection through Internal Pipeline Coatings

Date	Milestone
3/31/2023	Demonstrate a corrosion-protective coating that can reduce the corrosion rate of carbon steel (API 5L X65 grade) to < 0.1 mm/ year under realistic pipeline test conditions in the laboratory.
3/31/2023	Demonstrate a coated natural gas pipeline that features a low corrosion rate (< 0.01 mm/year) under actual field conditions.
09/31/2024	Technical support for successful demonstration of a coated natural gas pipeline that features a low corrosion rate (< 0.1 mm/ year) under actual field conditions as part of Subtask 7.4.

Corrosion Protection through Liners

3/31/20222	Successful pressure testing (no leaks) of a 1-foot section of a 6-inch diameter composite liner.
3/31/2023	Present a detailed description of the composite liner installation technology.
03/31/2024	Manufacture a prototype composite liner that can be installed and tested in the field.

Appendix

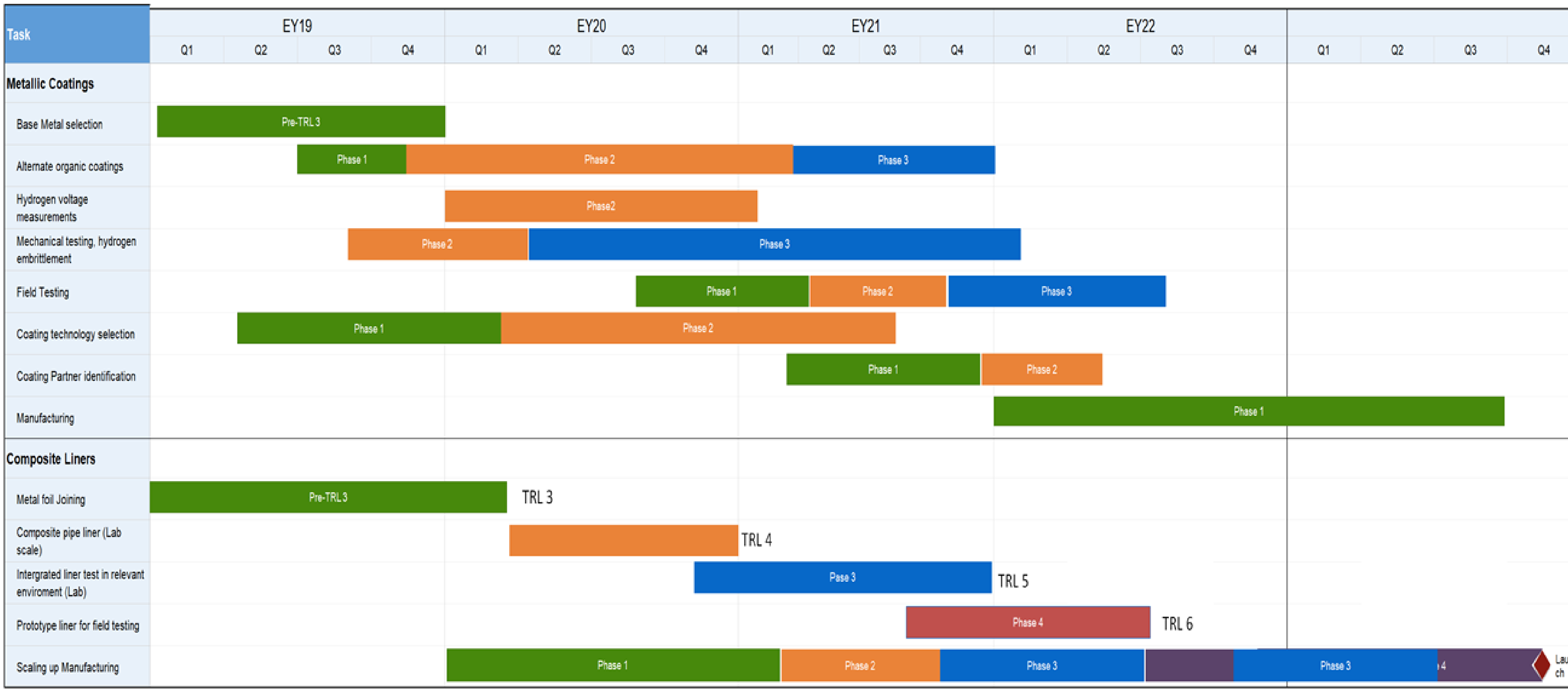
Organization Chart

- **National Energy Technology Laboratory**
  - **Research & Innovation Center**
    - **Materials Engineering & Manufacturing Engineering Directorate**
      - **Structural Materials Team Members** working on the Advanced Pipeline Materials Development Project focusing on *Materials Development and Design* :
        - *Ömer Doğan,* PI-Task 3 ; area of expertise-materials science and engineering
        - *Peter Hsieh*, area of expertise-*materials science and engineering*
      - **Functional Materials Team**:
        - *David Hopkinson,* area of expertise: *chemical engineering*
      - **NETL/ Leidos Research Support** *Members* with expertise in materials science and engineering:
        - *Zineb Belarbi, Lucas Teeter, Kyle Rozman, Kaimiao Liu*, *Fangming Xiang*

- **External Collaborators**: DNV-GL, Oak Ridge National Laboratory (ORNL), Oregon State University (OSU), South Dakota School of Mines and Technology, GTI

Progress Chart

Development of Advanced Pipeline Materials: Metallic Coatings and Composite Liners



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Peer-review publication

1- A. Rodriguez, J.H. Tylczak, M. Ziomek-Moroz, “Corrosion behavior of CoCrFeMnNi high-entropy alloys (HEAs) under aqueous acidic conditions,” ECS Trans. 2017 77(11): 741-752

2- R. Feng, ,M. Ziomek-Moroz, J. H., Tylczak, P.R. Ohodnicki, “Corrosion of Carbon Steel in CO_2-Saturated Brines Investigated by Rotating Disk Electrode and Scanning Vibrating Electrode Technique.” ECS Transactions, 77(11), 809-822

3- A. Rodriguez, J. Tylczak, M. Gao, P. Jablonski, M. Detrois, M. Ziomek-Moroz, J. Hawk, "Effect of Molybdenum on the Corrosion Behavior of High-Entropy Alloys CoCrFeNi2 and CoCrFeNi2Mo0.25 under Sodium Chloride Aqueous Conditions," Advances in Materials Science and Engineering, (2018): 11 pages

4- A. Rodriguez, J. Tylczak, M. Ziomek-Moroz “Corrosion Evaluation of CoCrFeMnNi High-Entropy Alloys (HEAs) for Corrosion Protection of Natural Gas Transmission Pipelines,”, NACE/ CORROSION 2018, Paper No. 11174

5- R.F. Wright, E. R. Brand, M. Ziomek-Moroz, J. H. Tylczak, P. R. Ohodnicki Jr Effect of HCO_3^- on Electrochemical Kinetics of Carbon Steel Corrosion in CO_2-saturated Brines,” Electrochimica Acta, 2018 (290): pp. 626-638

6- A. Rodriguez, J. Tylczak, M. Ziomek-Moroz, T.D. Hall, J. Xu, S. H. Vijapur, “Characterization and corrosion behavior of electrodeposited binary and ternary nickel alloys in a CO_2-saturated NaCl solution, NACE/ CORROSION 2019, Paper No. C2019-13381

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8- C. Koerner, D. Hopkinson, M. Ziomek-Moroz, F. Xiang, “Environmentally Friendly Tannic Acid Multilayer Coating for Carbon Steel Corrosion Prevention,” Industrial & Engineering Chemistry Research 2021(60) 243-250

9- M. Ziomek-Moroz, A. Rodriguez,” High Entropy Alloys-Aqueous Corrosion, Encyclopedia of Materials: Metals and Alloys-in press

10- Z. Belarbi, J. Tylczak, M. Ziomek-Moroz,” Investigations of Corrosion Protection of Natural Gas Pipeline Steel by Al Sacrificial Corrosion Coatings Using Electrochemical Technique” AMPP/CORROSION 2021, Paper No. C2021-16689

11- L. Teeter, J. Tylczak, M. Ziomek-Moroz, G. Crawford, “ZnCr and ZnNb Thermal and Cold Spray Coatings” AMPP/ CORROSION 2021, Paper No. C2021-16977

12- F. Xiang, D. Hopkinson. “Environmentally Friendly Multilayer Coating for Carbon Steel Corrosion Prevention” presented at Materials Science & Technology 2019, Portland, OR, September 29-October 3, 2019

Patent Application

– US2020/0283874 A1 “High performance corrosion-resistant high-entropy alloys” J. Hawk. P. Jablonski, M. Ziomek-Moroz, J. Tylczak, A. Rodriguez, M. Gao, published September10, 2020