HyBlend: Pipeline CRADA
Materials R&D

Kevin Simmons (PNNL)
Chris San Marchi (SNL)

DOE Hydrogen Program 2023 Annual Merit Review
and Peer Evaluation Meeting, June 6, 2023

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Project Goal: provide community with scientific basis to assert safety of piping and pipelines for hydrogen service

Vision

*Develop general framework to evaluate structural integrity in the context of distribution and transmission of hydrogen by pipeline*

**What**
- Assess degradation of piping and pipelines for service with hydrogen blends
- Develop science-based understanding of variables (and mechanisms) that contribute to hydrogen-induced degradation of piping and pipeline materials

**How**
- Leverage DOE/lab capabilities to assess and understand materials performance in hydrogen environments
- **Design probabilistic analysis tools** to quantify structural integrity of piping and pipeline networks for hydrogen service

**Why**
- Ensure safety of decarbonized energy infrastructure for both transitional and long-term strategies of hydrogen conveyance
- Provide natural gas pipeline operators information to assess conversion of existing assets and potentially construction of new, dedicated clean infrastructure
### Overview: Pipeline Blending CRADA

#### Timeline
- **Start:** October 2021
- **End:** September 2023
- 60% complete*

*As of April 7th, 2023

#### Barriers
- Inconsistent Data, Assumption and Guidelines
- Insufficient Suite of Models and Tools

#### Budget
- Total FY21-FY23 funding for collaborative HFTO project: $15 M
  - DOE Share: $11 M
  - Cost Share: $4 M

- Total DOE funds received to date (HFTO): $11 M

#### Partners

**National Labs**
- Argonne National Laboratory – Amgad Elgowainy, PI
- National Renewable Energy Laboratory - Mark Chung, PI
- Pacific Northwest National Laboratory – Kevin Simmons, PI
- Sandia National Laboratories – Chris San Marchi, PI

**Industry Stakeholders (alphabetical)**
- Air Liquide, Chevron, DNV, Enbridge, EPRI, ExxonMobil, GTI, Hawaii Gas, Hydril, National Grid, NJNG, ONEGAS, PRCI, SMUD, Southern Company, Stony Brook University, SWRI
Relevance: Pipeline Blending Benefits

• The U.S. possesses an extensive natural gas pipeline system comprising of 3 million miles\(^1\) of pipe of which 1.5 million miles\(^2\) is plastic pipe.

• Converting networks for hydrogen blending within the U.S. natural gas pipeline system may offer a low-cost pathway to distribute green hydrogen.

• Blending low-carbon hydrogen into the U.S. natural gas pipeline systems furthers national decarbonization objectives by:
  – Offering a pathway with incremental steps towards cost-efficient pure hydrogen transportation.
  – Promoting early-market access for hydrogen technology adoption.
  – Enable short-term carbon emissions reductions with the potential for long-term emissions reductions for hard-to-decarbonize sectors.

HyBlend Pipeline CRADA: Materials R&D

Transmission
• Mostly steels
• Extensive existing network

Distribution
• Legacy metals
• Extensive polymer networks

HyBlend Pipeline CRADA addresses both API steels and polymer piping
Approach: Polymers R&D
Hydrogen effects on aging of distribution infrastructure

Phase I: Basic Property Characterization
Modulus, yield stress, fracture strength, burst strength, elongation at break, crystallinity, etc

Define test environments
• Temperature
• Pressure
• H₂ amount
• Defects

Collect property data
• Tensile dog bones
• SENB Fracture
• Pipe geometry

Evaluate hydrogen effects on properties
• Measure properties with and without hydrogen exposure and characterize failure mechanism

Phase II: Life Prediction
Select appropriate life-prediction models and test method for shortened time based on Phase I results and failure mechanism analysis

Inputs from industry & literature survey

Inputs from industry & literature survey

Engineering Fracture Mechanics 101 (2013) 2–9
HyBlend: Pipeline CRADA Materials R&D
<table>
<thead>
<tr>
<th>Due Date</th>
<th>Lab</th>
<th>Description</th>
<th>Status</th>
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</thead>
<tbody>
<tr>
<td>Sept 2022</td>
<td>PNNL</td>
<td>Evaluation of slow crack growth response of existing pipeline materials in ambient and pure hydrogen conditions</td>
<td>Completed</td>
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<tr>
<td>Dec 2022</td>
<td>PNNL</td>
<td>Identification of damage mechanisms in vintage materials</td>
<td>Completed</td>
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<tr>
<td>June 2023</td>
<td>PNNL</td>
<td>Evaluation of slow crack growth in hydrogen blends</td>
<td>On Track</td>
</tr>
<tr>
<td>Sept 2023</td>
<td>PNNL</td>
<td>Evaluation of crack growth models for predicting pipe lifetime</td>
<td>On Track</td>
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Accomplishment: Polymers
Morphological effects of hydrogen over time

The crystallinity of HDPE increases significantly with hydrogen and methane exposure at 250 psi. Modern and vintage MDPE have negligible changes.

Ex situ measurements show time-sensitive results. In situ measurement techniques are under investigation using solid-state nuclear magnetic resonance spectroscopy.
Accomplishment: Polymers

Hydrogen effects on localized mechanical properties

Hydrogen causes 20-30% reduction in localized mechanical properties but only MDPE recovers; such property change not observed with argon gas in HDPE.
Accomplishment: Polymers
Hydrogen effects on fracture properties

The fracture energy of HDPE is significantly decreased by hydrogen (↓5%) and blended (↓42%) gas. MDPE has a negligible change.

Enlarged fracture surface = Lower fracture energy
Accomplishment: Polymers
Lifetime prediction experiments

(1) In-situ SENB slow crack growth

(2) In-situ tensile creep

Two long-term hydrogen in-situ creep experiments are in progress
Approach: Metals R&D
Structural integrity of pipe and pipelines for hydrogen gas service

- **Probabilistic tools** for Engineering Critical Assessment (ECA)
  - Develop probabilistic toolkit for fracture mechanics
  - Exercise tool to demonstrate sensitivity analysis
- **Subscale pipe test bed** to demonstrate integrity of pipes with controlled boundary conditions
  - Develop pressure loop to enable pressure cycling of pipe to high pressure to simulate stresses in pipelines
- Assess critical variables in **laboratory fatigue and fracture testing** of pipeline steels in gaseous hydrogen environments
  - Assess fatigue crack growth and fracture resistance of pipeline steels and their welds in gaseous hydrogen
## Approach: Milestones for Metals R&D

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<tbody>
<tr>
<td>June 2022</td>
<td>SNL</td>
<td>Preliminary assessment of pressure dependence of fatigue and fracture</td>
<td>Completed</td>
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<tr>
<td>Sept 2022</td>
<td>SNL</td>
<td>Implementation of H-embrittlement models in probabilistic fracture mechanics framework (HELPR)</td>
<td>Completed</td>
</tr>
<tr>
<td>Sept 2022</td>
<td>SNL</td>
<td>Demonstration of pressure cycling of subscale pipe specimen (delayed due to supply chain issues – expected June 2023)</td>
<td>In progress</td>
</tr>
<tr>
<td>Sept 2023</td>
<td>SNL</td>
<td>Public release of HELPR</td>
<td>On Track</td>
</tr>
<tr>
<td>Sept 2023</td>
<td>SNL</td>
<td>Comparison of subscale pipe failure with predictions from coupon testing</td>
<td>On Track</td>
</tr>
<tr>
<td>Sept 2023</td>
<td>SNL</td>
<td>Report on assessment of materials microstructures with corresponding fatigue and fracture behavior in hydrogen</td>
<td>On Track</td>
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Approach: Hydrogen Extremely Low Probability of Rupture (HELP)  
*A probabilistic fracture mechanics tool suite for NG assets containing hydrogen*

**Probabilistic Framework**

Use probabilistic distributions to describe pipeline system characteristics; sample distributions using statistical methods

- **dimensions**
- **pressure**
- **materials**
- **defects**

**Deterministic Models**

Integrate with deterministic fatigue and fracture models to evaluate pipeline structural integrity

**Probabilistic Structural Integrity Results**

Provide statistical representations of pipeline integrity measures accounting for uncertainty sources
Accomplishment: developed HELPR architecture for probabilistic fracture analysis

HELPR

- **Probabilistic fracture mechanics** toolkit for evaluating structural integrity of NG pipeline assets with blended H₂
- Developed module-based software architecture in **Python** to ease capability addition and improvement
  - **Modules:** crack initiation, crack growth, internal environment, pipe material, stress state, inspection & mitigation, failure analysis, probabilistic analysis
  - Probabilistic framework enables characterization of prediction **uncertainty quantification** and **sensitivity analysis**
  - “Alpha” version of **GUI** interface (PC & Mac) available to improve user experience

*Scatter plot of pipeline probabilistic evaluations of fatigue analysis predictions. Color represents minimum pressure values in pressure cycling, illustrating correlation.*

*Cumulative distribution ensemble of pipeline fatigue metric resulting from aleatory and epistemic uncertain inputs.*
Subscale pipe testing at high pressure allows simulation of relevant stresses on smaller scale than transmission pipe and enables manufacture of surrogate defects (such as cracks, dents, and gouges).

- Test bed is designed for nominally 50 mm diameter and pressure of 400 bar (6,000 psi)
  - Therefore, the high stresses in pipelines can be achieved in small diameter pipe (>50% SMYS, specified minimum yield strength)

Test pipe is sealed at the ends with high-pressure endcaps, but not axially constrained. Assembly is enclosed in secondary containment fixtured in a high-strength frame assembly.

Pressure cycling manifold with inert purge manifold and test fixturing installed.

Simplified diagram of pressure cycle loop and test apparatus. Test gas is recycled via low-pressure reservoir and compressor.
Accomplishment: Metals R&D
Correlating microstructure and fatigue/fracture response

- Significant database of properties show consistent **hydrogen-assisted fatigue** properties
- Relationship between microstructure, composition, hardness and **hydrogen-assisted fracture** are emerging
Accomplishments and Progress

Previous Year Reviewers’ Comments: none
Collaboration and Coordination

- Knowledge sharing and information dissemination
  - Emerging Fuels Institute (EFI)/ Pipeline Research Council International (PRCI)†
  - Gas Technologies Institute (GTI)†
  - Coordination with several Joint Industry Projects (JIPs) – e.g., with American Petroleum Institute (API)
  - Advisory/review role on several DOT-PHMSA projects (CAAP university projects, NIST)
  - B31.12 committee

- Materials provision
  - Coordination with EPRG project in Europe
  - Coordination with Future Fuels CRC activities in Australia
  - Materials supplied by multiple CRADA partners† (with promise to anonymize sources)

- Detailed microstructural characterization
  - Electric Power Research Institute (EPRI)† (in-kind cost contribution)
  - Oak Ridge National Laboratory (ORNL)

- Hydrogen testing (in-kind cost contributions)
  - Southwest Research Institute†
  - DNV†

†official CRADA partner
Remaining Challenges and Barriers

Translating laboratory tests to application in large-scale infrastructure remains a challenge

— Polymers:
  • Accelerating tests in meaningful ways requires knowledge of relevant physics – which remain largely unknown in structural thermoplastics
  • In-situ H$_2$ test remains a challenge in full-scale pipe structures
  • Ex-situ testing is very time dependent

— Metals:
  • Lack of rigor in available information – this effort can be viewed as a counterpoint (and context) to the incomplete and anecdotal information commonly circulated
  • Laboratory testing requires specialized knowledge and equipment
  • The Emerging Fuels Institute (EFI) has identified critical defects that require assessment, but testing/simulating these defects remains a challenge
Proposed Future Work

• Polymers
  – Fracture testing to evaluate crack propagation in creep conditions with various gases
  – In-situ measurement of crystallinity index of PE pipes under hydrogen and methane gases
  – Assess morphological and physical effects of hydrogen on heat fusion joints
  – Assess pipe lifetime effects of hydrogen blends

• Metals
  – Release probabilistic fracture mechanics tool - HELPR
  – Demonstrate and evaluate subscale pipe test bed
  – Compare design-based failure criteria with experimental failure of subscale pipe specimens
  – Amplify guidance on important variables (e.g., pressure, rates, constraint, microstructure/hardness)
  – Develop recommendations to assess hydrogen effects on line-pipe steels and minimize future testing burden (e.g., fatigue crack growth rules, hardness-fracture relationship)

Any proposed future work is subject to change based on funding levels.
Summary

• **HyBlend Pipeline CRADA** is multi-lab, stakeholder-driven project
  – Goal of Materials R&D: provide community with **scientific basis to assert safety of piping and pipelines for hydrogen service**

• **Polymers R&D**
  – Crystallinity and density of HDPE increase when it is exposed to hydrogen and methane gas. However, they return to the original value after 1 hour of decompression. MDPE has negligible changes.
  – HDPE’s fracture energy significantly decreased when it is exposed to blended gas. MDPE has insignificant change in their fracture energy.

• **Metals R&D** (see H2IQ Hour presentation 29 March 2022 for previous work)
  – **HELPR**: initial probabilistic framework is established, Sept planned release
  – **Subscale pipe testing**: basic system constructed, testing starting before end Q3
  – **Fatigue and fracture**: consistent trends established, working on hardness-fracture relationship
Thank You

Kevin Simmons <kl.simmons@pnnl.gov>
Chris San Marchi <cwsanma@sandia.gov>