HyBlend

U.S. DEPARTMENT OF ENERGY

HyBlend: Pipeline CRADA Materials R&D

Project ID: IN035
WBS 8.6.2.1

Kevin Simmons (PNNL)
Chris San Marchi (SNL)

DOE Hydrogen Program 2022 Annual Merit Review and Peer Evaluation Meeting, June 8 , 2022

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

25% complete*

*As of April 25th, 2022

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

Ref 1: Celestine, A. D. N., Sulic, M., Wieliczko, M., & Stetson, N. T. (2021). Hydrogen-Based Energy Storage Systems for Large-Scale Data Center Applications. *Sustainability*, *13*(22), 12654.
Ref 2: 2020 Annual Report Data from Gas Distribution, Gas Gathering, Gas Transmission, Hazardous Liquids, Liquefied Natural Gas (LNG), and Underground Natural Gas Storage (UNGS) Facility Operators. USDOT, PHMSA.

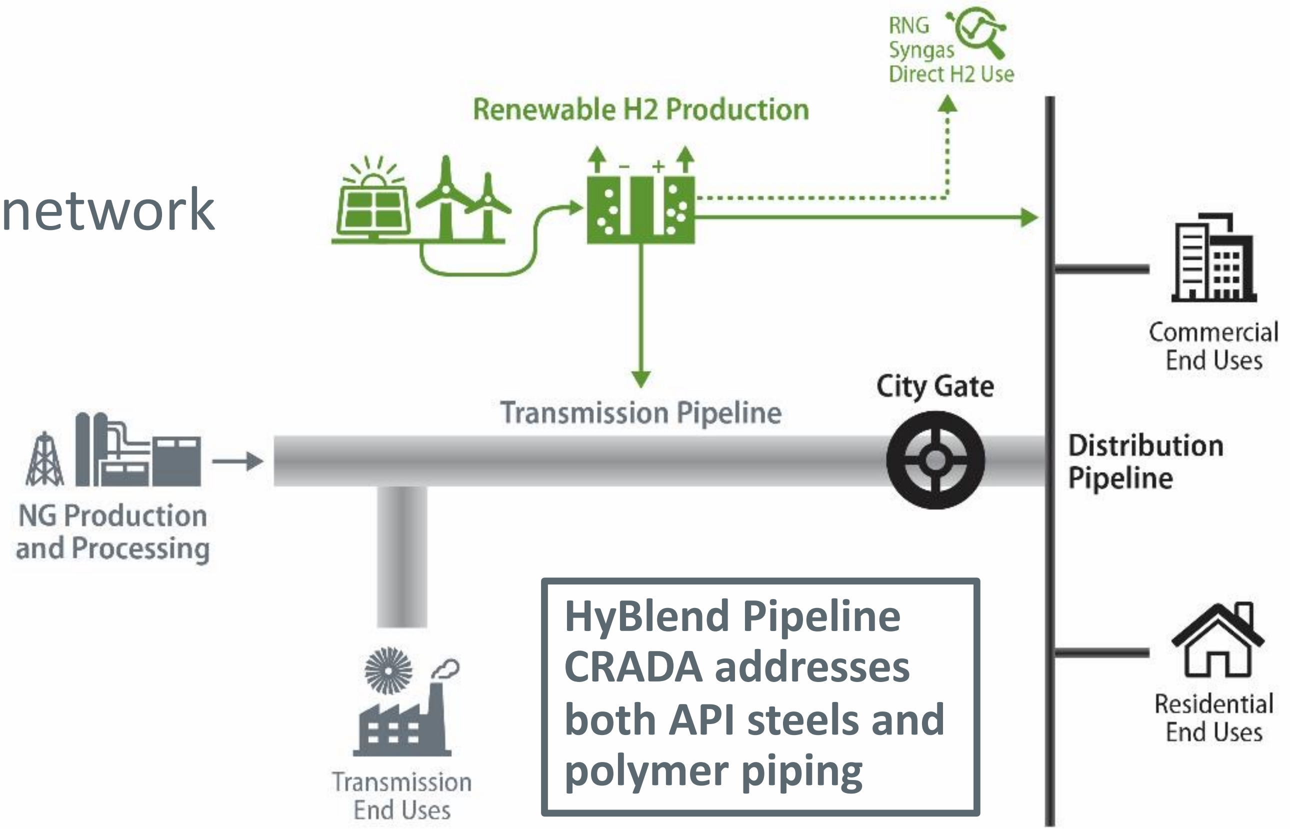
HyBlend Pipeline CRADA: Materials R&D

Transmission

- Mostly steels
- Extensive existing network

Distribution

- Legacy metals
- Extensive polymer networks



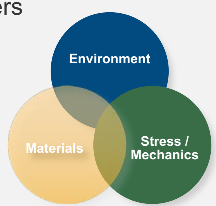
HyBlend Pipeline CRADA addresses both API steels and polymer piping

Approach: Metals R&D
Structural integrity for hydrogen gas infrastructure

How do we assess structural integrity of infrastructure with hydrogen?	*What is the structural risk to NG assets with blended hydrogen?*	*How do we formulate mechanistic models into predictions?*

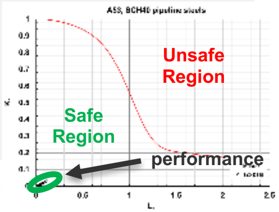
Database of design properties for NG assets with hydrogen

- Assessment of critical parameters determining materials response in hydrogen environments
- Survey of critical materials in ancillary equipment (e.g., pumping stations)
- Long-duration aging of polymers in piping systems
- Evaluation of vintage materials in existing infrastructure



Pipeline Structural Integrity Tool

- Tools to evaluate probability of rupture of NG assets based on Nuclear Regulatory Commission (NRC) framework
- Uncertainty analysis to inform experimental evaluation
- Sensitivity analysis to determine opportunities for system and operational improvements
- Regulations, Codes, and Standards (RCS)-based structural integrity assessment



Physics-based mechanisms of hydrogen embrittlement relevant to NG assets

- Develop deeper understanding of mechanisms of hydrogen embrittlement
- Establish models and framework for implementing physical phenomena into structural integrity tool
- Inform materials selection guidance and establish basis for potential future materials development activity

Guidance on operating conditions

+ partners

Industry-focused probabilistic framework for risk assessment

State-of-the-art characterization

International coordination *facilitates* definition of requirements, *reduces* redundancy, *enhances* rigor, and *improves* breadth of structural integrity tools

Approach: Polymers R&D
Hydrogen effects on aging of distribution infrastructure

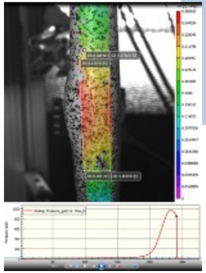
Phase I: Basic Property Characterization
Modulus, yield stress, fracture strength, burst strength, elongation at break, crystallinity, etc

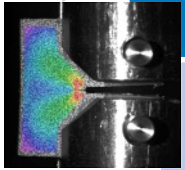
Phase II: Life Prediction
Select appropriate life-prediction models and test method for shortened time based on Phase I results and failure mechanism analysis

Inputs from industry & literature survey

Define test environments

- Temperature
- Pressure
- H_2 amount
- Defects



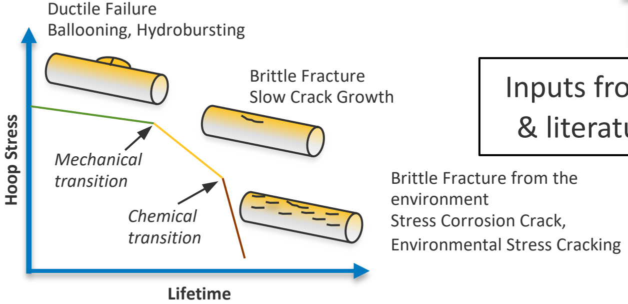


Collect property data

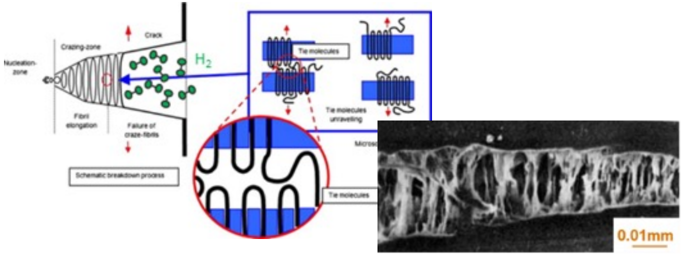
- Tensile dog bones
- SENB/CT Fracture
- Pipe geometry

Evaluate hydrogen effects on properties

- Measure properties with and without hydrogen exposure and characterize failure mechanism



Inputs from industry & literature survey



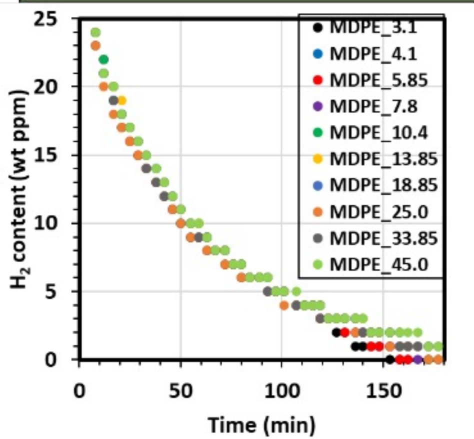
Engineering Fracture Mechanics 101 (2013) 2–9

Approach: Milestones

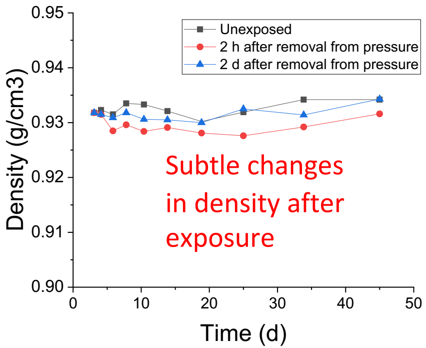
Due Date	Lab	Description	Status
Mar 2022	SNL	Report on assessment of literature data, gaps, and industrial relevance	Draft Complete
Mar 2022	PNNL	Gap analysis on the impacts H_2 addition to the NG infrastructure	Draft Complete
Jun 2022	PNNL	Assessment of impurity sources and quantity in natural gas systems for evaluating polymer interactions with the addition of hydrogen	On Track
Sept 2022	SNL	Implementation of H-embrittlement models in probabilistic fracture mechanics framework	On Track
Sept 2022	SNL	Demonstration of pressure cycling of pipe specimen (supply chain issues)	Likely delayed
Sept 2022	PNNL	Evaluation of slow crack growth response of existing pipeline materials in ambient and pure hydrogen conditions	On Track

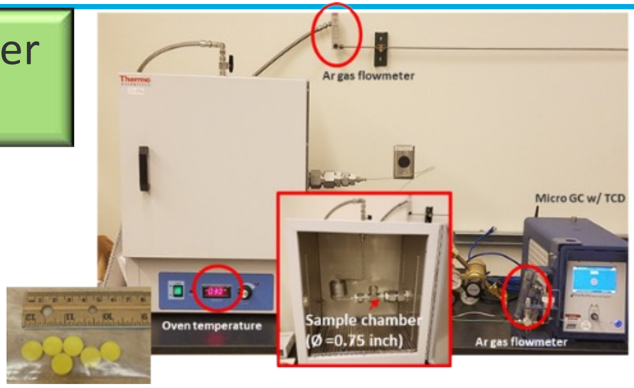
Accomplishment: polymers
Morphological effects of hydrogen over time

No significant change over time in 250 psi pure hydrogen after initial reductions in crystallinity and density

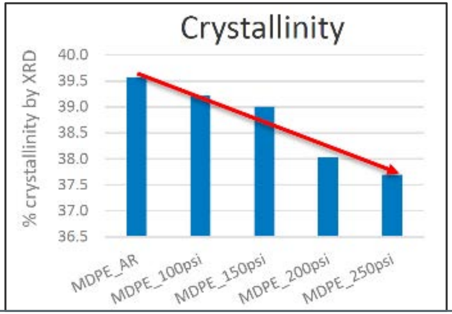


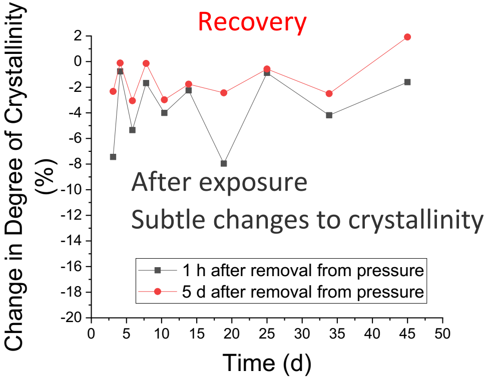
Avg C_0 (wt ppm) = 35





MDPE -PE2708





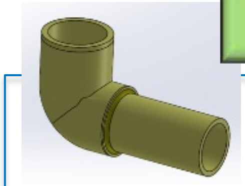
Data will support characterizing failure mechanisms and guiding exposure conditions for mechanical test

Previous work shows decreasing crystallinity with increasing H2 pressure

Accomplishment: polymers

Gap analysis on the impacts of H_2 addition to the NG network

Compatibility must go beyond chemical resistance considerations

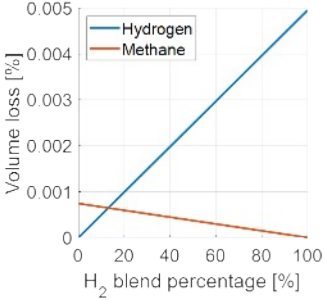


Joints – Heat Fusion

H_2 effects pre and post joining operation

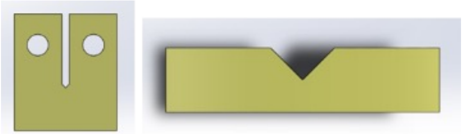
-Antioxidant depletion in fusion zone
-Morphological, physical, mechanical impacts
-Transport properties - Permeability

Permeation through 6.6” Diameter HDPE at 273 K, 10 bar



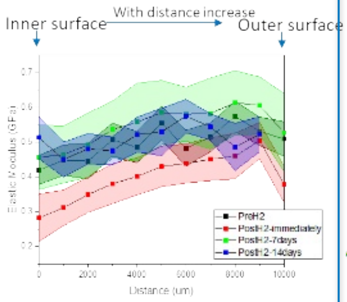
Data from [Zhou, Ersoy, 2010 GTI project Number 21029]

Effects of notches (defects) on creep & fatigue behavior of pipe in H_2 environment



ASTM D5045 Compact Tension & Single Edge Notch Bend

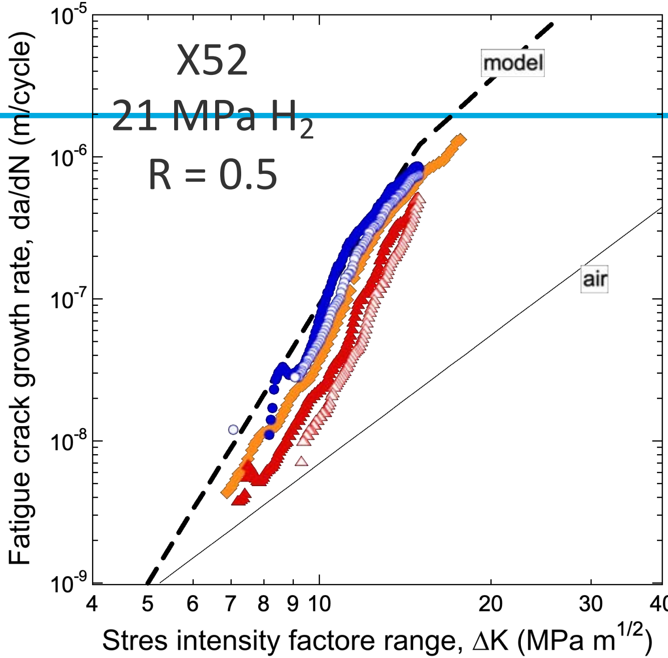
Local modulus decreases in H_2



How do small changes in material properties correlate to long term (50 + yrs) pipe performance?

Accomplishment: metals
Generalizing fatigue behavior

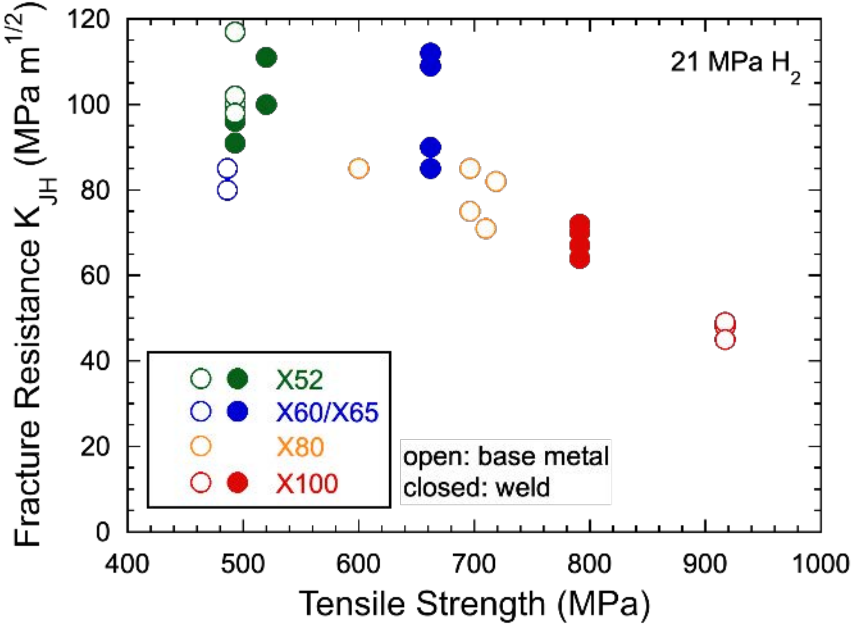
The project team has acquired about a dozen vintage materials from project team members and other stakeholders.



Preliminary assessment:
fatigue crack growth of vintage base metals can be adequately bounded

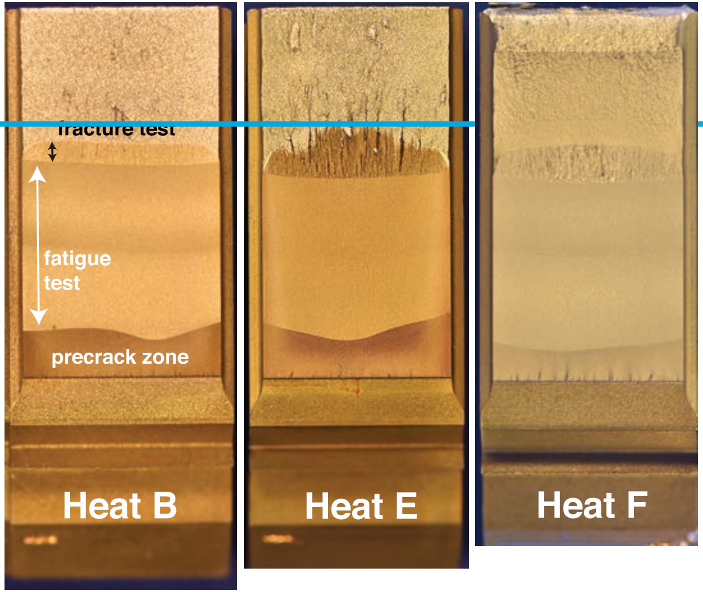
Accomplishment: metals

Assessing fracture resistance



Ref.: Ronevich et al, IJHE 46 (2021)

Ref.: San Marchi and Ronevich, ASME PVP2022-84757



Previous work:

Modern steels show ductile fracture behavior in gaseous hydrogen, vintage steels are anticipated to show lower fracture resistance

Accomplishments and Progress

Response to Previous Year Reviewers' Comments

- This is a new project and has not been reviewed before at AMR

Collaboration and Coordination

- **U.S. DOE National Laboratories**
  - NREL: Project Lead, Techno-economic analysis
  - ANL: Life cycle assessment and emissions analysis
  - PNNL: Polymeric material testing and analysis
  - SNL: Metallic material testing and analysis; supporting polymeric material testing
- **Industry stakeholders**
  - Guide and inform research to yield insights to better inform industry-wide solutions
  - Help identify critical natural gas supply chain segments and hydrogen blending knowledge gaps
  - Provide insight or guidance on how HyBlend-developed tools can be most useful

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
  - High elongation of plastic pipe materials presents in-situ H_2 test challenge
- Metals:
  - Uncertainty remains about the performance vintage steels and their welds in controlled hydrogen environments
  - Mechanisms of hydrogen-assisted fatigue and fracture remain elusive for most materials, including carbon steels

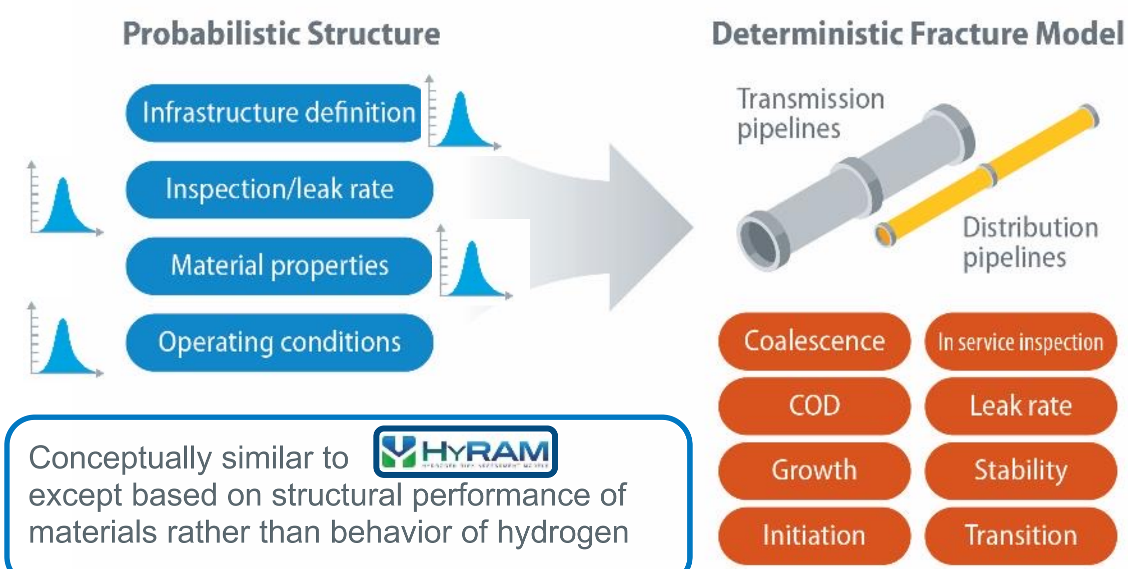
Proposed Future Work

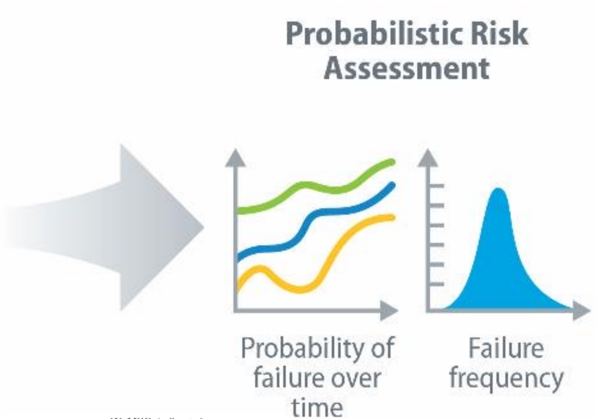
- **Polymers**
  - Fracture testing to evaluate crack propagation in quasi-static, fatigue, and creep conditions
  - Oxidative induction time (OIT) evaluation of antioxidant depletion in pipe operating conditions with new and vintage pipe
  - Assess morphological and physical effects of hydrogen on heat fusion joints
  - Assess pipe lifetime effects of hydrogen blends
- **Metals**
  - Evaluate fatigue and fracture of vintage welds in situ as a function of hydrogen pressure
  - Assess microstructural variety in vintage materials (base and welds) to aid prioritization of testing - *supported by ORNL and EPRI*
  - Develop recommendations to assess hydrogen effects on line pipe steels and minimize future testing burden
  - Deploy probabilistic fracture mechanics tool - **Hydrogen Extremely Low Probability of Rupture (HELPR)**

Proposed Future Work

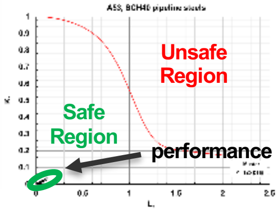
Hydrogen Extremely Low Probability of Rupture (HELPR)

Goal: use NRC framework (xLPR) and state-of-the-art uncertainty analysis to develop probabilistic tool suite for quantitative risk assessment of NG assets containing hydrogen environments





Conceptually similar to HyRAM except based on structural performance of materials rather than behavior of hydrogen



Outputs intended to be aligned with relevant RCS

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**
- **Metals R&D** (see H2IQ Hour presentation 29 March 2022 for previous work)
  - *Preliminary fatigue assessment*: crack growth behavior in hydrogen is bounded and not dependent on alloy or microstructure
  - *Hydrogen-assisted fracture* may be more sensitive to microstructure
- **Polymers R&D**
  - Initial testing shows no change, after initial reduction, in crystallinity or density of MDPE over time in pure hydrogen at constant pressure
    - Previous work did show a hydrogen pressure effect
  - Hydrogen effects on heat fusion joints and effects of defects on the performance of pipe in hydrogen have been identified as gaps

Thank You

Kevin Simmons <kl.simmons@pnnl.gov>

Chris San Marchi <cwsanma@sandia.gov>

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA-0003525.

Technical Backup and Additional Information

Technology Transfer Activities

- **Materials data is intended to be published in the open scientific literature or as unlimited release laboratory authored reports.**
  - Content is often available through https://osti.gov/
  - Hydrogen-assisted fatigue and fracture data is available through an online materials property database: https://granta-mi.sandia.gov/
  - Additional materials content is available at https://h-mat.org/
- **Hydrogen Extremely Low Probability of Rupture (HELPR)**
  - This tool (name subject to change) is intended to be an open-source tool for evaluating structural integrity of piping and pipelines

Special Recognitions and Awards

- none

Publications and Presentations

1. C. San Marchi and J.A. Ronevich, Fatigue and fracture of pipeline steels in high-pressure hydrogen gas (PVP2022-84757), ASME 2022 Pressure Vessels and Piping Conference, 17-22 July 2022, Las Vegas NV (joint with SCS005)
2. R. Shrestha, J.A. Ronevich, L. Fring, K. Simmons, N.D. Meeks, Z.E. Lowe, T.J. Harris Jr, C. San Marchi; “Compatibility of medium density polyethylene (MDPE) for distribution of gaseous hydrogen” (PVP2022-84791), ASME 2022 Pressure Vessels and Piping Conference, 17-22 July 2022, Las Vegas NV (partly funded under previous CRADA).
3. C. San Marchi, “Design and Operation of Metallic Pipelines for Service in Hydrogen and Blends” (SAND2022-3598PE), H2IQ Hour DOE webinar, 29 March 2022.
4. C. San Marchi, J.A. Ronevich, “Hydrogen-assisted fatigue and fracture of carbon steels and the implications of blending hydrogen into natural gas transmission infrastructure“ (SAND2022-0993PE) 2022 HYDROGENIUS, I^{2}CNER, HydroMate and SINTEF Joint Research Symposium (invited), 27 January 2022.
5. C. San Marchi and J.A. Ronevich, “Implications of Gaseous Hydrogen on Welded Construction of Pipelines” (SAND2022-0429PE), 2022 API/AGA Joint Committee on Oil and Gas Pipeline Welding (invited) 26 January 2022.
6. J.A. Ronevich, C. San Marchi, “Pipeline steels for hydrogen service” (SAND2022-0241PE), LRCI – Delivery and Storage Technical Subcommittee, 11 January 2022.
7. C. San Marchi and J.A. Ronevich, “HyBlend Overview” (SAND2021-11647O), presentation to API Task Group – Welding of Hydrogen Fuel Gas Pipelines 21 September 2021.

Contributors to Materials R&D tasks

Sandia National Laboratories
- Chris San Marchi (PI)
- Joe Ronevich (fatigue and fracture)
- Remi Dingreville (HELPR)
- Ben Schroeder (HELPR)
- Khalid Hattar (mechanisms)
- Nalini Menon (polymers)
- Rakish Shrestha (post-doc)
- Kathryn Small (post-doc)
- Ryan DeMott (post-doc)
- James McNair (testing)
- Brendan Davis (testing)

Pacific Northwest National Laboratories
- Kevin Simmons (PI)
- Lisa Fring (polymers)

Other key contributors (performing activity level work)
- Yanli Wang (ORNL)
- Zhili Feng (ORNL)
- Prof. T.A. Venkatesh (Stony Brook U.)
- Michael Gagliano (EPRI)
- Jonathan Parker (EPRI)

And our many stakeholders