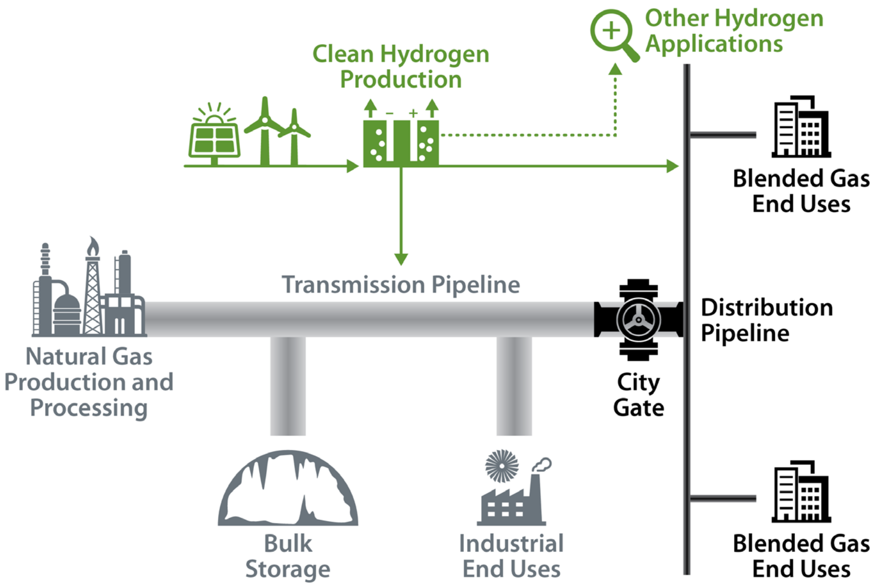
Hydrogen Blending in Natural Gas Pipelines

HyBlend
U.S. DEPARTMENT OF ENERGY

Reducing the Carbon Intensity of the Natural Gas Grid via Hydrogen Blends

Phase I: Two-year, $15MM CRADA Project

- 4 National Labs + 31 partners from industry and academia
- Objectives
  - Pipeline materials compatibility R&D
  - Techno-economic and life-cycle analyses



Key Findings and Outputs

- Metals R&D (SNL)
  - Providing scientific bases and probabilistic tools for structural integrity assessment of H_2 pipelines (HELPR software release date: Fall 2023)
- Polymer R&D (PNNL)
  - Blended gases affect the semicrystalline morphology of high-density polyethylene (HDPE), impacting toughness, pipe stability, and outcome depending on polymer chemistry
- Life-cycle Analysis (ANL)
  - Maintaining energy delivery limits the H_2 blending ratio to ~30%, resulting in ~6% life cycle GHG emissions reduction
- Techno-economic Analysis (NREL)
  - Open-source software providing case-by-case economic analysis of preparing transmission pipelines to blend H_2 (PPCT software release date: Fall 2023)

- **Learn more at the October H2IQ Hour**
  - Lab leads will present results from first CRADA at the webinar
  - Thursday October 26 at 12:00 Eastern time

Visit the HyBlend™ Initiative webpage for details and links to tools and publications

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Seeking Partners to Contribute to a Second Pipeline Blending CRADA

In Planning Stage of Follow-on CRADA (Phase II)

- Same core labs
- 3-year CRADA open to new partners from industry, academia, nonprofits
- $12MM DOE funding*
- Seeking $5.4MM cash cost share
  - Asking partners for minimum $25k/year cash commitment
  - Additional in-kind contributions welcome
- In-person kickoff meeting anticipated in December 2023

Benefits of Partnership

- Partners get access to the following:
  - National Lab expertise
  - Data generated by the labs for the CRADA
  - Input on scope of work
  - Monthly project update meetings
  - Quarterly materials meetings
  - Quarterly analysis meetings
  - Lab-generated reports prior to publication
- Partners can advertise they are part of / contributors to HyBlend CRADA

Contact HyBlend_CRADA@nrel.gov for more details

** subject to the availability of appropriated funds, contingent on cost share, not a FOA*

Techno-economic Analysis of Blending Hydrogen into Natural Gas Transmission Networks

Kevin Topolski, Evan Reznicek, Jamie Kee, and Mark Chung (PI)

National Renewable Energy Laboratory (NREL)

Oct 31st, 2023

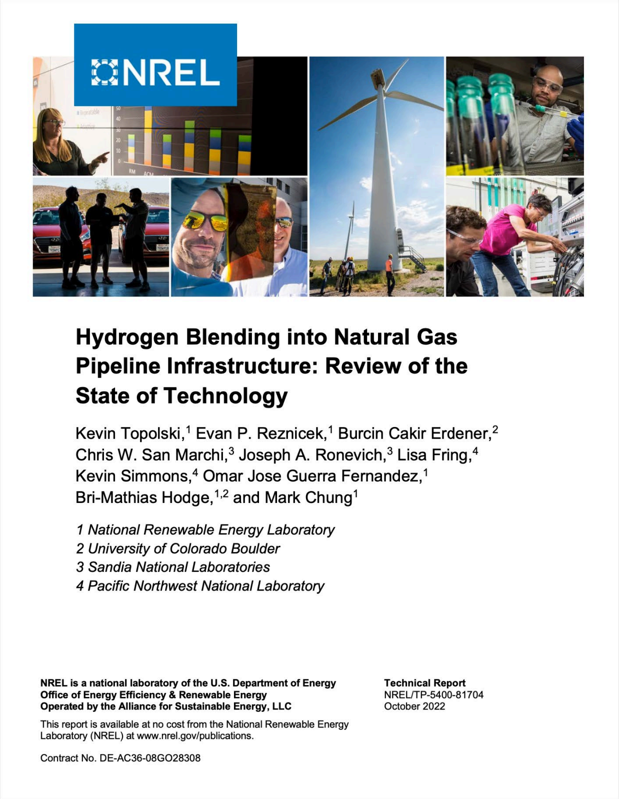
NREL's primary task: develop a model to determine required pipeline upgrades for blending hydrogen and the associated costs

- Develop a Pipeline Preparation Cost Analysis Tool (PPCT) that:
  - Is flexible, open-source and can estimate the system cost to blend hydrogen on a case-by-case basis
  - Captures key natural gas infrastructure elements (e.g compressors, piping, materials, etc.) in techno-economic analysis
  - Uses and improves underlying gas network models to understand hydrogen concentration along the network and its impact on upgrade costs

- Apply analysis to evaluate pipeline network upgrade costs over a range of hydrogen blending scenarios and pipeline networks

- Benchmark hydrogen blending economics (with Argonne National Laboratory) against alternative natural gas decarbonization pathways

NREL's initial efforts in the Pipeline Blending CRADA involved developing a comprehensive literature review



NREL

Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology

Kevin Topolski,[1] Evan P. Reznicek,[1] Burcin Cakir Erdener,[2] Chris W. San Marchi,[3] Joseph A. Ronevich,[3] Lisa Fring,[4] Kevin Simmons,[4] Omar Jose Guerra Fernandez,[1] Bri-Mathias Hodge,[1,2] and Mark Chung[1]

1 National Renewable Energy Laboratory
2 University of Colorado Boulder
3 Sandia National Laboratories
4 Pacific Northwest National Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Technical Report
NREL/TP-5400-81704
October 2022

https://www.osti.gov/biblio/1893355

- Result of a collaborative effort between U.S. Department of Energy Hydrogen and Fuel Cell Technology Office, 3 National Labs and 17 consortium partners

- Key Review Takeaways:
  - Consensus is emerging on H_2 impacts on steel materials and pipeline performance
  - More research is needed on polymers, components, and economics
  - Demonstrations have primarily been conducted on low-pressure distribution systems with residential and commercial end users
  - There are numerous active blending projects today, many applied to the transmission network and some attempting up to 100% H_2

- Ability to blend H_2 in a pipeline is dependent on numerous factors such as end user compatibility, pipeline design and operating conditions; a **case-by-case approach to evaluation is necessary**

NREL developed a Pipeline Preparation Cost Analysis Tool (PPCT) that provides case-by-case TEA capabilities

- The PPCT is a Python tool that answers the following:
  - What modifications to the pipeline network are necessary to enable blending up to *X*% of hydrogen in pipeline gas?
  - What incremental capital investment and operating expense are required to upgrade the natural gas pipeline network for *X*% of hydrogen in pipeline gas?
- This model targets application at the initial project assessment stage for transmission pipelines
- Intent is to provide the user with an understanding of the <u>most promising opportunities</u> before proceeding with more detailed pipeline inspections based on "probable" economic outcome

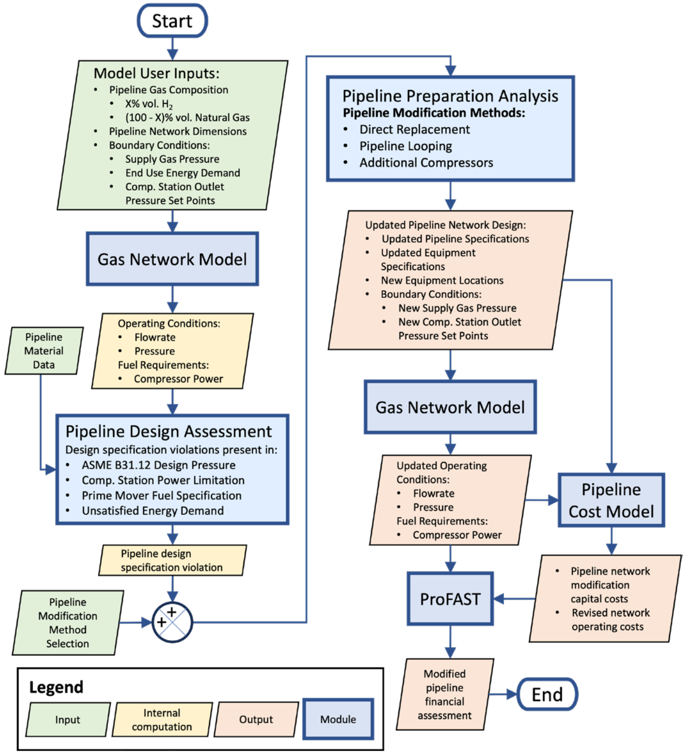
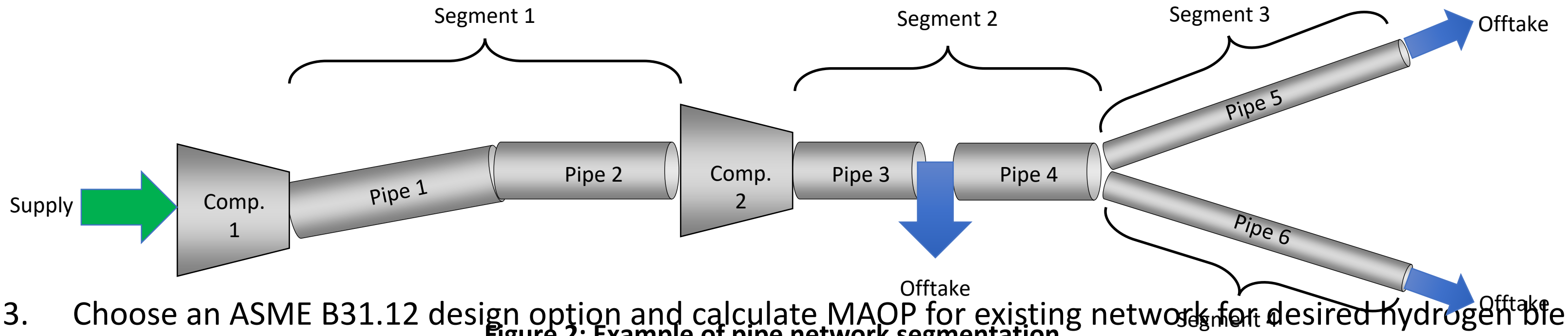


Figure 1: Pipeline Preparation Cost Analysis Tool framework.

The design assessment module models existing pipeline, identifies pipe segments, and calculates design pressures

1. Given network data (pipe topology, length, diameter, schedule) and desired hydrogen fraction, model the existing pipeline network to identify necessary operating pressures and flowrates to meet demand

2. Identify independent pipe segments:
   - Separated by compression stations or pressure reduction stations for line-packing
   - Separated by changes in pipe diameter for in-line inspection
   - May have multiple pipes within one segment with different age, grade, elevation, etc.
   - Can have an offtake mid-segment if it does not result in change in diameter



3. Choose an ASME B31.12 design option and calculate MAOP for existing network for desired hydrogen blend

Figure 2: Example of pipe network segmentation.

The design modification module models three independent methods for accommodating hydrogen

- **Method 1: Directly replace existing pipes that cannot meet required pressure**
  - Identify pipes that violate ASME B31.12 requirements for a chosen design option
  - Replace those pipes with new pipes of the same diameter (presumably use design option B for new pipes)
  - *Modify or replace compressors necessary to meet required operating pressure*
  - *Replace valves and meters as necessary to handle hydrogen*
  - This method requires removing existing pipe, but we assume no new right-of-way costs

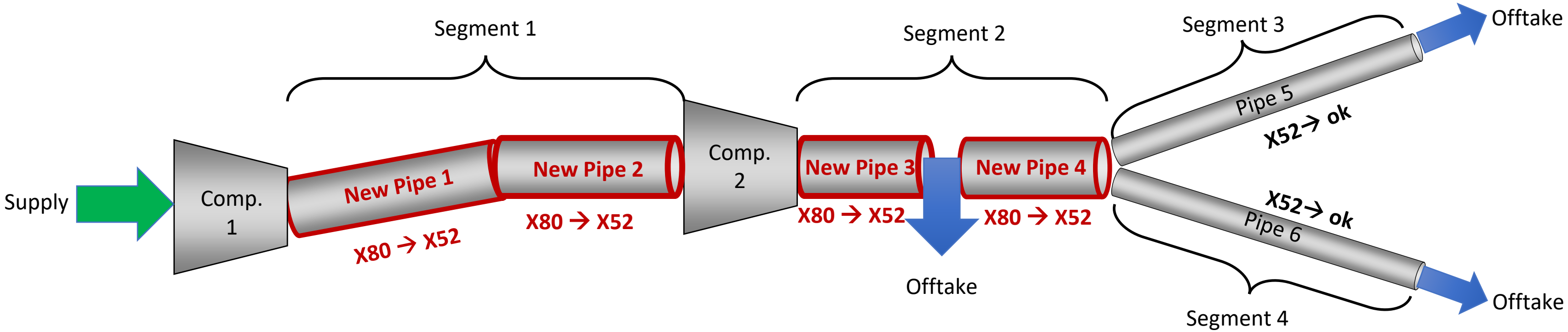


Figure 3: Example of pipe network modification with direct pipe replacements.

The design modification module models three independent methods for accommodating hydrogen

- **Method 2: Build parallel loops to increase capacity at reduced operating pressure**
  - Reduce operating pressure of existing pipe to that allowed by ASME B31.12 given design option employed
  - Build pipe parallel to existing pipe to accommodate higher volumetric flow at lower operating pressure
    - Calculate loop length for different diameters
    - Select least-cost loop diameter and schedule that allows network to meet all demand
  - *Modify or replace compressors as necessary to meet required operating pressure*
  - *Replace valves and meters as necessary to handle hydrogen*
  - This method keeps existing pipe but incurs additional right-of-way costs for added new parallel pipe

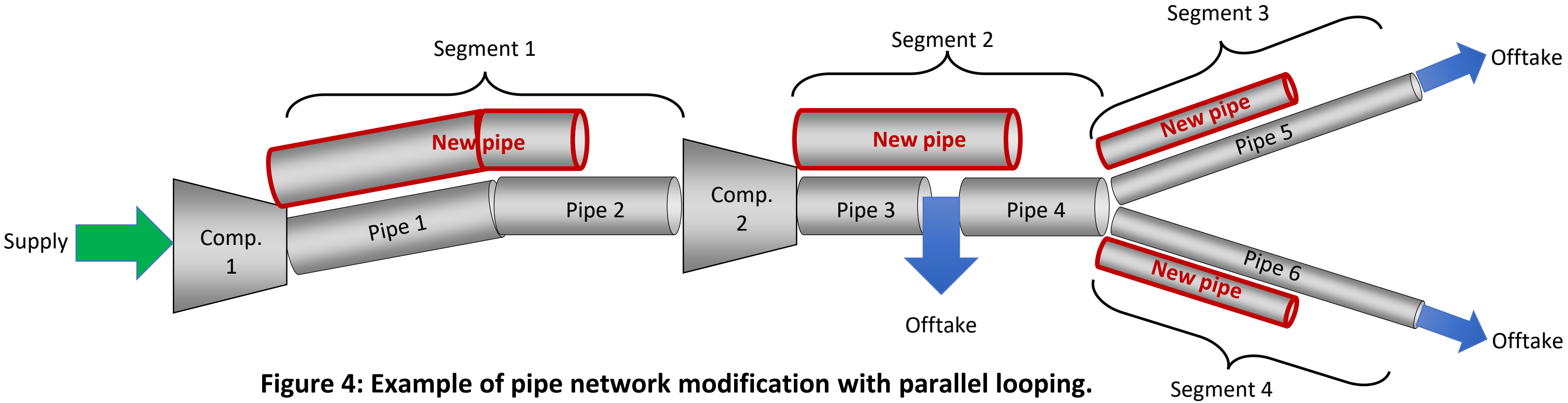


Figure 4: Example of pipe network modification with parallel looping.

The design modification module models three independent methods for accommodating hydrogen

- **Method 3: Build new compressor stations along existing pipeline and operate at reduced pressure**
  - Reduce operating pressure of existing pipe to that allowed by ASME B31.12 given design option employed
  - Calculate number and placement of additional compression stations to increase volumetric flow through existing pipeline at reduced operating pressure
  - *Modify or replace existing compressors necessary to meet required operating pressure*
  - *Replace valves and meters as necessary to handle hydrogen*
  - This method keeps existing pipe but requires more frequent compression stations

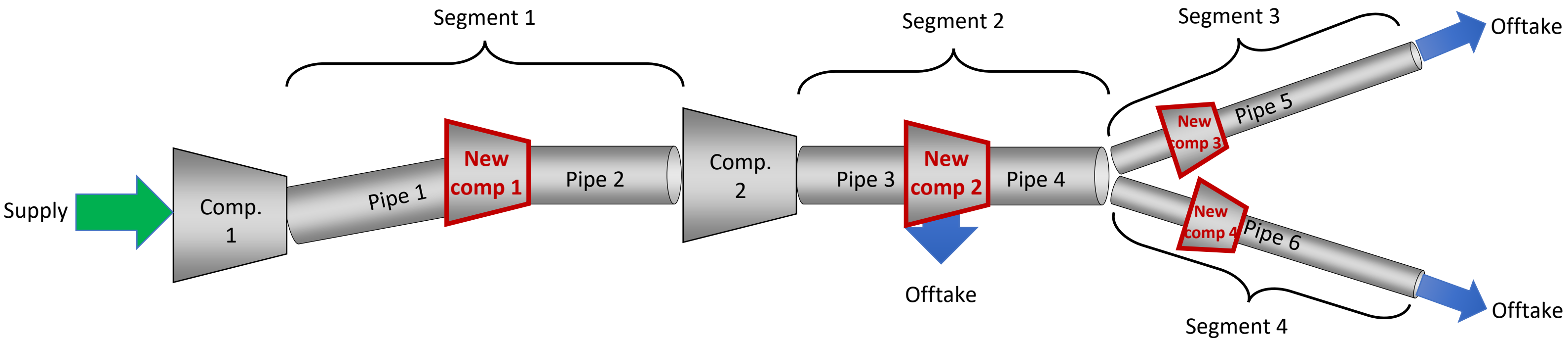


Figure 5: Example of pipe network modification with additional compression capacity.

Alliance Pipeline serves as a preliminary PPCT case study demonstration

- Alliance Pipeline is a well-documented, large-scale pipeline representative of future potential blending scenarios

- Case study covers 327 mi segment of U.S. pipeline; simulated to transport 1,544,000 MMBTU/d of gas to end users (enough to heat 924,000 homes a day*)

- Demonstrated each modification method to assess costs to achieve up to 40% vol H_2 for a 2030 cost scenario
  - Assumed revised design factor of 0.4 – worst case scenario based on ASME B31.12

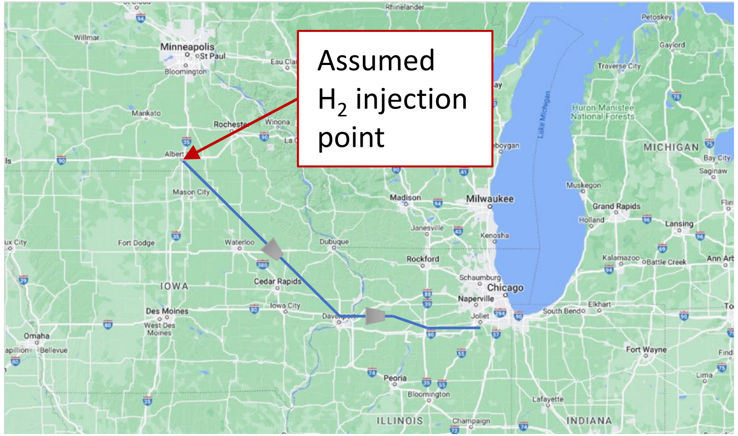


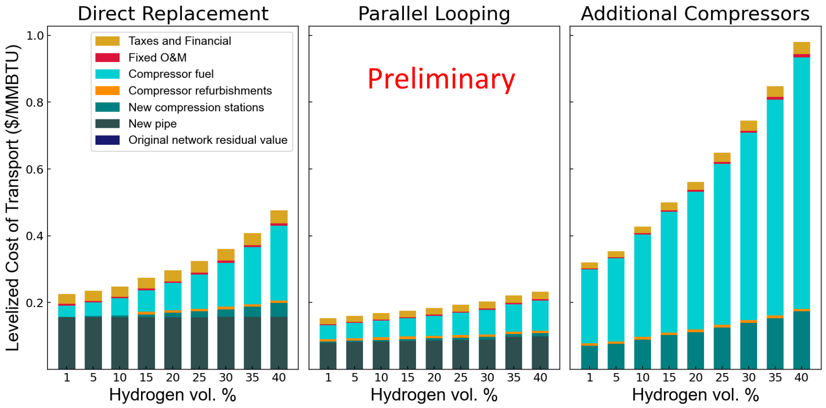
Figure 6: Segments of Alliance Pipeline (—) and compressor stations (▶) represented in case study

Table 1: Preliminary Network design modification results for each method applied for blending to 20% by vol. hydrogen

Applied PPCT Modification Method	ASME B31.12 Design Pressure	Required length of added new pipe	Compressor stations (CS) added	Required increase in CS rated power	Transported gas used as fuel
Direct pipe replacement	1989 psig	327 miles	-	102%	1.09%
Parallel looping	992 psig	288 miles	-	50%	0.82%
Additional Compressors	992 psig	-	11	925%	5.51%

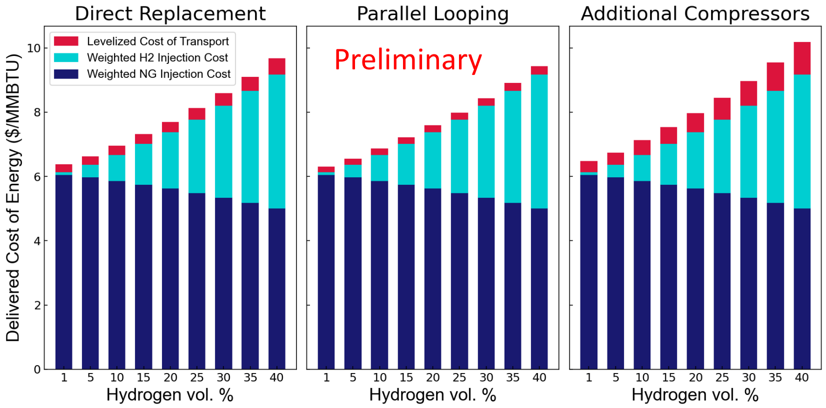
*Assuming 1,037 Btu/cf gas heat content and 588 cf/yr average residential natural gas consumption

Levelized cost of transport (LCOT) is estimated for blends up to 40% vol. H_2 in Alliance Pipeline case study w/o IRA incentives and w/ considering 40% SMYS design factor for existing pipe



Levelized cost of transport for each pipeline modification method applied to case study from 1% to 40% vol. H_2 in pipeline gas

- Direct replacement and parallel looping modifications are favored for this case study
  - Direct replacement involves higher pipe costs than parallel looping
  - Compressor capex and fuel costs are greater for direct replacement relative to parallel looping for blends ≥ 10%
  - Additional compressors method has no new pipe costs but very high compressor capex and fuel costs



Delivered energy cost for each pipeline modification method applied to case study from 1% to 40% vol. H_2 in pipeline gas

- LCOT is a small portion of delivered cost of energy
- Delivered energy cost increases with increasing H_2 blending (at **\$23.99 - \$25.13 per MMBTU H_2** projected for 2030 w/out incentives)

Capital and operating costs associated with pipeline modification to accommodate hydrogen have a small impact on the delivered cost of energy

PPCT Summary

- The PPCT provides users with the capabilities to:
  - Identify potential system upgrades to blend H_2 up to *X%* in pipeline gas
  - Estimate capital and operating expenses associated with system upgrades

- The PPCT captures the following:
  - Consideration for a variety of pipeline network design and operating conditions to enable case-by-case pipeline network assessment and modification
  - Three industry pipeline network modification strategies as potential methods that users could apply in analysis
  - The economic impact of applying ASME B31.12 design option and modification method to existing natural gas transmission pipelines when converting service to transport blended H_2

- The results present users with an understanding of preliminary economic outcomes associated with H_2 blending during early-stage project concept screening

Thank You

NREL/PR-5400-87676

NREL is hosting a webinar to provide a tutorial on how use the PPCT on Jan. 16th, 2024. See QR code (above) for the webinar registration

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Hydrogen-assisted fatigue and fracture of line pipe steels

Chris San Marchi (PI), Joe Ronevich

Sandia National Laboratories (SNL)

Oct 31st , 2023

Scope of Work for CRADA phase 2

- Materials Compatibility – Metals
  - Probabilistic Fracture Mechanics software:
    - Extend probabilistic tools
    - Add new defect configurations (including ML algorithms)
  - Subscale Pipe Testing
    - Develop strategies to quickly and efficiently test surrogate defects
  - Fatigue and Fracture Testing in Gaseous Hydrogen
    - HAZ and welds of seam and girth
    - Crack nucleation and propagation from PRCI threats (hard spots, dents, wrinkle bends, etc)
    - Assess operational influences: constraint (SENT), overloading, non-uniform stress cycles, etc

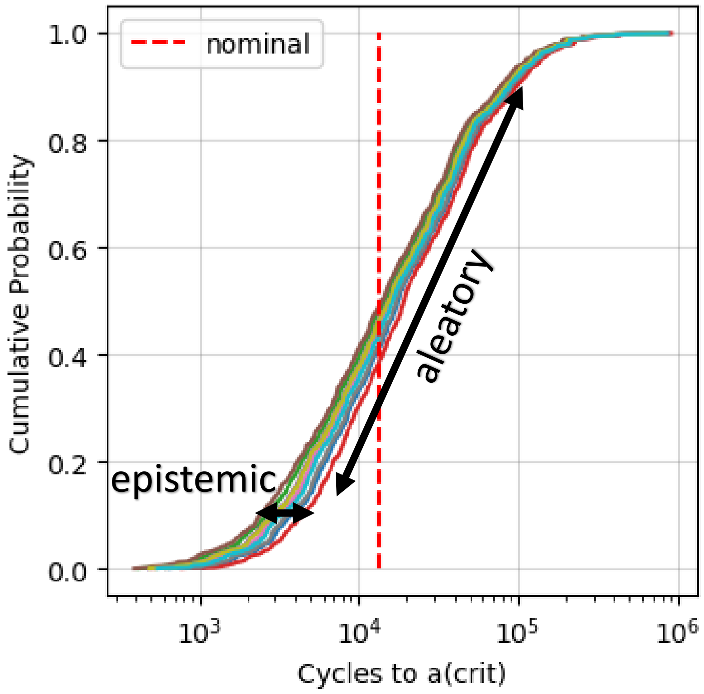
H

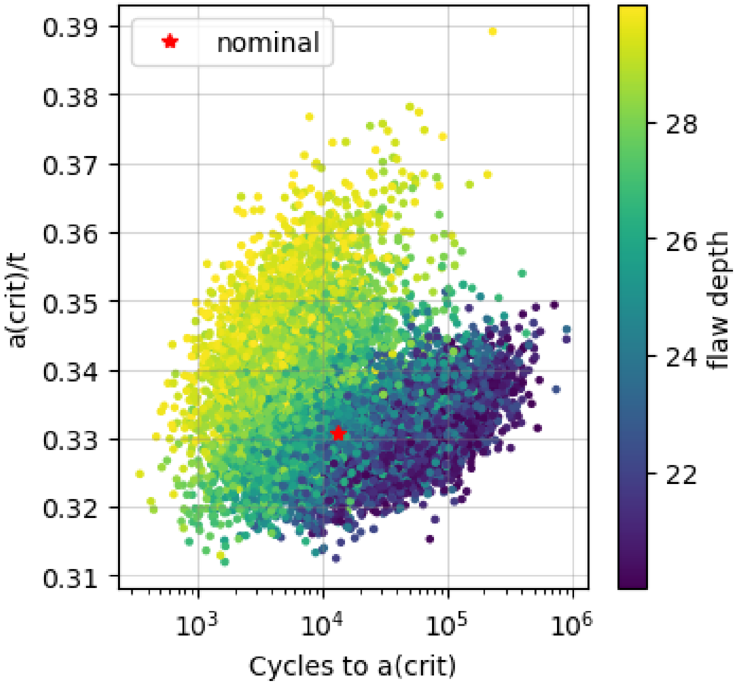
f Rupture

Probabilistic fracture mechanics software

f Rupture

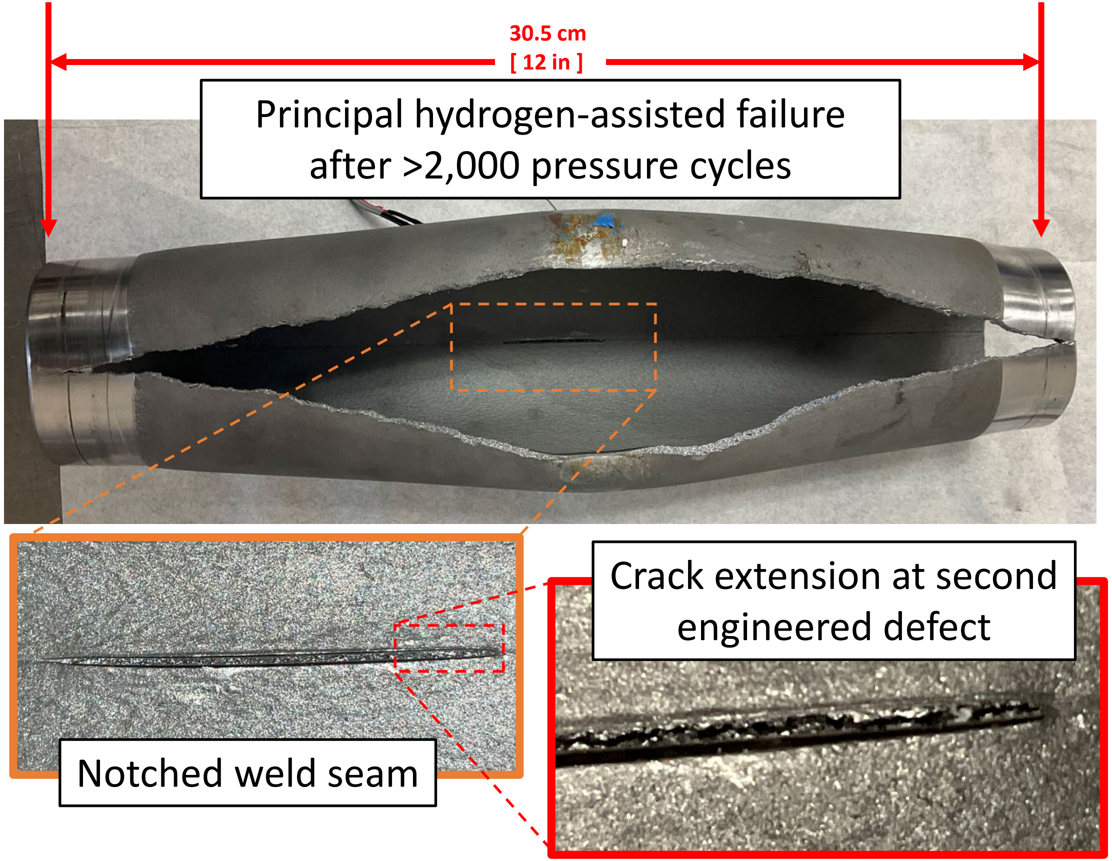
Implementation of both aleatory & epistemic uncertainty

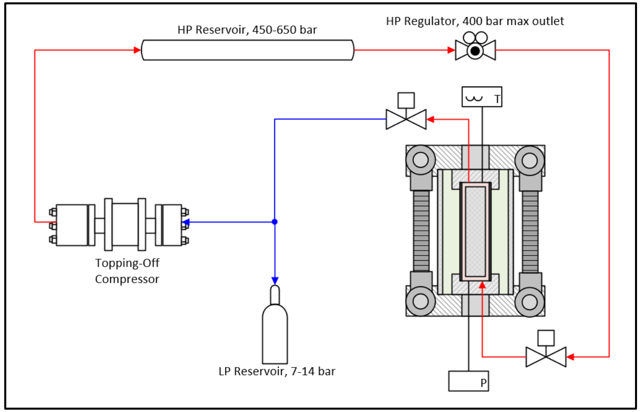




Probabilistic prediction of fatigue (& fracture) response

Subscale pipe testing

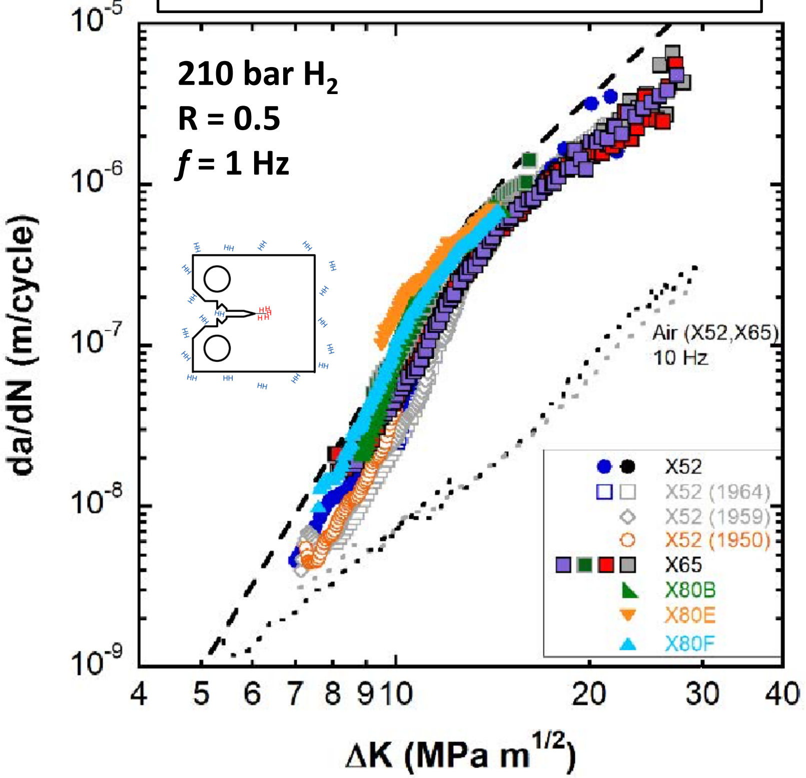




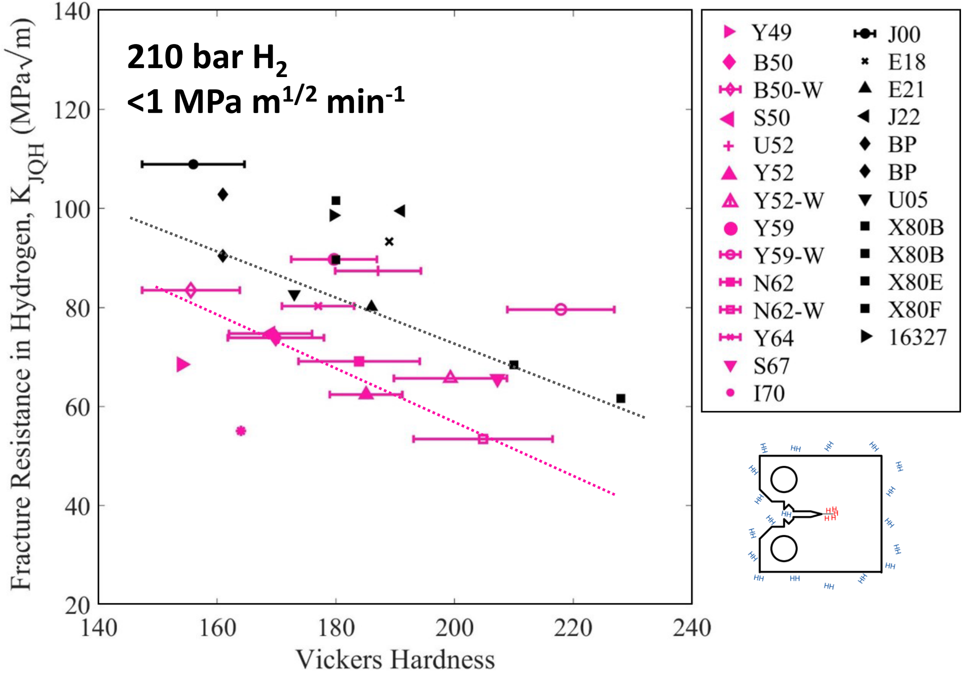
- Subscale Component Hydrogen Test System (SCHyTS) constructed and deployed
- Hydrogen-assisted fatigue failure demonstrated
- Additional tests underway

Hydrogen-assisted fatigue and fracture

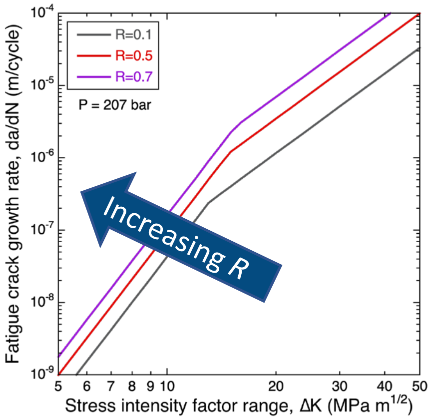
Hydrogen-assisted fatigue in consistent for line pipe steels



- Hydrogen-assisted fracture scales with hardness
- Modern steels are moderately more resistant



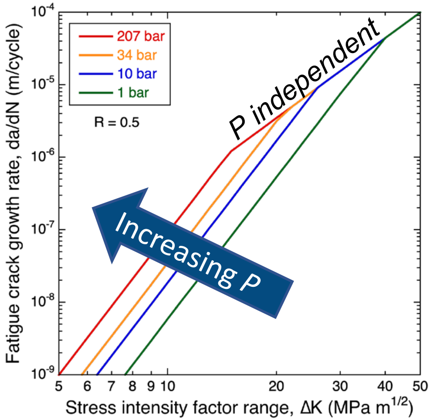
ASME B31.12 Code Case 220

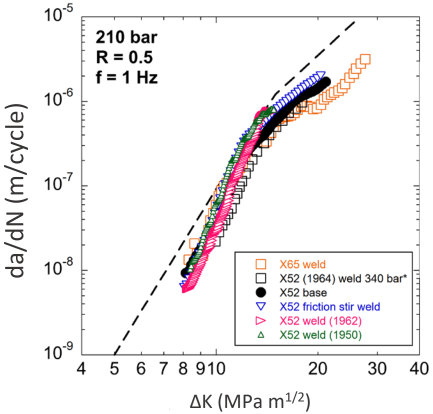


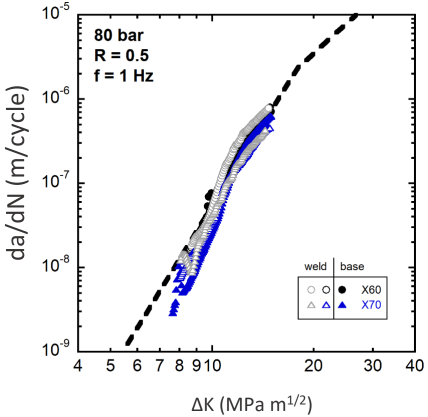
The effects of pressure and load ratio on fatigue crack growth are captured in conventional power law formulation:

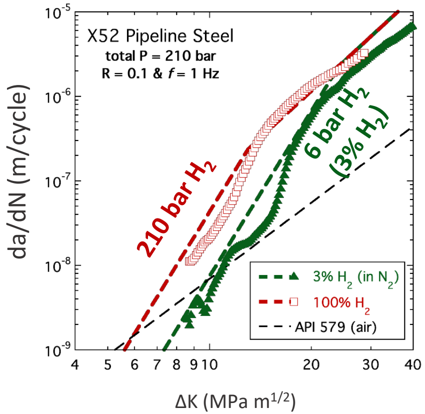
Low ΔK → $$\frac{da}{dN} = 3.5x10^{-14}\left[\frac{1+0.4286R}{1-R}\right]\Delta K^{6.5}g(P)$$

High ΔK → $$\frac{da}{dN} = 1.5x10^{-11}\left[\frac{1+2R}{1-R}\right]\Delta K^{3.66}$$









Outcomes from CRADA phase 1

- Materials Compatibility – Metals
  - Probabilistic Fracture Mechanics software:
    - Basic platform and GUI established for simulation of thumb-nail cracks loaded by hoop stress
  - Subscale Pipe Testing
    - Methodology demonstrated, hydrogen-assisted failure can be induced in subscale pipe test specimens with engineered defects
  - Fatigue and Fracture Testing in Gaseous Hydrogen
    - Basic trends of fatigue crack growth and fracture established for vintage and modern line pipe steel
    - Improved design curves developed (sensitive to pressure and load ratio) and implemented in B31.12 (Code Case 220)

H

f Rupture

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Thank You

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Additional resources:

- https://h-mat.org/
- https://www.sandia.gov/matlsTechRef/
- https://granta-mi.sandia.gov/

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Hydrogen effects on MDPE and HDPE Pipeline Materials

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Oct 26th, 2023

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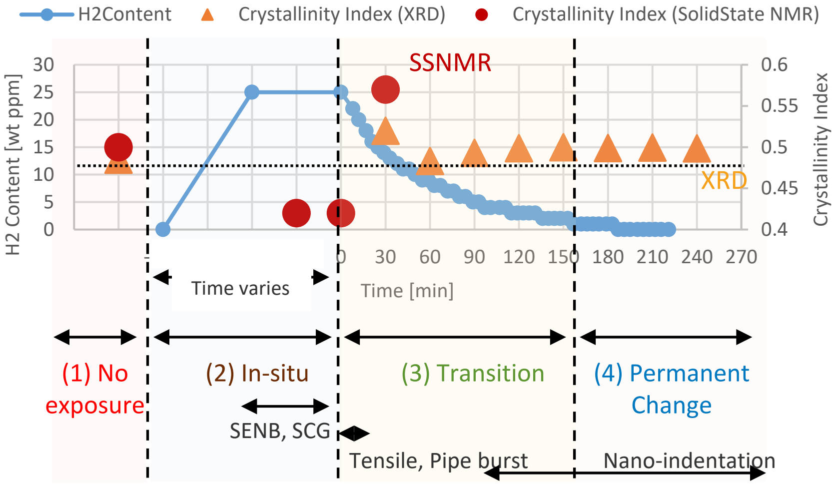
Outcomes from CRADA Phase 1

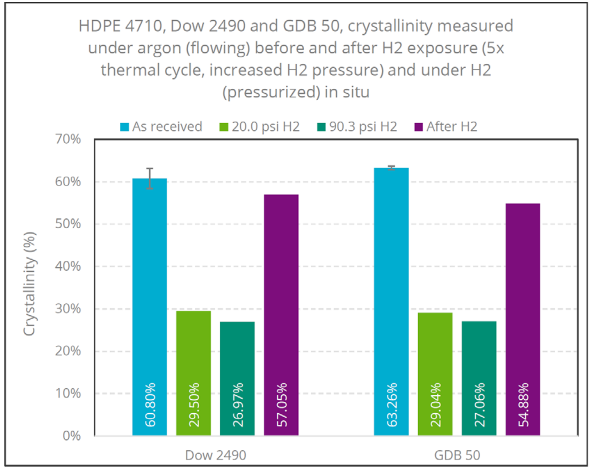
- Materials Compatibility – Polymers
  - Time dependence on testing
    - In situ testing and time after exposure are important factors for material evaluation
    - Hydrogen gas influences the crystalline morphology
    - Polymer chain branches influence the effects of hydrogen
  - Hydrogen influences material properties
    - Tensile,, single-edge notched beam, and slow crack growth demonstrated that pipeline materials can have improved performance with exposure to hydrogen with a few materials that had reduced performance
    - Butt fusion joints show improved tensile strength performance with hydrogen and blended gas exposure

Time dependence on polymer crystallinity

Hydrogen effects on crystallinity and their relationship with time

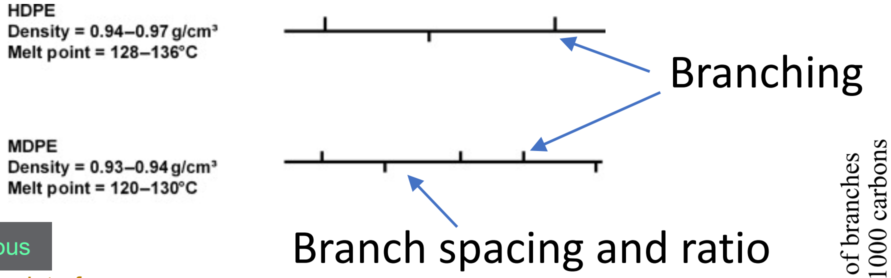


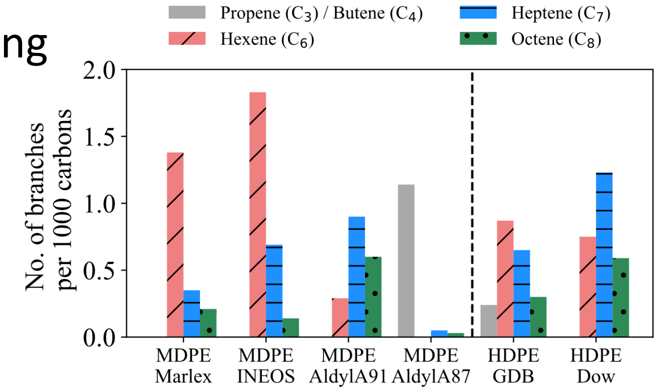
High-Pressure DSC with hydrogen at two pressures confirms effect on crystallinity

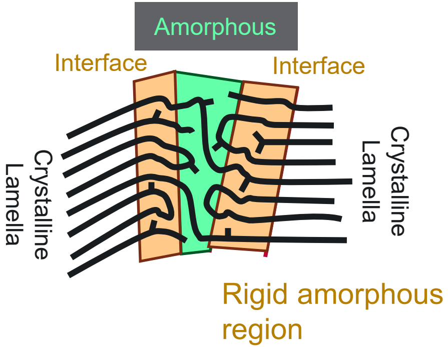


Hydrogen influences chain mobility through a plasticization effect

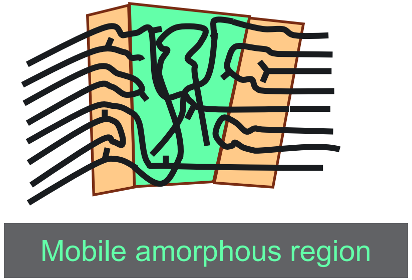
Polymer structure influences crystalline and amorphous regions

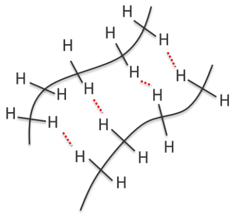




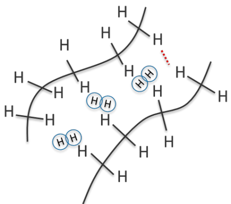


Plastic Manufacturers design their polymers with different branch lengths and ratios

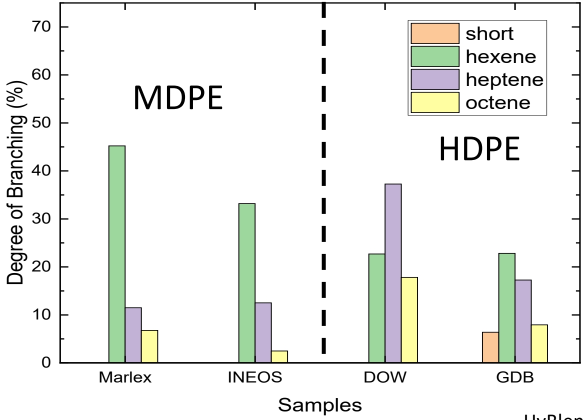




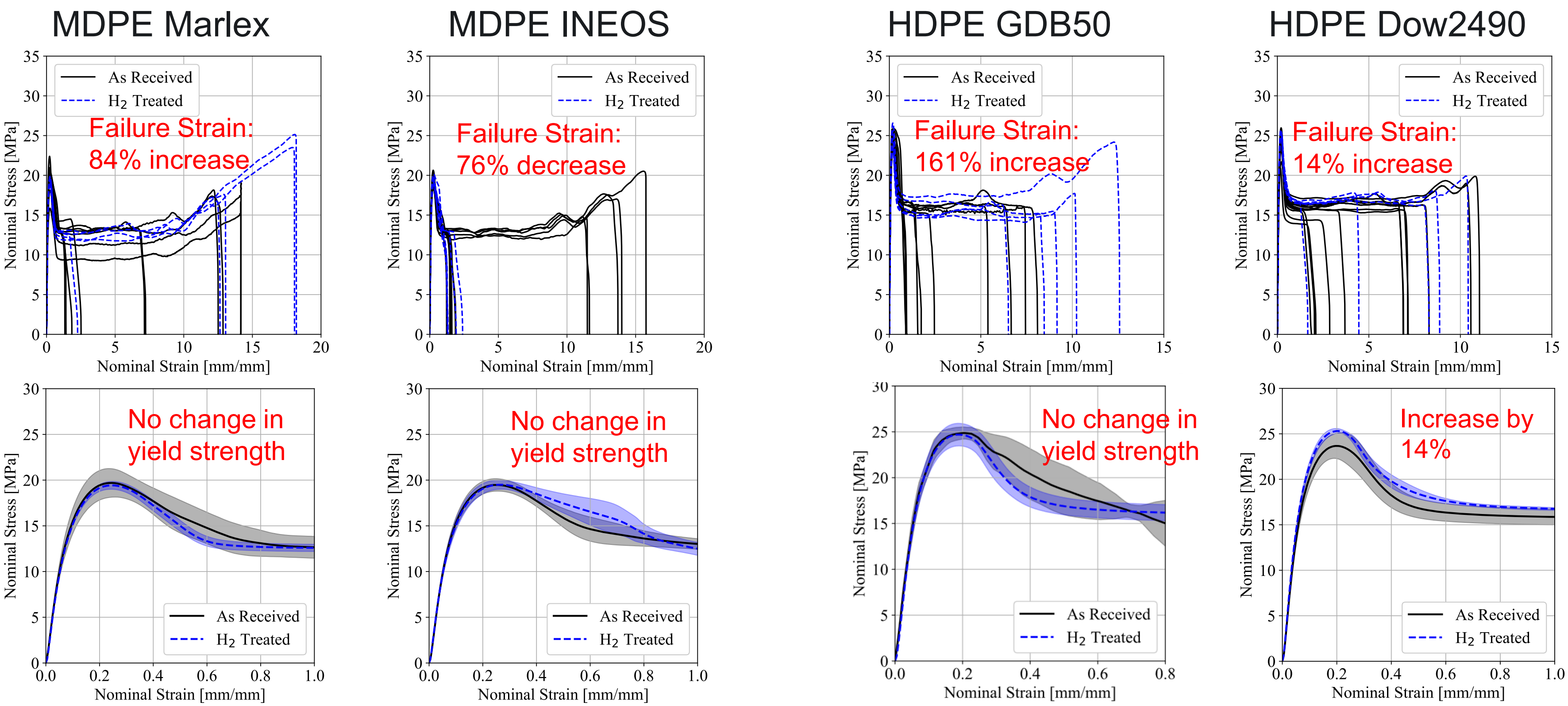
Weak intermolecular bonding exists



Similarly, hydrogen molecules interrupts intermolecular bonds



Hydrogen influence on tensile properties



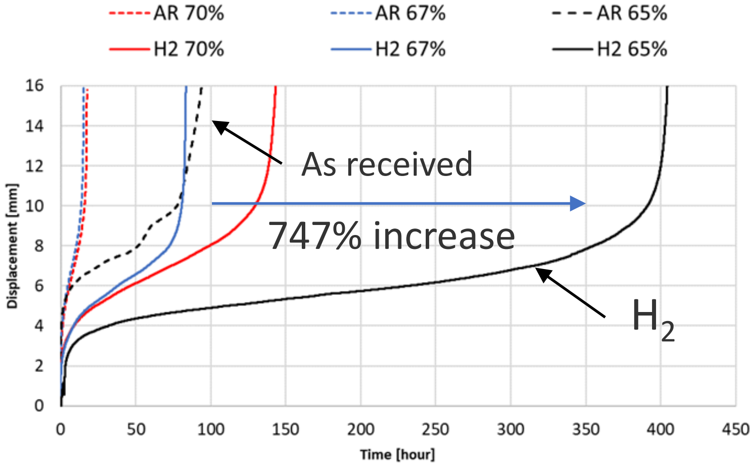
Hydrogen has different effects depending on the polyethylene chemical compositions.

Slow crack growth and hydrogen molecules

In situ
experiment

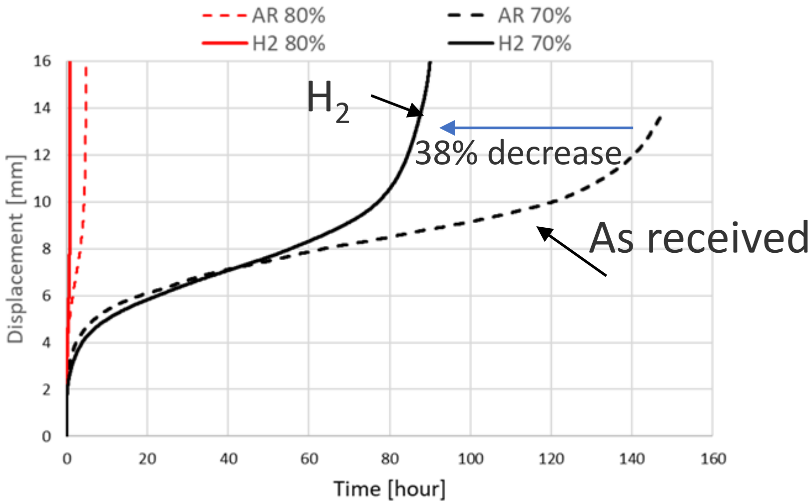
Slow crack growth rate changed under the hydrogen environment (250 psi at room temperature).

HDPE$_{Dow}$



From As-Received to H_2
Time-to-failure increases by 747 %

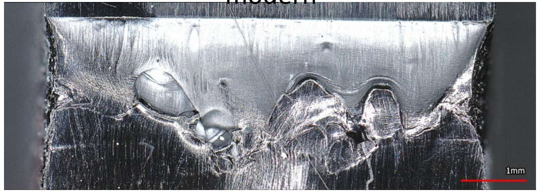
MDPE$_{INEOS}$



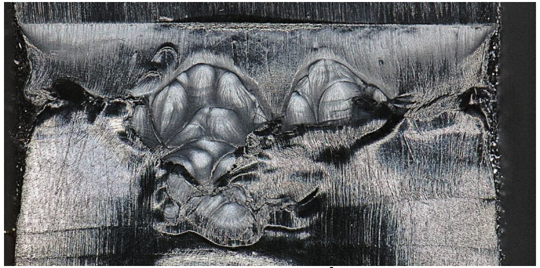
From As-Received to H_2
Time-to-failure decreases by 38 %

Enhanced void nucleation in HDPE under different gases

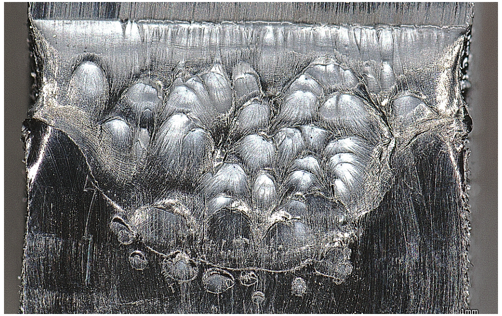
$HDPE_{modern}$ in air



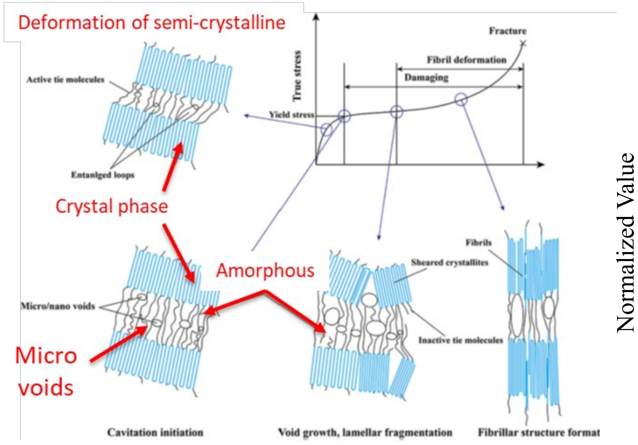
$HDPE_{modern}$ in H_2



$HDPE_{modern}$ in 80/20 blend

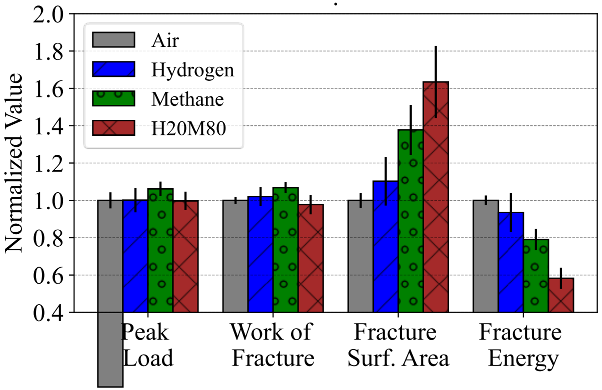


Enhanced dimple pattern



[Zhang et al. 2019, JMaterSci]

PE 4710 $HDPE_{modern}$

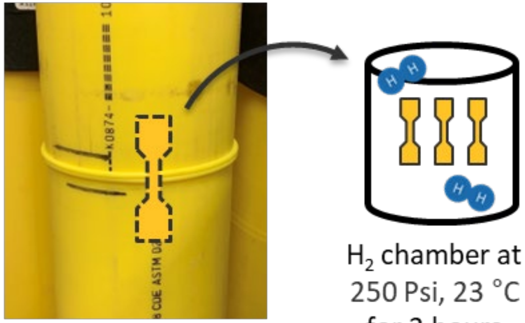


$HDPE_{GDB50}$ experiences fracture energy degradation from the hydrogen (↓5%), methane (↓21%), and the blended (↓42%) gases. $MDPE_{Marlex}$ is increased by 15% and 18% for hydrogen and methane, respectively.

Hydrogen improved butt-fusion joints hydrogen and blended gas

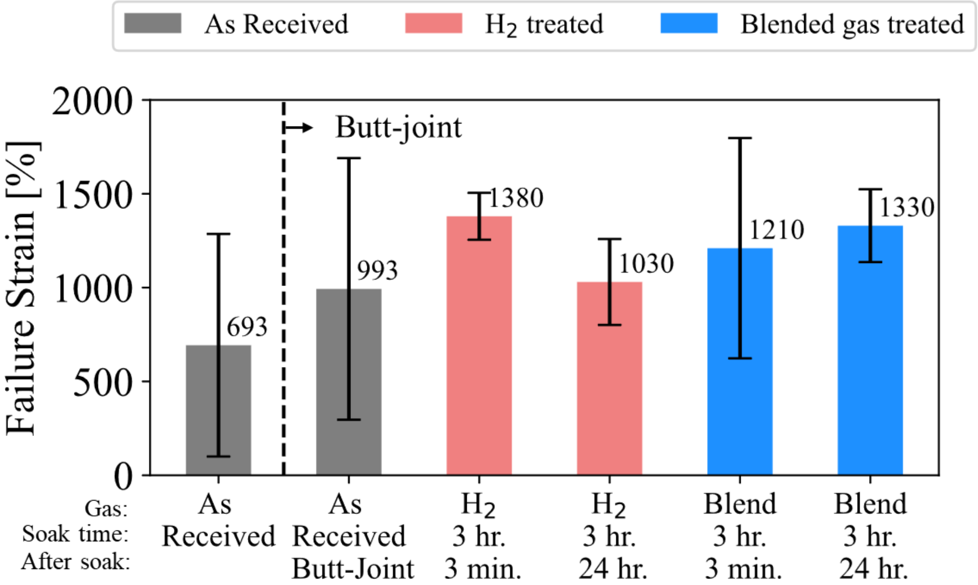
$MDPE_{INEOS}$ @ 250 psi, RT

$MDPE_{INEOS}$



Butt-fusion joint pipes from SoCalGas

H_2 chamber at 250 Psi, 23 °C for 3 hours



The average failure strains are improved and the property variations are reduced.

Scope of Work for CRADA Phase 2

- Materials Compatibility – Polymers
  - Aging Threats to Polymer Piping
    - Long-term material performance
    - Modeling of long-term performance for 50 years and beyond
  - Aging Threats to Fused Butt Joints
    - Evaluating the effects of long-term butt fused joints
  - Materials for Mechanical Fittings
    - Evaluation of materials used in mechanical fittings for dissimilar joint materials
  - Gaskets and Seals
    - Blended gas effects on elastomer seal swelling and compression set
    - Lifetime performance of seals
    - Seal leak behavior

Thank You

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Additional resources:

- **https://h-mat.org/**
- **https://www.sandia.gov/matlsTechRef/**
- **https://granta-mi.sandia.gov/**

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