HyBlend
U.S. DEPARTMENT OF ENERGY

# HyBlend: Pipeline CRADA Materials R&D

Project ID: IN035
WBS 8.6.2.1

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# **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** | **Barriers** |
| --- | --- |
| Start: October 2021<br>End: September 2023<br><br>95% complete*<br><br>*As of February 2024 | • Inconsistent Data, Assumption and Guidelines<br>• Insufficient Suite of Models and Tools |

| **Budget** | **Partners** |
| --- | --- |
| Total FY21-FY23 funding for collaborative HFTO project: $15 M<br>• DOE Share: $11 M<br>• Cost Share: $4 M<br><br>Total DOE funds received to date (HFTO): $11 M | ***National Labs***<br>Argonne National Laboratory – Amgad Elgowainy, PI<br>National Renewable Energy Laboratory - Mark Chung, PI<br>Pacific Northwest National Laboratory – Kevin Simmons, PI<br>Sandia National Laboratories – Chris San Marchi, PI<br><br>***Industry Stakeholders*** *(alphabetical)*<br>Air Liquide, Chevron, DNV, Enbridge, EPRI, ExxonMobil, GTI Energy, Hawaii Gas, Hydril, National Grid , NJNG, ONEGAS, Operation Technology NFP, PRCI, SMUD, Southern Company, Stony Brook University, SWRI, Utilization Technology Development NFP |

# **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

[1] Celestine et al., *Sustainability 13* (2021) 12654.
[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. U.S. DOT PHMSA.

# HyBlend Pipeline CRADA: Materials R&D

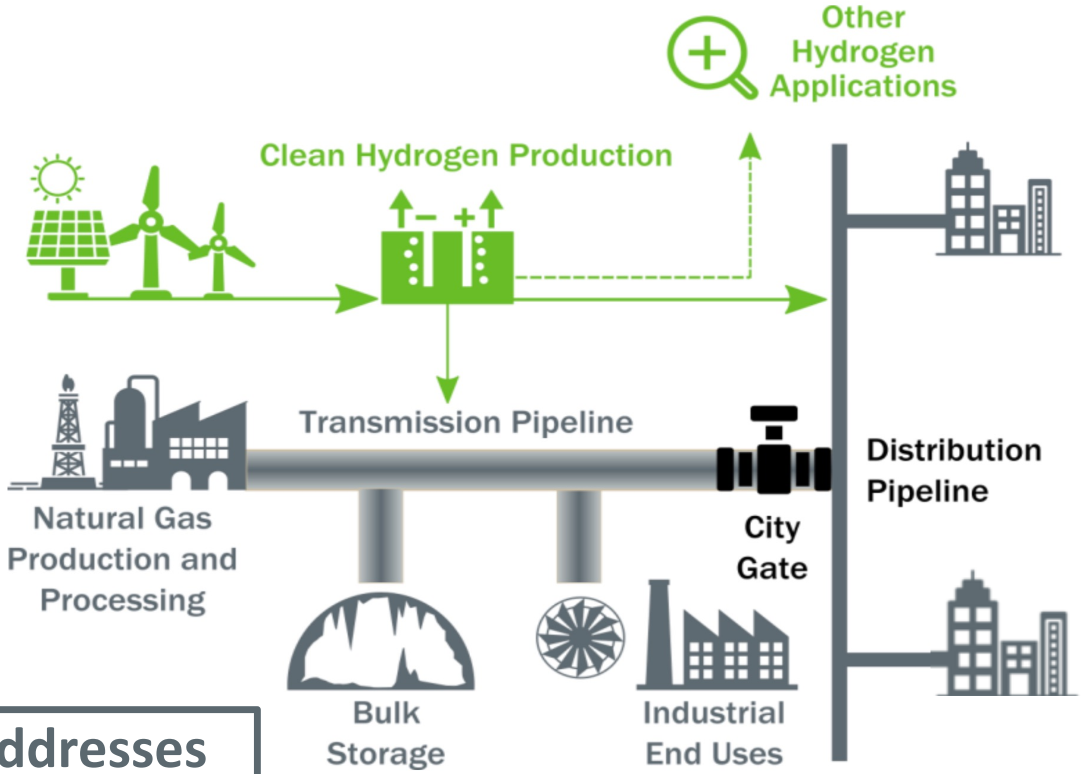
## Transmission

- Mostly steels
- Extensive existing high-pressure networks

## Distribution

- Legacy metals
- Extensive polymer networks

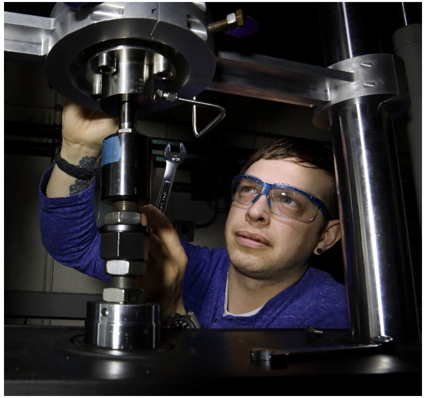
**HyBlend Pipeline CRADA addresses both API steels and polymer piping**



# Approach: Safety Planning and Culture

This project was not required to submit a safety plan for review by the HSP.

- **National Laboratories have over 2 decades of experience in hydrogen R&D**
  - DOE labs have extensive corporate requirements based on state and DOE requirements
  - Dedicated full-time staff to operate high-pressure experiments
- **Weekly safety, planning and discussion meetings**
  - Lab experimental teams meet every week to discussion safety concerns and plan activities for the week as well as share best practices and results
- **Layered safety approach**
  - Gas storage and handling outside building
  - Closed systems (designed with redundant seals and for venting above roof line)
  - Minimized gas volumes
  - Flammable gas sensors integrated with fire alarm system
  - Remote experimental operations (whenever feasible)



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

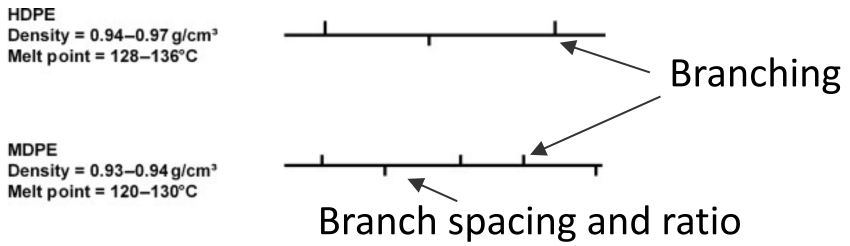
- **Material characterization**
  - Identify morphological characteristics of supplied PE resin systems.
  - Measure in-situ and ex-situ molecular structure changes after hydrogen exposure.
- **Evaluation of slow crack growth performance**
  - Assess long-term slow crack growth performance of polymer pipeline materials in gaseous hydrogen environments.
  - Investigate accelerated slow crack growth testing methodology.
- **Polymer pipe material lifetime prediction model**
  - Evaluate available lifetime performance prediction models.
  - Select and apply the model to slow crack growth test data.

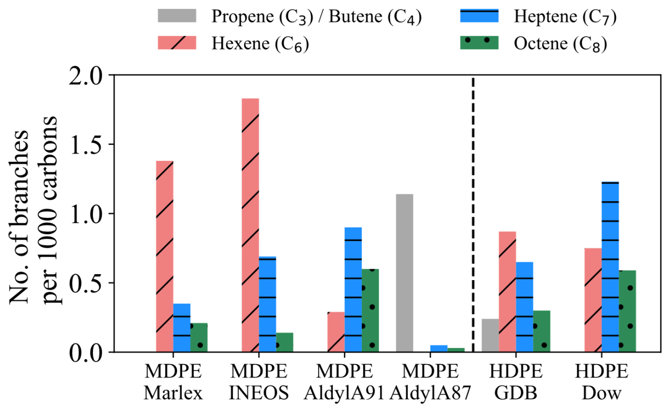
# **Approach:** Milestones for Polymers R&D

| Due Date | Lab | Description | Status |
|---|---|---|---|
| **June 2023** | **PNNL** | Evaluation of slow crack growth in hydrogen blends | **Completed** |
| **Sept 2023** | **PNNL** | Evaluation of crack growth models for predicting pipe lifetime | **Completed** |
| **Dec 2023** | **PNNL** | Test method development of long-term mechanical, thermal, and morphological changes in PE materials | **Completed** |
| **March 2024** | **PNNL** | Evaluation of hydrogen effects on viscoplastic mechanical properties of thermally fused PE materials | **On Track** |

# Accomplishment: Polymers

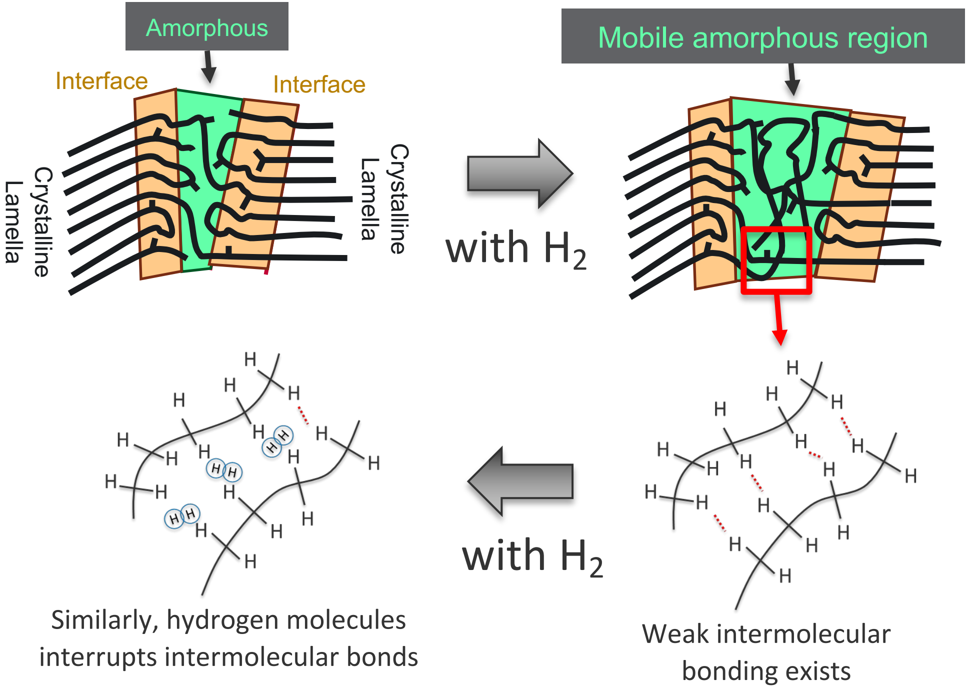
## Morphological characterization of supplied PE resin systems




MDPE → Shorter branches

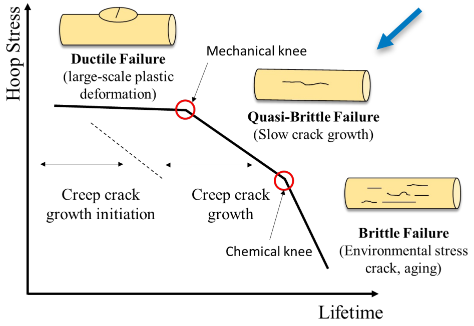
HDPE → Longer branches



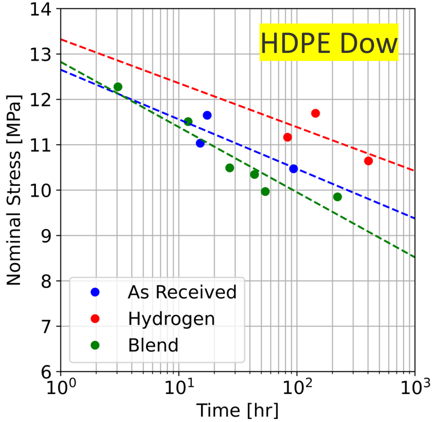

Hydrogen disrupts the amorphous region of PE structures. But the disrupting effects are different depending on the PE resin formulation.

# Accomplishment: Polymers

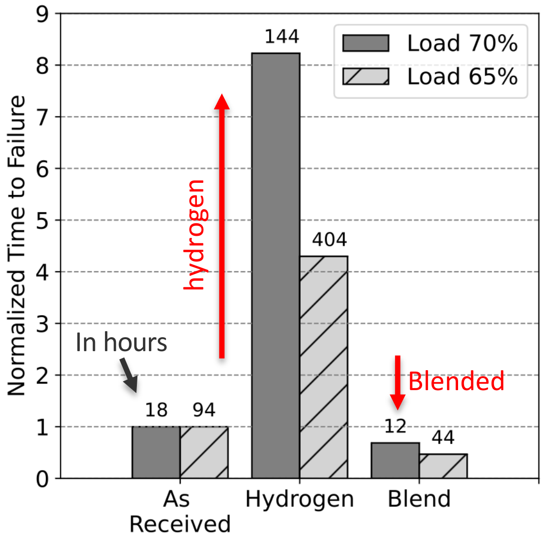
## Long-term slow crack growth testing



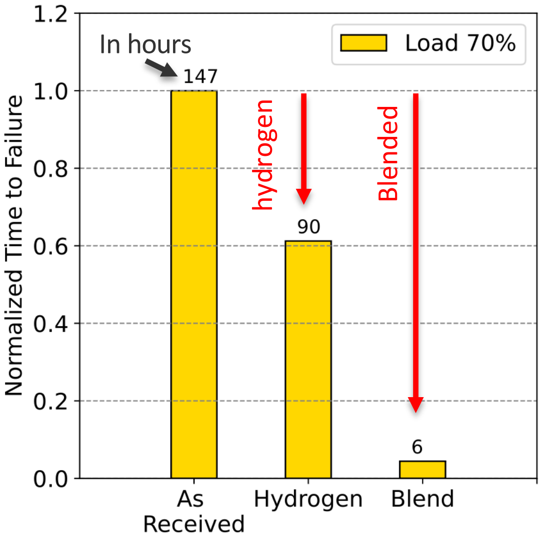

Preliminary slow crack growth results:
250 Psi at Room Temperature




HDPE Dow




MDPE INEOS

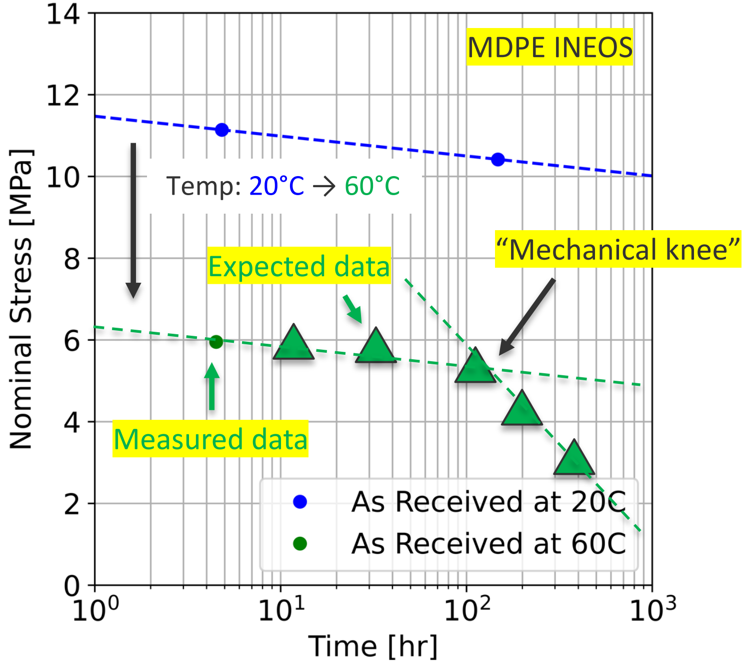



Again, the hydrogen effect on the long-term slow crack growth depends on the PE resin system. Hydrogen may improve (for HDPE Dow) or reduce (for MDPE INEOS) the performance.

# Accomplishment: Polymers

## Method development on accelerated Long-term slow crack growth testing

Slow crack growth:
250 Psi at RT and 60°C




Finding the "Mechanical knee" is critical.

Load level: 80%
Time to Failure: 4.8 hr
Temperature: 23°C


Load level: 40%
Time to Failure: 4.5 hr
Temperature: 60°C


Accelerated long-term SCG testing is on-going. Reduced stress-whitening due to increased molecular mobility can be observed. We plan to use these data to complete the stress-rupture curve.

# Progress: Polymers
## Lifetime prediction model development

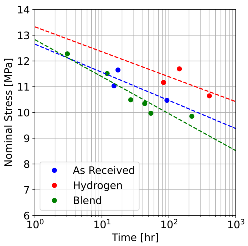
- Physical/Acceleration models
- Statistical/lifetime distribution models
- Weibull accelerated failure time (AFT)

2) Models

3) Output

- Prediction of lifetime at service condition.
- Reliability of a pipe at service condition.

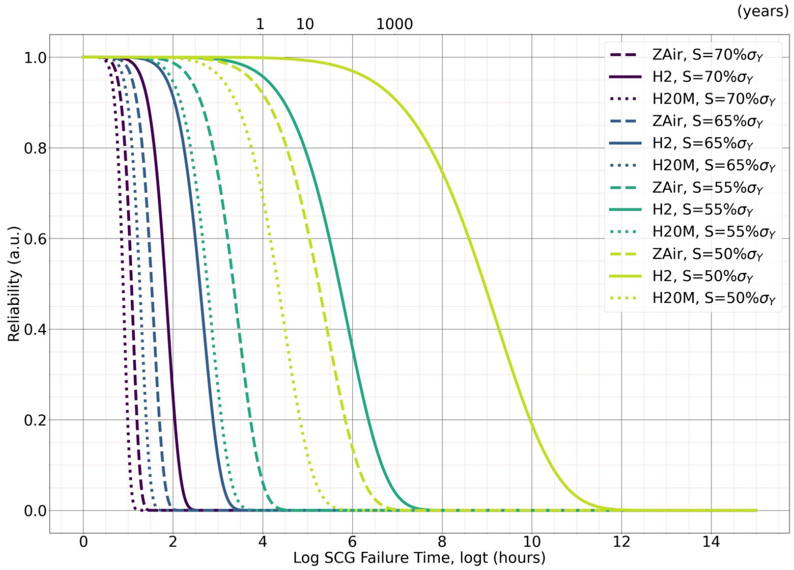
Slow crack growth data




1) Input

- Stress-rupture curve
- Acceleration factors
- Gaseous environment
- Geometry

HDPE Dow




Using the Weibull accelerated failure time model, we can generate reliability of the pipe structures at different load levels.

# **Approach:** Metals R&D

## Structural integrity of pipe and pipelines for hydrogen gas service

- **Hydrogen Extremely Low Probability of Rupture (HELPR)**
  - Open-source probabilistic tool for fracture mechanics assessment
  - Reduced-order models for Monte Carlo analysis of probabilistic behavior
- **Subscale component hydrogen test system**
  - Pressure cycling of subscale pipe to simulate stresses in ‘real’ pipelines
  - Demonstrate hydrogen-assisted failures and compare to output from HELPR
- **Hydrogen-assisted fatigue and fracture testing**
  - Assess critical variables in laboratory fatigue and fracture testing of pipeline steels in gaseous hydrogen environments
  - Identify role of microstructure, vintage and strength on hydrogen-assisted fatigue and fracture resistance of pipeline steels and their welds

# **Approach:** Milestones for Metals R&D

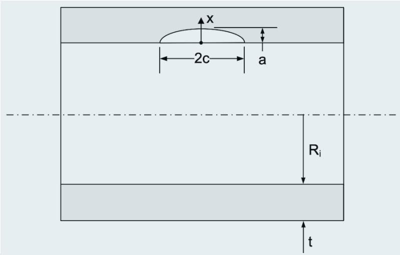
| Task | Description | Status |
|---|---|---|
| ***HELPR*** | • Implement probabilistic fracture mechanics framework for hydrogen service (HELPR)<br>• Public release of HELPR | open-source, GUI-driven tool set available at https://helpr.sandia.gov |
| ***Pipe testing*** | • Demonstrate pressure cycling of subscale pipe<br>• Compare subscale pipe failure with predictions from coupon testing | manuscript for ASME International Pipeline Conference (IPC) – September 2024 |
| ***Materials testing*** | • Assess pressure dependence of fatigue and fracture<br>• Assess role of microstructure on hydrogen-assisted fatigue and fracture of line pipe steels | • ASME B31 Code Case 220 for hydrogen-assisted fatigue design rules (in collaboration with SCS program)<br>• Several releases/pending manuscripts (see publication list - e.g., ASME PVP, AMPP Annual Conference) |

# Accomplishment: Metals R&D

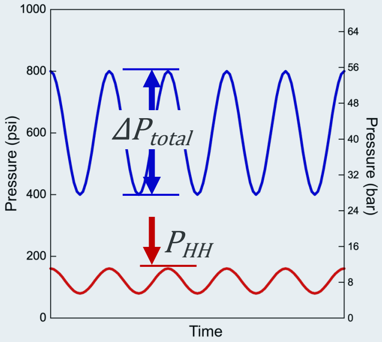
## Technical basis and structure of HELPR established

HELPR — Hydrogen Extremely Low Probability of Rupture

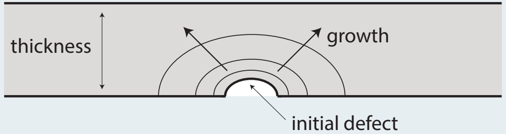
### Initial flaw defined in API-579




$$\sigma = f(P_{total})$$

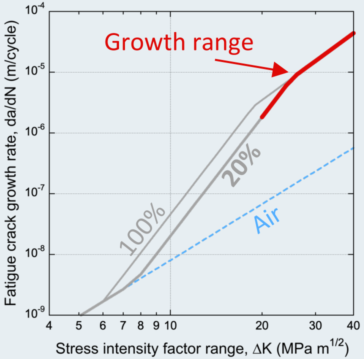



### Crack growth according to ASME empirical relationships

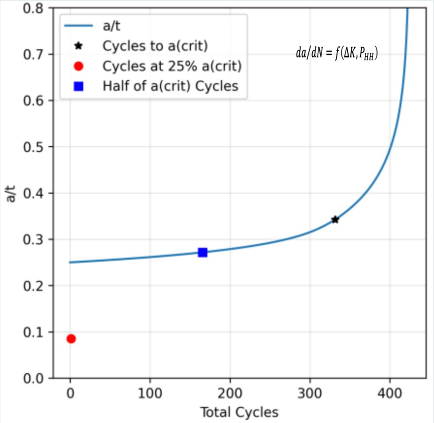



$$\Delta K = f(\Delta\sigma, a)$$

$$da/dN = f(\Delta K, P_{HH})$$




### HELPR deterministic output

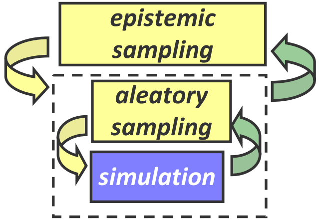


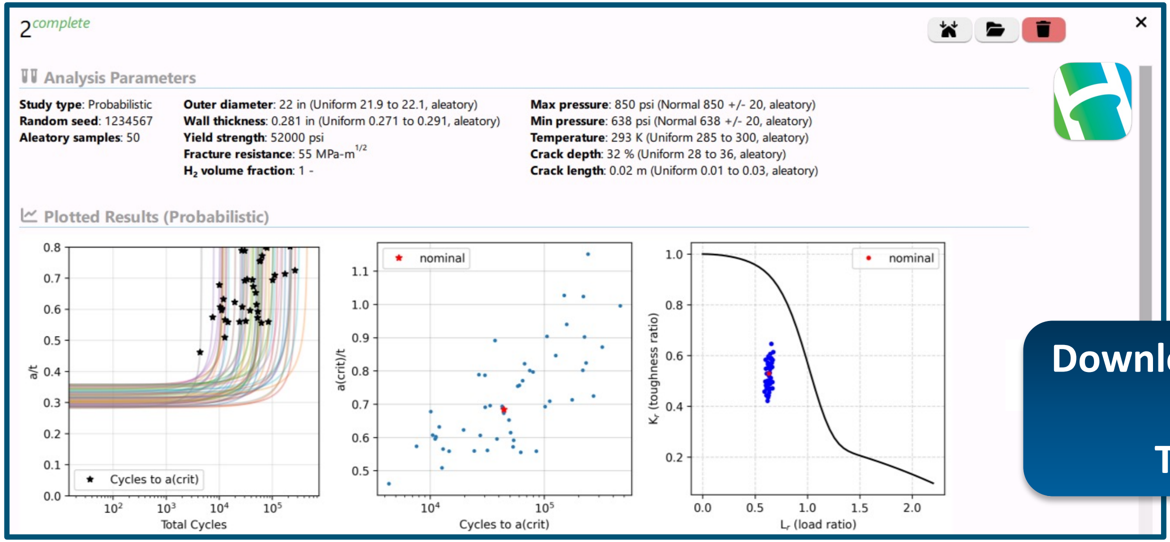
# Accomplishment: Metals R&D

## Open-source, GUI-driven software available

HELPR
Hydrogen Extremely Low Probability of Rupture

- **HELPR enables analysis of uncertain inputs (pipe dimensions, operating conditions, and/or defect sizes) and runs 100s or 1000s or $10^6$s of deterministic calculations**
  - **Additionally, the type of uncertainty can be segregated: aleatory vs epistemic**



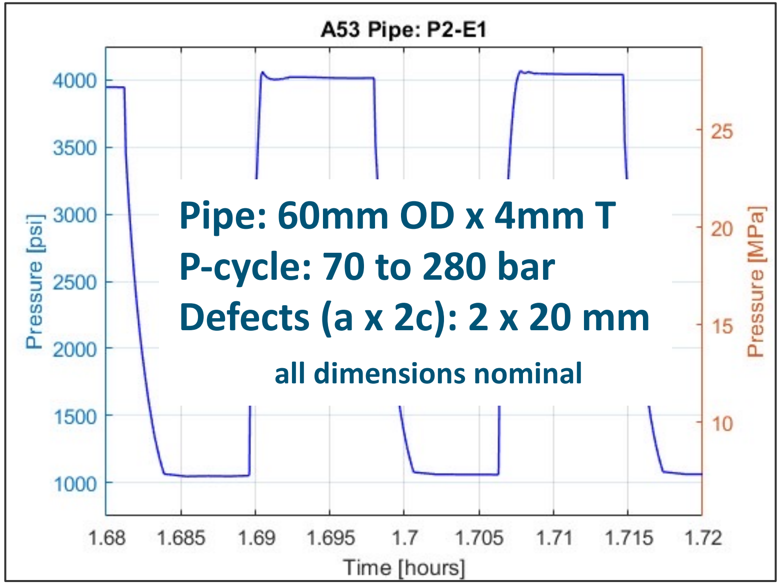

**Example output shows the range of responses for fatigue (left) and fracture (right) – in this case – for 50 samples**

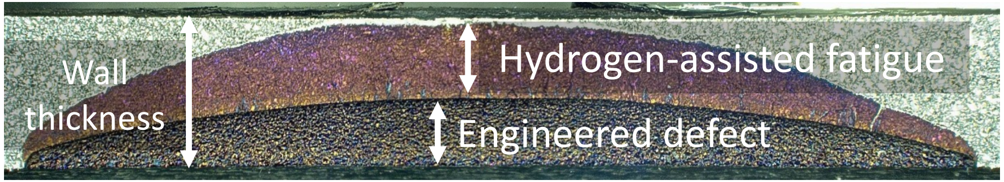
**Download at: https://helpr.sandia.gov**

**Tutorial: SAND2023-14270PE**

# Accomplishment: Metals R&D

## Demonstrated critical role of hydrogen on pipe failure



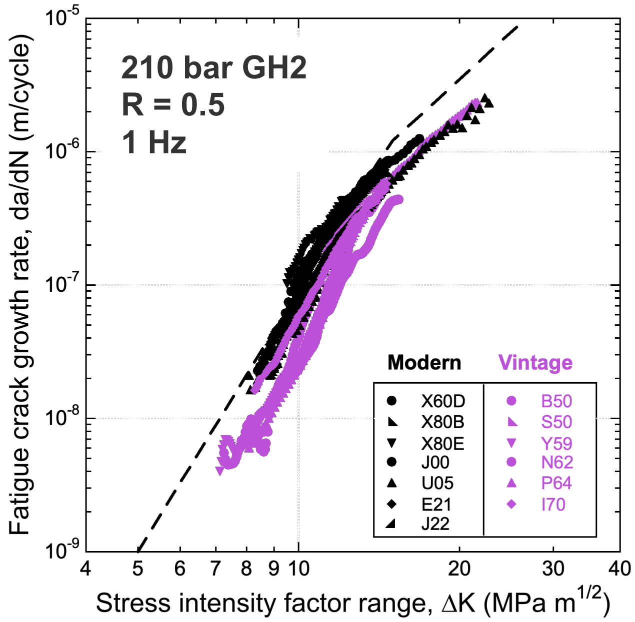



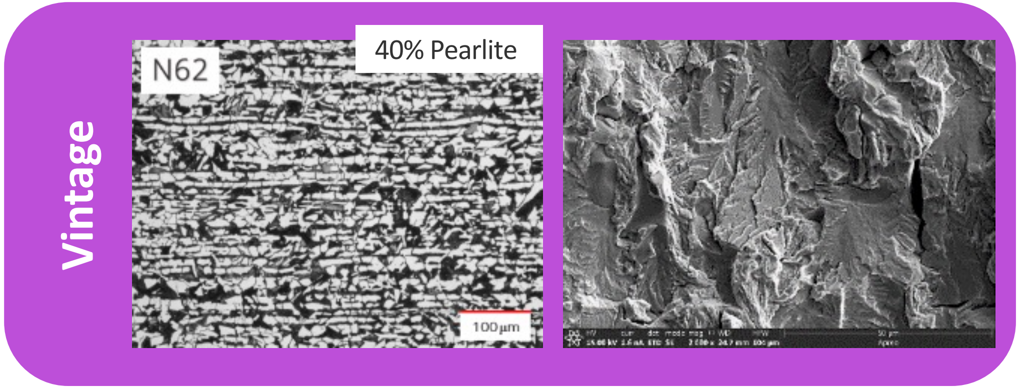

| | Specimen | Gas | Cycles to Failure | Estimated Cycles |
|---|---|---|---|---|
| internal | P2-I1 | $H_2$ | 637 | 440 |
| internal | P2-I2 | $H_2$ | TBD | 440 |
| internal | P2-I3 | $N_2$ | TBD | 17,100 |
| external | P2-E1 | $H_2$ | 1,099 | ? |
| external | P2-E2 | $H_2$ | 1,275 | ? |
| external | P2-E3 | $N_2$ | 10,201 | ? |

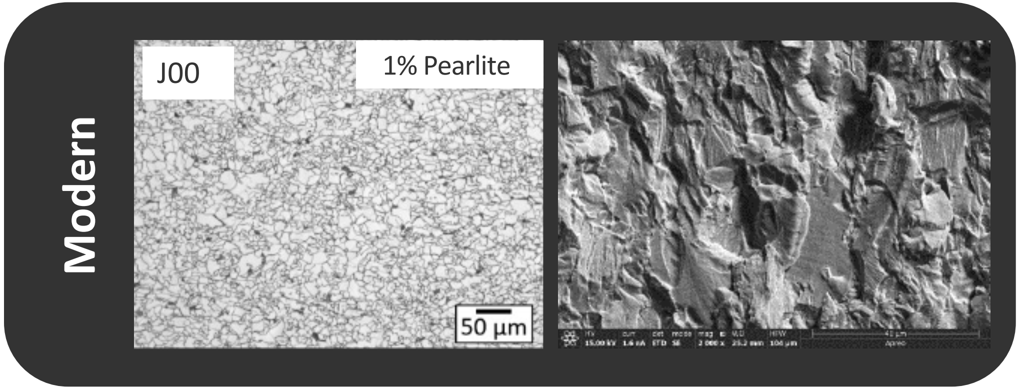
**Hydrogen reduces the cycle life of pipe with both internal (I) and external (E) defects regardless of mill scale**

# Accomplishment: Metals R&D

## Vintage steels tend toward slightly lower fatigue crack growth




**Compared to modern steels, vintage pearlitic steels show**
- **Better H-assisted fatigue resistance**
- **Poorer H-assisted fracture resistance**

# Response to Reviewer Comments

| comment: | response: |
|---|---|
| “Further development is needed to evaluate the inventory of existing assets…” | Agreed, evaluation of existing assets is critical, but well beyond the scope of this R&D project. Engineering Critical Assessment (ECA) and other asset evaluation is the responsibility of the owners and operators. The HyBlend team works closely with stakeholders (e.g., PRCI, EPRG) to identify priority needs of the industry with the aim of providing the scientific principles needed to assess hydrogen-induced degradation of materials properties. |
| “… the tool [HELPR] can be used right away.”<br><br>“… ensure HELPR has flexibility to add modules” | HELPR is available as open-source, GUI-driven software (helpr.sandia.gov) and can be used by anyone. Important additional tools are being added to HELPR to enable more diverse analysis (e.g., external defects, hoop defects). We appreciate feedback from the community on the current framework and gaps for future development. |
| “existing hydrogen materials [polymers?] work could have been leveraged more [with other projects]…”<br><br>”Better alignment with other office activities is highly suggested.” | The HyBlend Materials R&D effort is highly integrated with other HFTO efforts and leverages the unique NL capabilities for hydrogen compatibility studies (SCS, H-Mat, and others). Additionally, the team participates in projects funded by other offices, such as FECM (e.g., XMAT, SHASTA), as well as projects with other federal and state offices. The project team also supports JIPs, PHMSA projects, and labs around the world in SME and advisory roles. |

# Collaboration and Coordination

- Knowledge sharing and information dissemination
  - Emerging Fuels Institute (EFI)/ Pipeline Research Council International (PRCI)†
  - Gas Technologies Institute (GTI)†
  - Individual industry partners – e.g., Evonik, SoCalGas, Enbridge
  - 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:**
  - Time-dependent $H_2$ effect requires time-sensitive measurement techniques on material characterization and mechanical properties.
  - In-situ $H_2$ test remains a challenge in full-scale pipe structures.
  - Evaluation of joints and bonded structures under $H_2$ environment is a challenge.
- **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 (Phase 2)

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

- **Polymers**
  - Continue slow crack growth testing to evaluate performance of polymer pipe with various gaseous environment.
  - Measure in-situ morphological changes of polymer materials under hydrogen and blended gases.
  - Evaluate viscoplastic performances of thermally fused joints.
- **Metals**
  - Add additional defect geometries to HELPR (including API solutions for internal and external longitudinal defects)
  - Establish experimental framework to characterize critical defects using both subscale pipe and materials testing
  - Develop quantitative guidance to assess hydrogen-assisted fracture properties (e.g., role of hardness, effect of pressure, weld microstructures, and influence of constraint)

# 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**
  - *Material characterization*: Hydrogen tends to plasticize the PE materials but the effects are strongly dependent on specific PE resin system.
  - *Material testing*: Hydrogen has an opposite effect on slow crack growth performances of MDPE-INEOS and HDPE-DOW.
  - *Lifetime prediction*: the model successfully combines mechanical testing with statistical analysis to provide reliability of measured PE pipe materials.
- **Metals R&D**
  - *HELPR*: open-source, GUI-driven software available (April 2024 H2IQ webinar)
  - *Subscale pipe testing:* hydrogen degradation with both internal and external defects
  - *Materials testing*: technical basis established for ASME design rules; complex role of pearlite hypothesized to explain fatigue and fracture of vintage and modern steels

HyBlend

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**Join the team:**

HyBlend partner overview

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# Thank You

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