U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

# Hydrogen Network Components R&D

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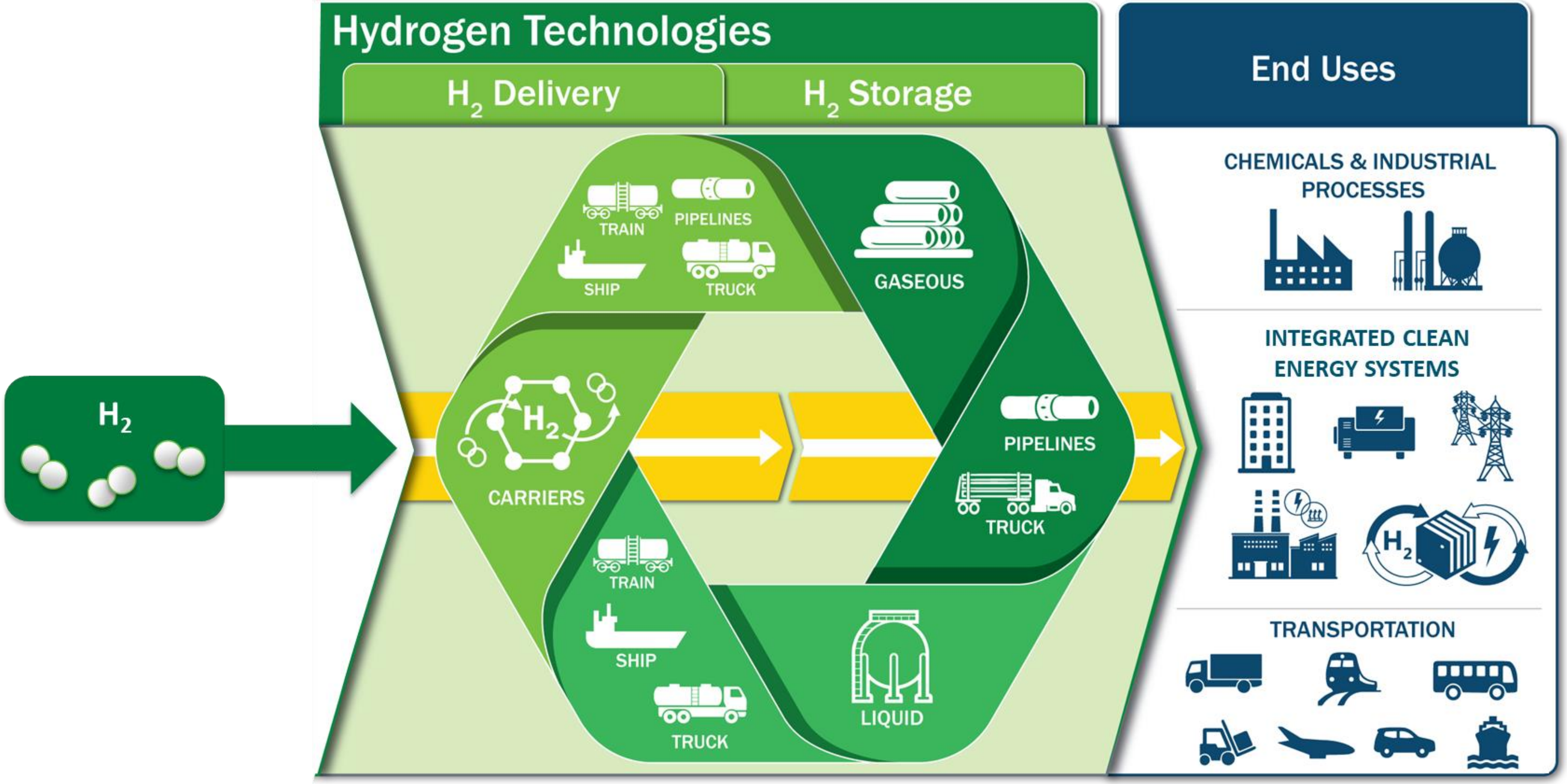
Pipeline Transportation: Hydrogen and Emerging Fuels R&D Public Meeting and Forum, U.S. Department of Transportation
December 1, 2021

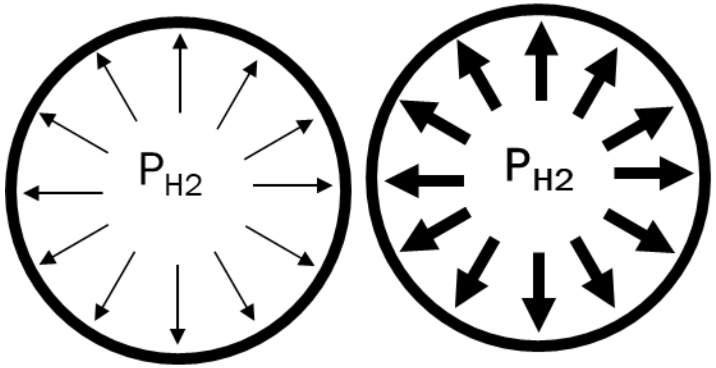
# Hydrogen Infrastructure: Delivery, Storage and Dispensing

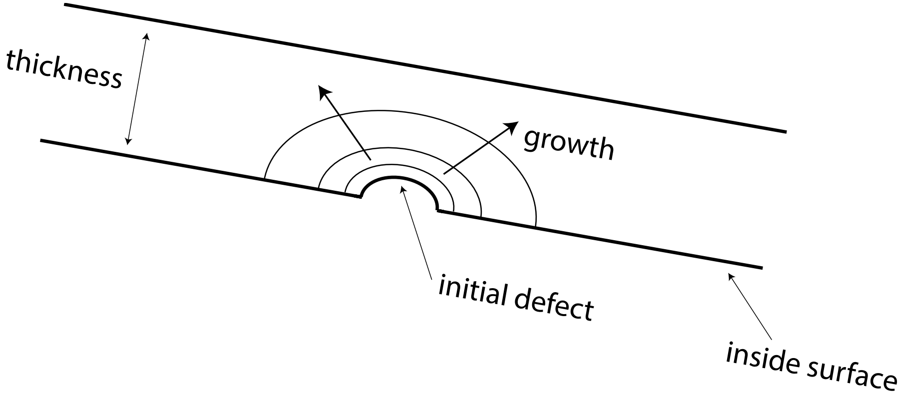
Hydrogen infrastructure includes a wide range of technologies that are designed for compatibility with hydrogen under their expected operating conditions (e.g., pressure, temperature).



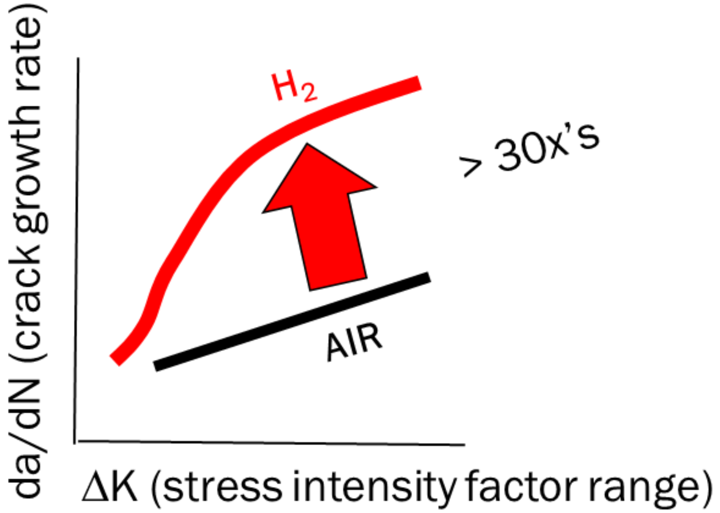
# Hydrogen Pipelines R&D Concepts

Fatigue: Loading of pipe caused by **fluctuations in operating pressure**





*Example configuration of pipeline. Cracks are most likely to grow at locations with existing defects.*



*Crack growth under fatigue loading is faster in $H_2$ Service. Rate of growth depends heavily on operating pressure, depth of pressure cycles, and pipeline materials and dimensions.*

# Design of Hydrogen Pipelines: Metals

- ASME B31.8 ***Natural Gas*** pipeline thickness

$$t = \frac{PD}{2SFET}$$

P = design pressure
S = specified min yield stress
t = thickness
D = outside diameter
E = longitudinal joint factor
T = temp derating factor
F – Location-specific design factor

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- ASME B31.12 ***Hydrogen*** pipeline thickness
  - Prescriptive Design Method

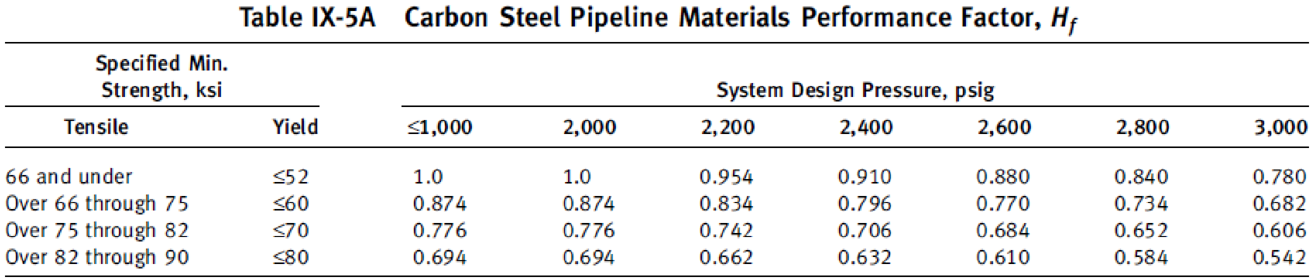


**Table IX-5A Carbon Steel Pipeline Materials Performance Factor, $H_f$**

| Specified Min. Strength, ksi | | System Design Pressure, psig | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Tensile | Yield | ≤1,000 | 2,000 | 2,200 | 2,400 | 2,600 | 2,800 | 3,000 |
| 66 and under | ≤52 | 1.0 | 1.0 | 0.954 | 0.910 | 0.880 | 0.840 | 0.780 |
| Over 66 through 75 | ≤60 | 0.874 | 0.874 | 0.834 | 0.796 | 0.770 | 0.734 | 0.682 |
| Over 75 through 82 | ≤70 | 0.776 | 0.776 | 0.742 | 0.706 | 0.684 | 0.652 | 0.606 |
| Over 82 through 90 | ≤80 | 0.694 | 0.694 | 0.662 | 0.632 | 0.610 | 0.584 | 0.542 |

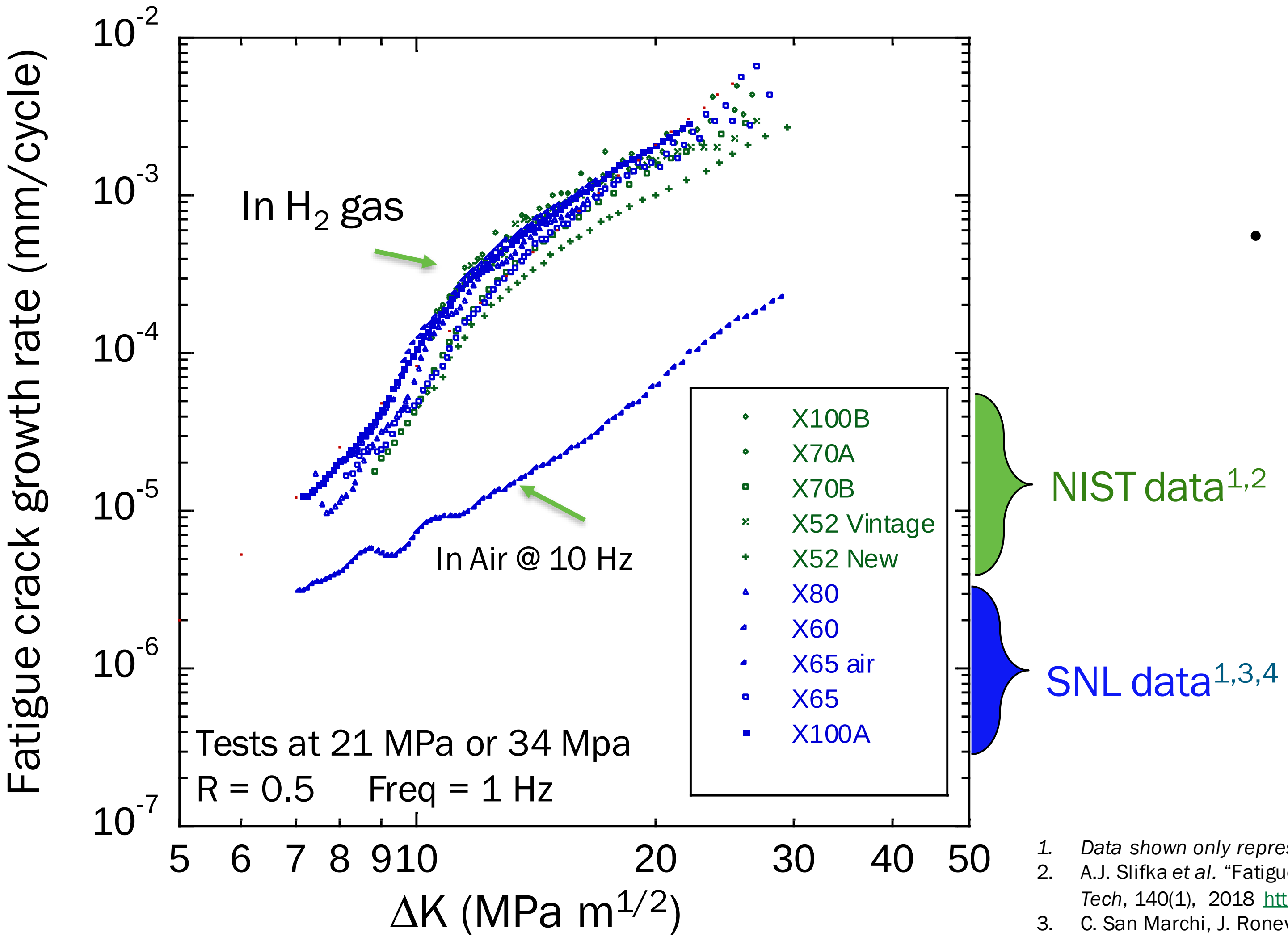
$$t = \frac{PD}{2SFETH_F}$$

$H_F$ = Materials performance factor to account for hydrogen effects

  - Performance-based Design Method

***Allows for use of an $H_F$ of 1 if the fracture toughness of materials is tested in hydrogen***
*Applicable for materials up to 80 ksi yield strength and 100 ksi tensile strength*

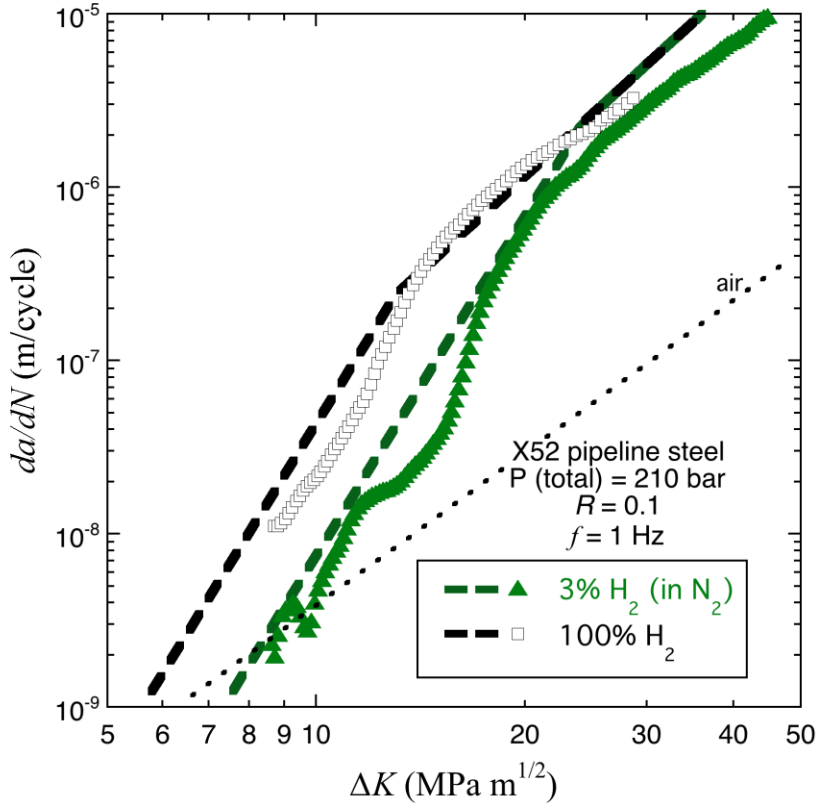
# Prior R&D: Compatibility of Pipeline Steels with Hydrogen



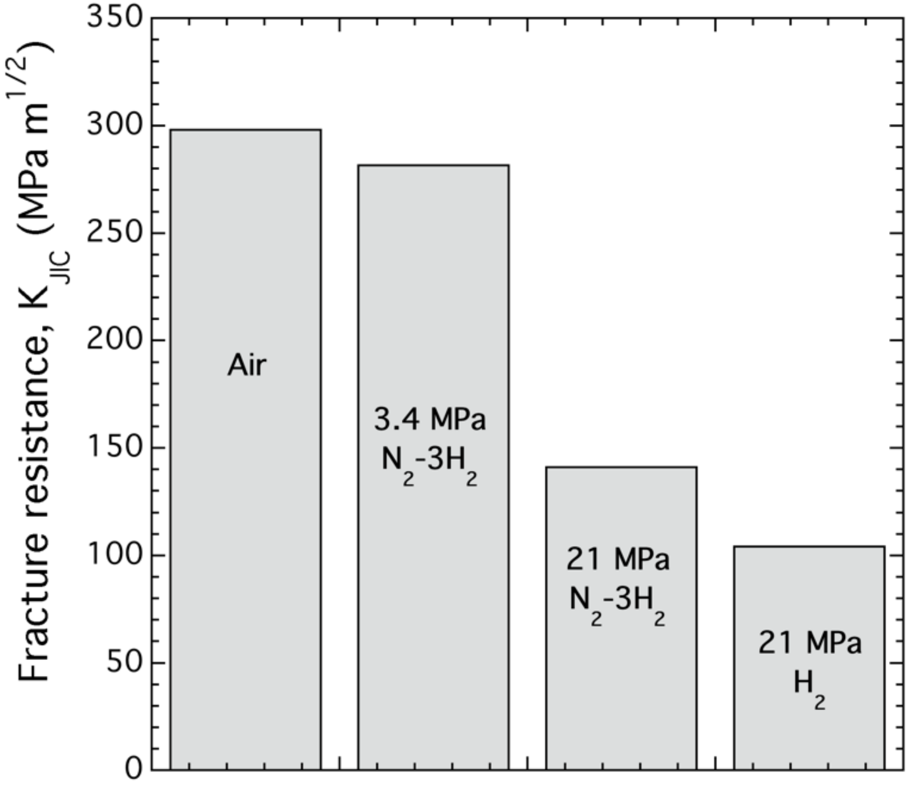
- Data on fatigue life of vintage and modern pipeline steels collected at Sandia National Laboratories (SNL) and National Institute of Standards and Technology (NIST)
- All pipeline fatigue data fell within similar band
  - **Fatigue life does not appear to depend solely on strength**, and high-strength steels (X70), do not appear to be as susceptible to hydrogen assisted fatigue as originally thought
  - Welds (not shown here) and base metal appear to have similar performance in hydrogen.
  - Data used to inform performance-based design method in ASME B31.12 code

1. *Data shown only represents small fraction of pipeline data generated*
2. A.J. Slifka *et al.* "Fatigue measurement of pipeline steels for the application of transporting gaseous hydrogen," *J. Pressure Vessel Tech*, 140(1), 2018 https://doi.org/10.1115/1.4038594
3. C. San Marchi, J. Ronevich, "Materials Evaluation for Hydrogen Service," SAND2021-10712PE
4. J. Ronevich, B. Somerday, "Hydrogen-accelerated fatigue crack growth in arc welded X100 pipeline steel," in proceedings of 2016 International Hydrogen Conference: Material Performance in Hydrogen Environments. Sept 11-14, 2016, Jackson Lake Lodge, WY.

# Prior R&D: Hydrogen Blending in Natural Gas Pipelines



The impact of blends on fatigue damage appear to depend on the magnitude of pressure cycles in a pipeline. Shallow fatigue cycles cause less damage in blends than in 100% hydrogen.[1]

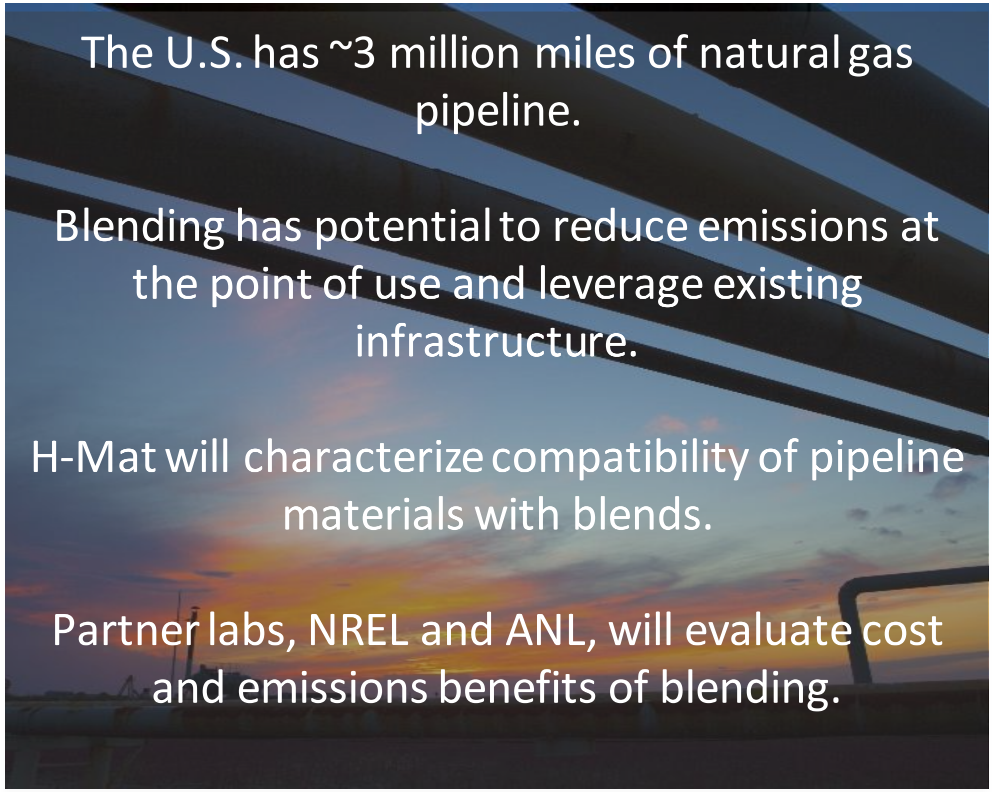


The impact of blends on fracture toughness of pipeline steels appears to depend on pressure. At 21 MPa, small concentrations of blends (3%) reduce fracture toughness in X52 steel by over 50%.[1]

1. Source: Ronevich, J., San Marchi, C., 2021 https://asmedigitalcollection.asme.org/PVP/proceedings-abstract/PVP2021/85345/V004T06A052/1122144

# Ongoing R&D on Hydrogen Blending in Natural Gas

***HyBlend collaboration between H-Mat, NREL, ANL, and ~30 stakeholders will assess the viability of hydrogen blending in natural gas pipelines.***



The U.S. has ~3 million miles of natural gas pipeline.

Blending has potential to reduce emissions at the point of use and leverage existing infrastructure.

H-Mat will characterize compatibility of pipeline materials with blends.

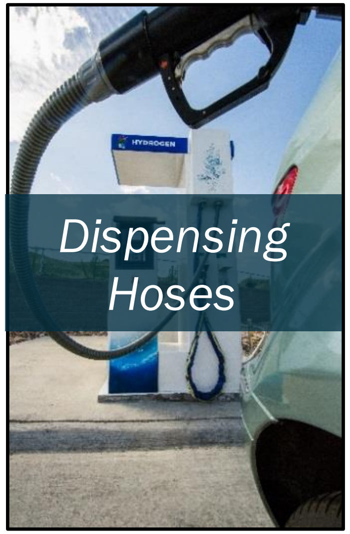
Partner labs, NREL and ANL, will evaluate cost and emissions benefits of blending.

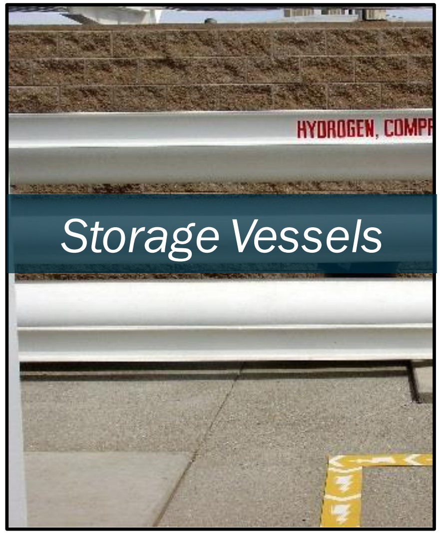
- **Developing public model of pipeline integrity to identify opportunities and risks of blending given a system's age, operating conditions, and materials of construction.**
  - Evaluate microstructures of both legacy and anticipated pipeline installations.
  - Conduct experimentation to evaluate life of polymer and metallic materials used in pipeline segments and joints, under varying concentrations, temperatures, and pressures of blends.
  - Characterize relationships between pipeline microstructure, condition, and integrity under blend environments.

*For more information, please see:* *https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines*

# Cross-cutting Materials Compatibility R&D

## H-Mat Consortium conducts cross-cutting R&D on hydrogen effects on polymers and metals.


*Dispensing Hoses*



*Storage Vessels*

*Pipelines*


*Compressor Components and Seals*

**Focuses of current activities include:**

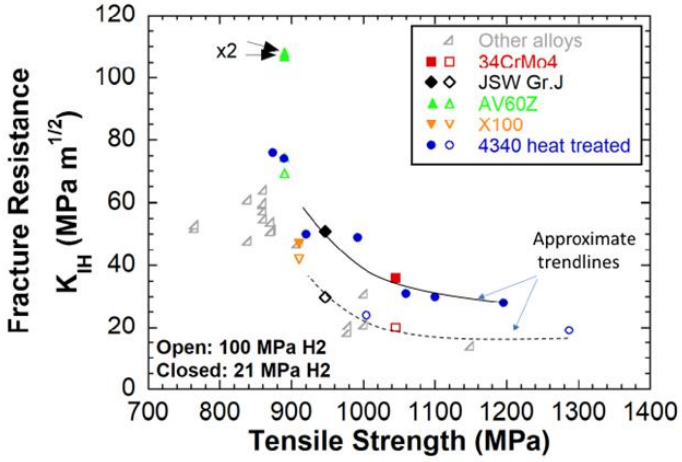
1) **Assess performance of pipeline materials in hydrogen blends, through HyBlend collaboration**
2) **Reduce expansion of seals in hydrogen by 50%**
3) **Enhance life of vessels by 50% through improved understanding of crack nucleation.**
4) **Enhance fracture toughness of high-strength (>950 MPa) steels by 50%.**

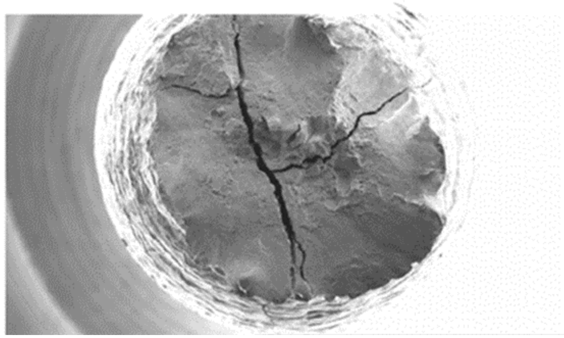
Sandia National Laboratories
Pacific Northwest NATIONAL LABORATORY
OAK RIDGE National Laboratory
Savannah River National Laboratory® OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS
Argonne NATIONAL LABORATORY

*For more information, please visit https://h-mat.org/ or contact h-matinfo@pnnl.gov*

# Example R&D Activity: Metals

*Completed systematic testing in high-pressure hydrogen and developing robust computational modeling techniques to predict damage evolution.*



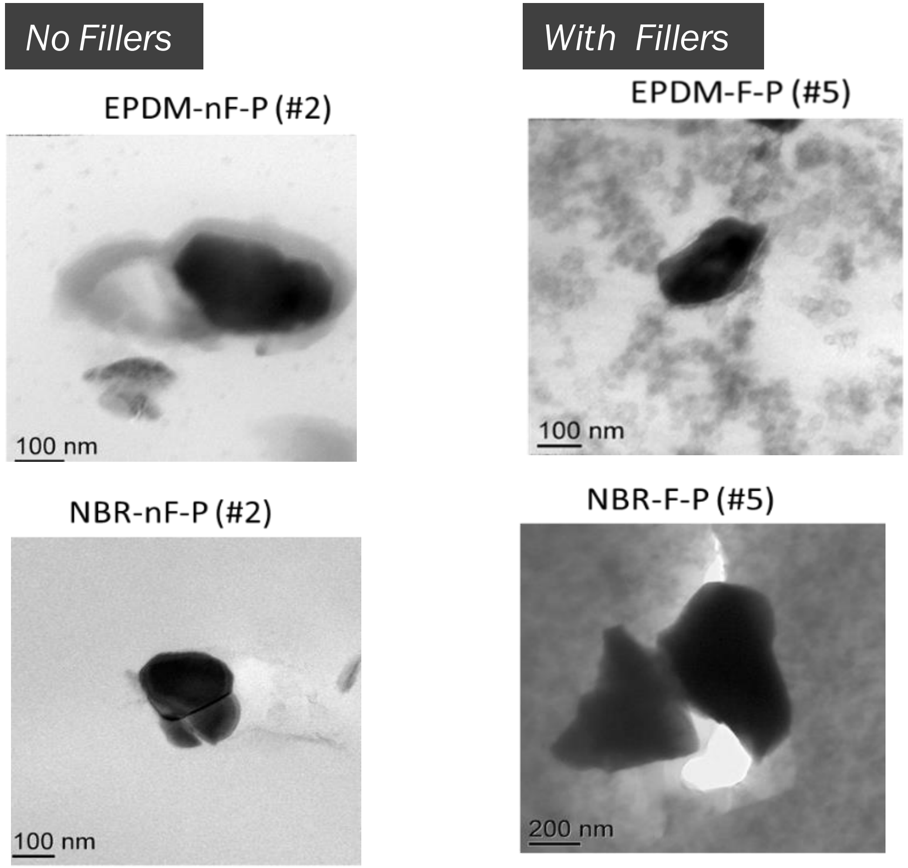


*Hydrogen pre-charging shown to reduce ductility in stainless steel by ~50% at 20K*

- **Testing of 9 microstructures of pressure vessel steels**
  - Tensile strength controls fracture resistance in gaseous hydrogen
- **Molecular dynamics models of crack initiation**
  - Being developed to inform predictions of microstructural features (e.g., grain boundary interactions) most likely to result in evolution of voids, both with and without hydrogen.
- **Experimentation and modeling of aluminum** indicates that moisture aids hydrogen ingress.
- **Testing of stainless steels in cryogenic hydrogen** identified 50% reduction in ductility of hydrogen-soaked materials at 20K, relative to ambient.

# Example R&D Activity: Polymers

## *Identified microstructural constituents that are common locations of failure in elastomers*


*No Fillers*

*With Fillers*

EPDM-nF-P (#2)

EPDM-F-P (#5)

NBR-nF-P (#2)

NBR-F-P (#5)

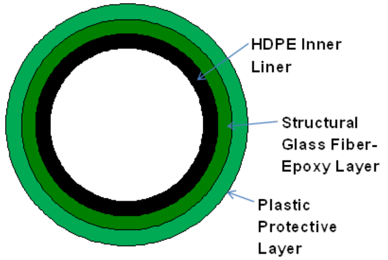
*Transmission electron microscopy of EPDM (top) and NBR (bottom) after 100 cycles to 90 MPa hydrogen.*

- EPDM and NBR rubbers are commonly used in seals.
- H-Mat team cycled these materials in hydrogen and utilized advanced imaging techniques to visualize damage.
- Filler materials appear to mitigate hydrogen effects in EPDM, but not in NBR.
- Zinc oxide and sulfur additives, (used to vulcanize and cure rubbers), were found to be common locations of failure in elastomers.
- Team has generated experimental elastomers with alternative constituents (e.g., peroxides instead of sulfur) and is now testing their durability in hydrogen.

# Potential for Fiber Reinforced Polymer Pipelines in Hydrogen

## Existing Technology

- FRP is currently employed in the oil & gas industry
- Spoolable commercial products up to 8” diameter and 2,500 psig rating.
- Site manufactured products are available up to 12” diameter and 1,000 psig rating.



**FRP Cross Section**

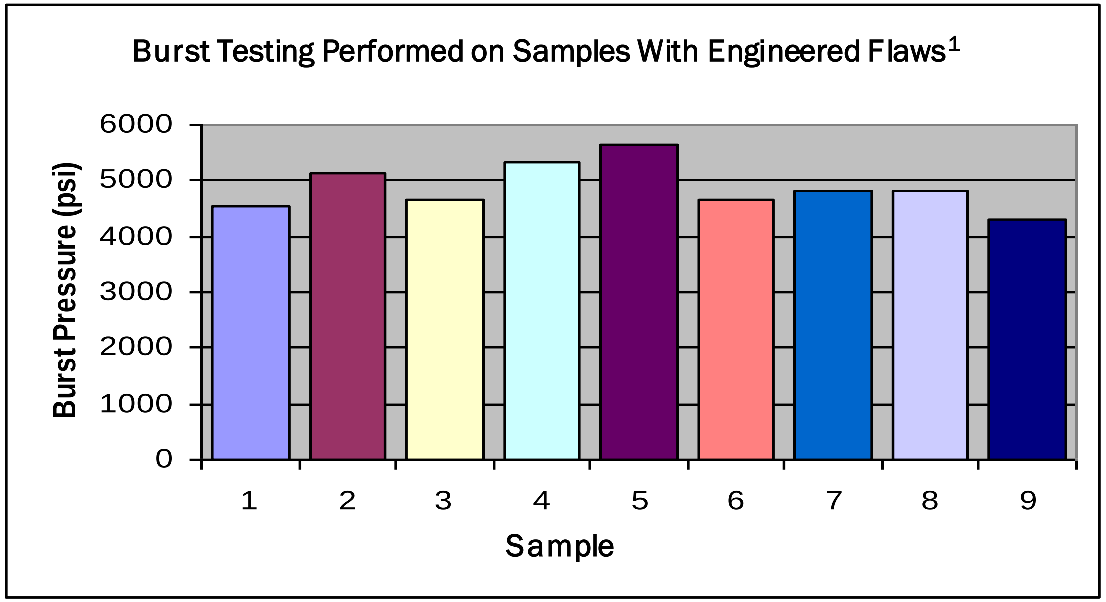
## Impact

- 0.5-mile lengths can be spooled for delivery to installation sites, **reducing installation cost by up to 25%**
- Can be manufactured on-site in **lengths of 2-3 miles**
- FRP is not susceptible to hydrogen embrittlement.
- FRP has superior chemical and corrosion resistance.

Site Manufactured FRP

**Spooled FRP Installation**

# Prior R&D: Fiber Reinforced Polymer Piping



1. *Flaws were through 40% of pipe wall thickness. The burst pressure of unflawed samples was 6300 psi.*

*Testing conducted to evaluate long-term resistance of FRP to hydrogen effects at Savannah River National Laboratory (SRNL) and Oak Ridge National Laboratory (ORNL). Included:*

- Tensile, compression, and burst testing of specimens of FRP before and after months of hydrogen exposure
- Tensile strength of glass fibers before and after weeks of hydrogen exposure
- Fatigue testing of FRP samples in hydrogen
- Measurements of hydrogen permeation and leakage from joints
- Burst testing of samples before and after exposure to extreme pH levels, to represent environmental effects (e.g., impacts of aggressive soil constituents)

Testing used to support ASME B31.12 Code Case for FRP use in hydrogen at pressures up to 170 bar and up to 50 years of service life.

# Other Example Collaborations

***H-Mat is collaborating with numerous materials R&D projects led by universities and industry through DOE and NSF awards***

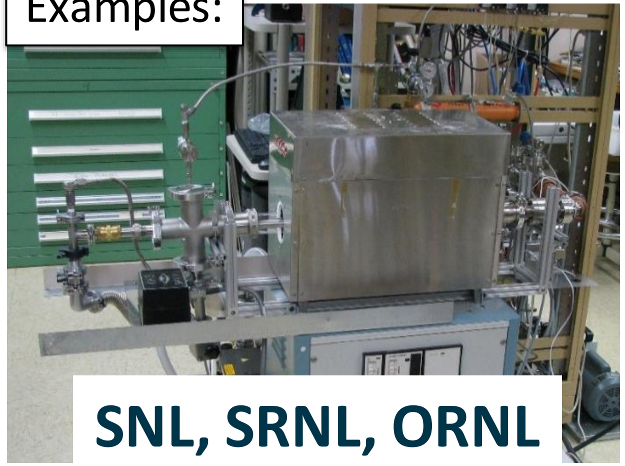
*Examples of projects with ongoing partnerships include*

- **University of Illinois at Urbana Champaign, Arcelor-Mittal, Swagelok, Linde/Praxair Swagelok:** Characterizing propensity for hydrogen embrittlement as a function of microstructural features, such as short-range order, to inform development of lower cost alloys for use in hydrogen
- **Colorado School of Mines, Los Alamos National Laboratory, National Renewable Energy Laboratory, Wiretough, U.S. Steel, General Motors, Chevron, Posco:** Developing microstructures with a higher resistance to hydrogen embrittlement than ferritic steels at a cost lower than conventional austenitic stainless steels
- **Clemson University:** Developing self-healing polymers for use in hydrogen dispensing hoses
- **Massachusetts Institute of Technology, Harvard University:** Designing high-throughput techniques to evaluate resistance of high-entropy alloys to hydrogen effects
- **Stonybrook University, Stanford University, MIT, National Grid:** Characterizing evolution of micron-scale damage in pipeline materials with higher fidelity, to inform integrity management programs
- **Luna Technologies**: Developing non-destructive techniques to identify micrometer-scale flaws in pressure vessels

# Methods of Engaging with H-Mat

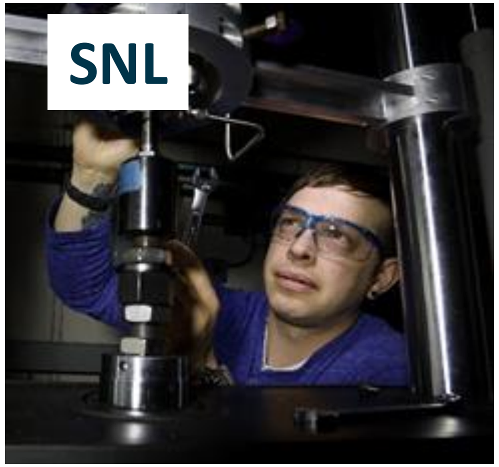
**Leverage lab capabilities through cooperative research and development agreements (CRADAs) and DOE funding opportunities**

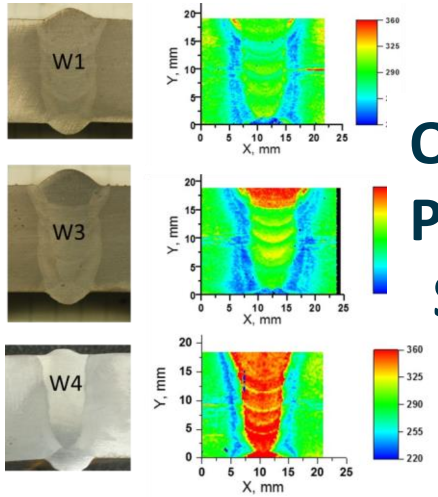
Examples:



Hydrogen permeation, diffusion and thermal desorption spectroscopy

Fatigue and fracture testing in gaseous hydrogen at pressure of 140MPa and temperature as low as 220K

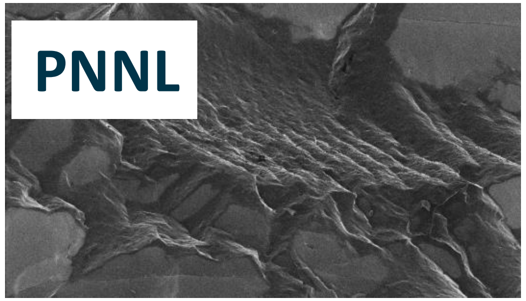




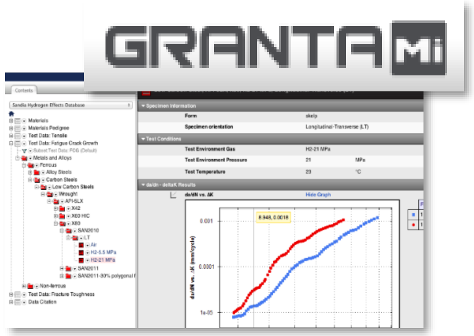
ORNL
PNNL
SNL

Fabrication and characterization of alternative lower cost welds

Helium ion microscopy to visualize nanoscale feature of materials



**Search and contribute non-proprietary data on material properties**



Form: skelp
Specimen orientation: Longitudinal-Transverse (LT)
Test Environment Gas: H2-21 MPa
Test Environment Pressure: 21 MPa
Test Temperature: 23 °C
da/dN vs. ΔK

**Follow H-Mat R&D activities through workshops and published Technical References**

For more information, please see:
https://h-mat.org/

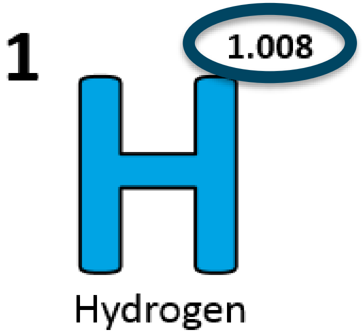
# Upcoming Opportunities for Engagement

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

## DOE Annual Merit Review and Peer Evaluation Meeting June 6 -9, 2022

## Hydrogen and Fuel Cells Day October 8

- Held on hydrogen's very own atomic weight-day
- DOE EERE comms campaign all week



INCREASE YOUR $H_2IQ$

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H2IQ Hour Webinars

**Download**
H2IQ For Free

**Visit H2tools.Org For Hydrogen Safety And Lessons Learned**

[https://h2tools.org/](https://h2tools.org/)

CENTER FOR Hydrogen SAFETY
Connecting a Global Community

**www.aiche.org/CHS**

## Sign up to receive hydrogen and fuel cell updates

www.energy.gov/eere/fuelcells/fuel-cell-technologies-office-newsletter

**Learn more at: energy.gov/eere/fuelcells AND www.hydrogen.energy.gov**

# Thank you

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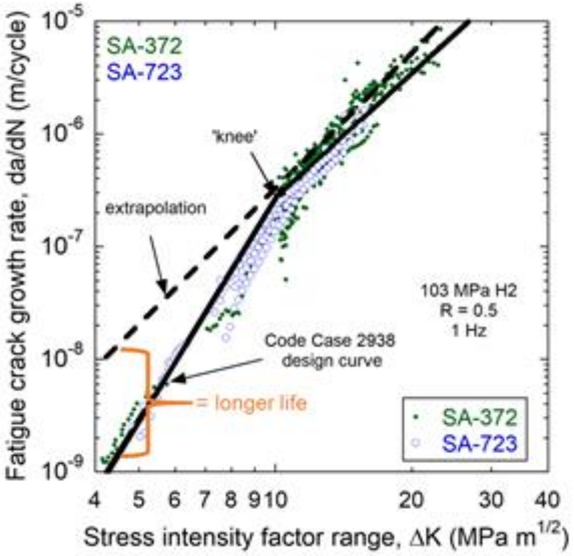
U.S. Department of Energy

**www.energy.gov/fuelcells**
**www.hydrogen.energy.gov**

# Back-up

# Example Collaboration: Safety, Codes & Standards

*H-Mat labs work closely with the codes & standards community to inform science basis for design requirements and enable harmonization*



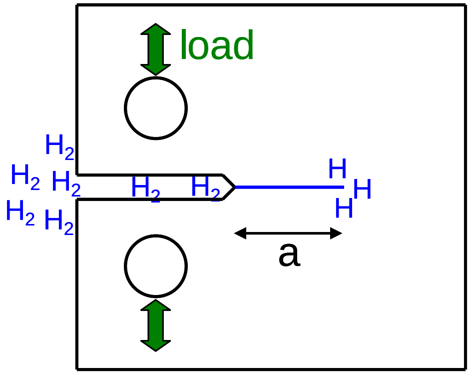
*Examples of recent accomplishments include:*

- Developed simplified and harmonized set of materials test requirements for vehicle applications in SAE and GTR codes
- Developed ASME Code Case 2938 with fatigue life design curves for common pressure vessel steels, enabling up to 3X increase in vessel cycle life and reducing testing requirements for developers
- Conducting R&D to address gaps identified by stakeholders, such as life of pressure vessels in low-pressure service or under cycles of variable depth

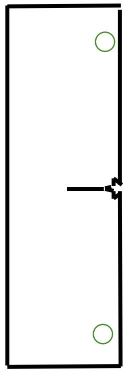
# Background: Measurements of Fatigue

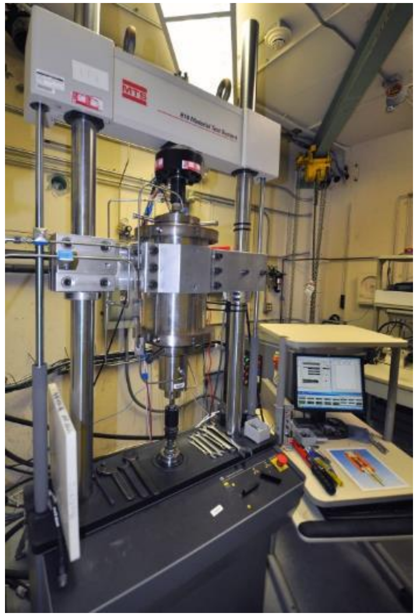
ASTM E647

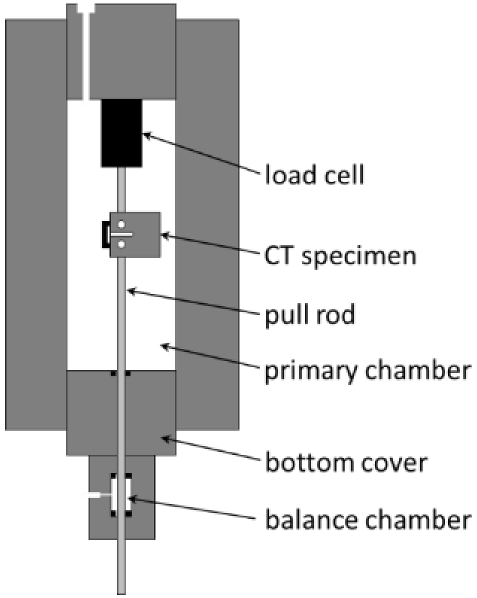
Compact Tension (C(T))



ESE(T)







- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT or clip gauge
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude

$$R = \frac{P_{\min}}{P_{\max}} = 0.5 \qquad frequency = 1Hz$$

- Environment
  - Supply gas: 99.9999% $H_2$
  - Pressure = 21 MPa (3 ksi)
  - Room temperature