INCREASE YOUR H_2IQ

The #H2IQ Hour

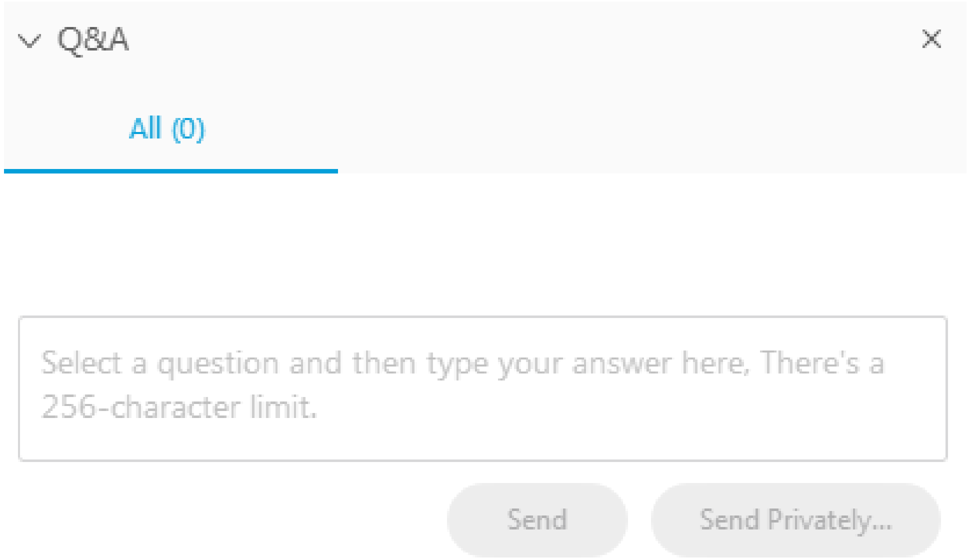
Today's Topic:

Design and Operation of Metallic Pipelines for Service in Hydrogen and Blends

This presentation is part of the monthly H2IQ hour to highlight research and development activities funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



Design and Operation of Metallic Pipelines for Service in Hydrogen and Blends

Chris San Marchi
Sandia National Laboratories (Livermore CA)

H2IQ Hour

29 March 2022

SAND2022-3598 PE

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.

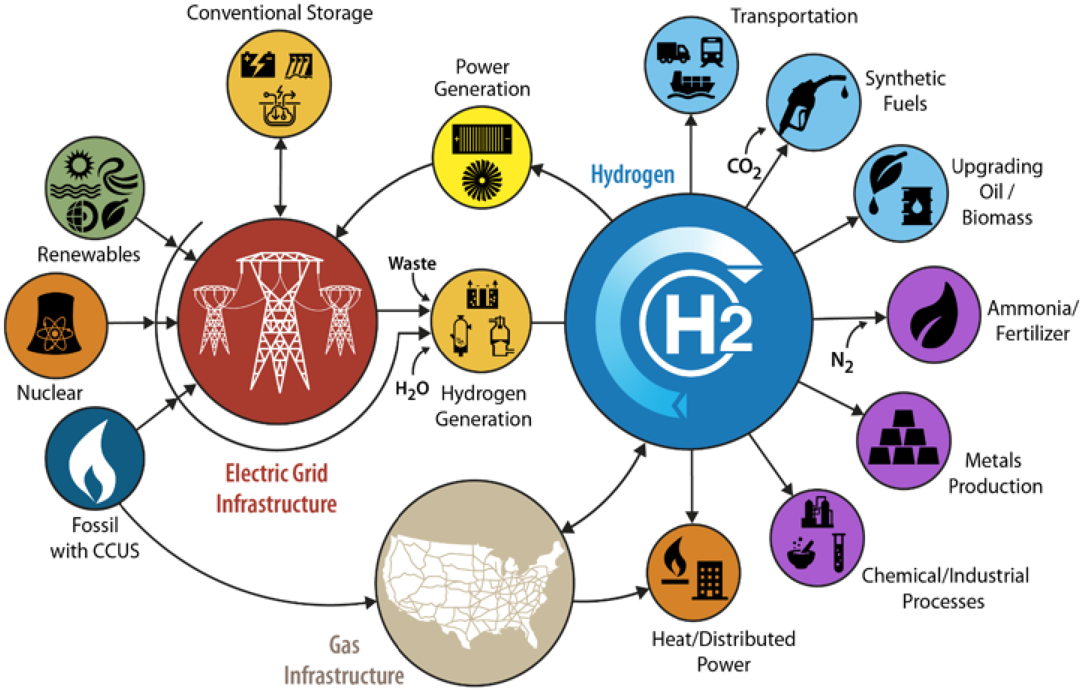
Outline

- **Introduce DOE-funded Pipeline Blending CRADA†, part of the DOE HyBlend initiative**
- **State of knowledge of pipeline steels in hydrogen**
  - **Fracture mechanics-based characterization of materials, mechanics and environmental variables**
  - **Variance of welds from basic trends**
- **Simple example of implications of hydrogen on structural integrity**

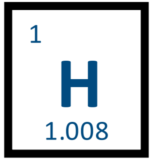
†CRADA: Cooperative Research and Development Agreement

Hydrogen has broad potential for decarbonization

H2@Scale is an enabler for deep decarbonization across sectors



Hydrogen can decarbonize end uses that are difficult to electrify, such as boilers and turbines in industry as well as some building appliances



=

- simple
- clean
- flexible

Source: U.S. DOE Hydrogen and Fuel Cell Technologies Office, https://www.energy.gov/eere/fuelcells/h2scale

HyBlend Pipeline Blending CRADA: Analysis and Materials R&D

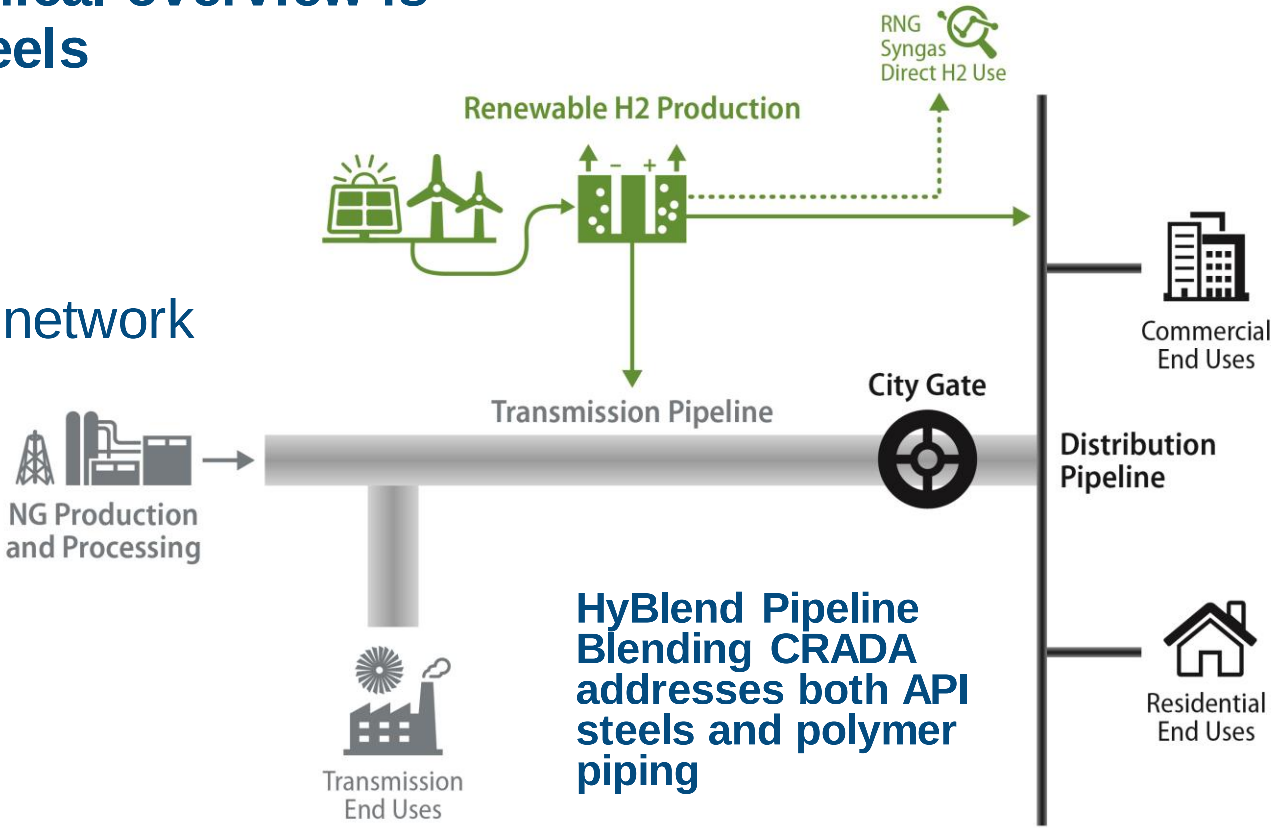
Focus of this technical overview is compatibility of steels

Transmission

- Mostly steels
- Extensive existing network

Distribution

- Legacy metals
- Extensive polymer networks



HyBlend Pipeline Blending CRADA addresses both API steels and polymer piping

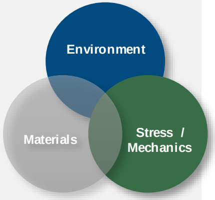
HyBlend

Materials activities in HyBlend Pipeline Blending CRADA:
Structural integrity for hydrogen gas infrastructure

How do we assess structural integrity of infrastructure with hydrogen?

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



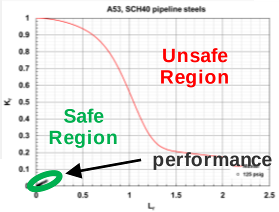
Guidance on operating conditions

+ partners

What is the structural risk to NG assets with blended hydrogen?

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



Industry-focused probabilistic framework for risk assessment

How do we formulate mechanistic models into predictions?

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

State-of-the-art characterization

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

Motivation

With growing interest in decarbonization, hydrogen is being considered as a means to reduce carbon in energy infrastructure

Challenge

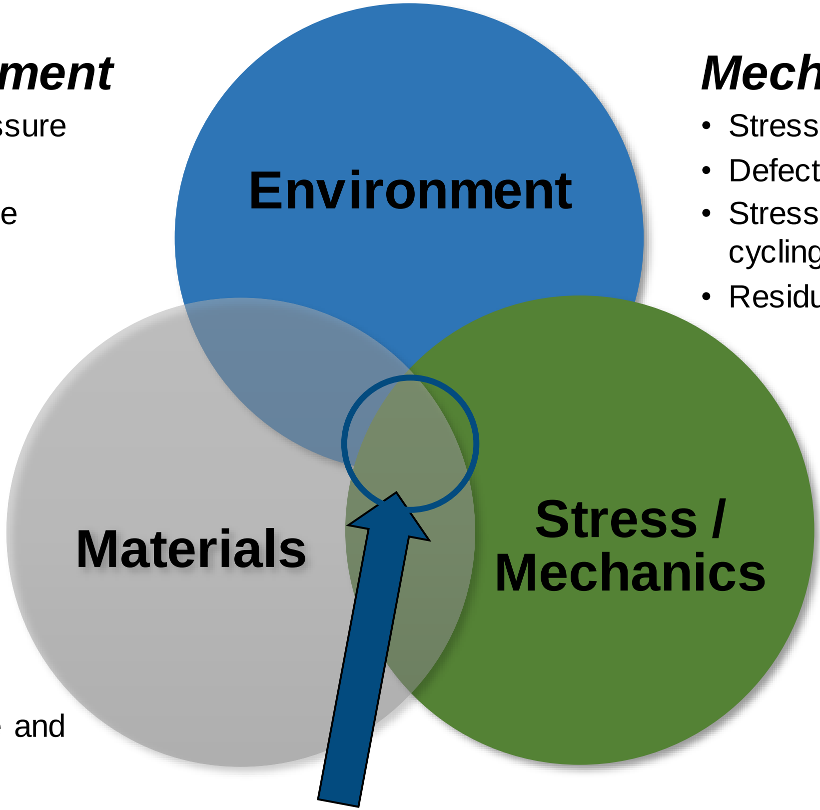
Hydrogen degrades fatigue and fracture resistance of steels, and the effects on pressure vessel and line pipe steels are significant

Environment

- Partial pressure
- Impurities
- Temperature

Mechanics

- Stress
- Defects
- Stress (pressure) cycling
- Residual stresses

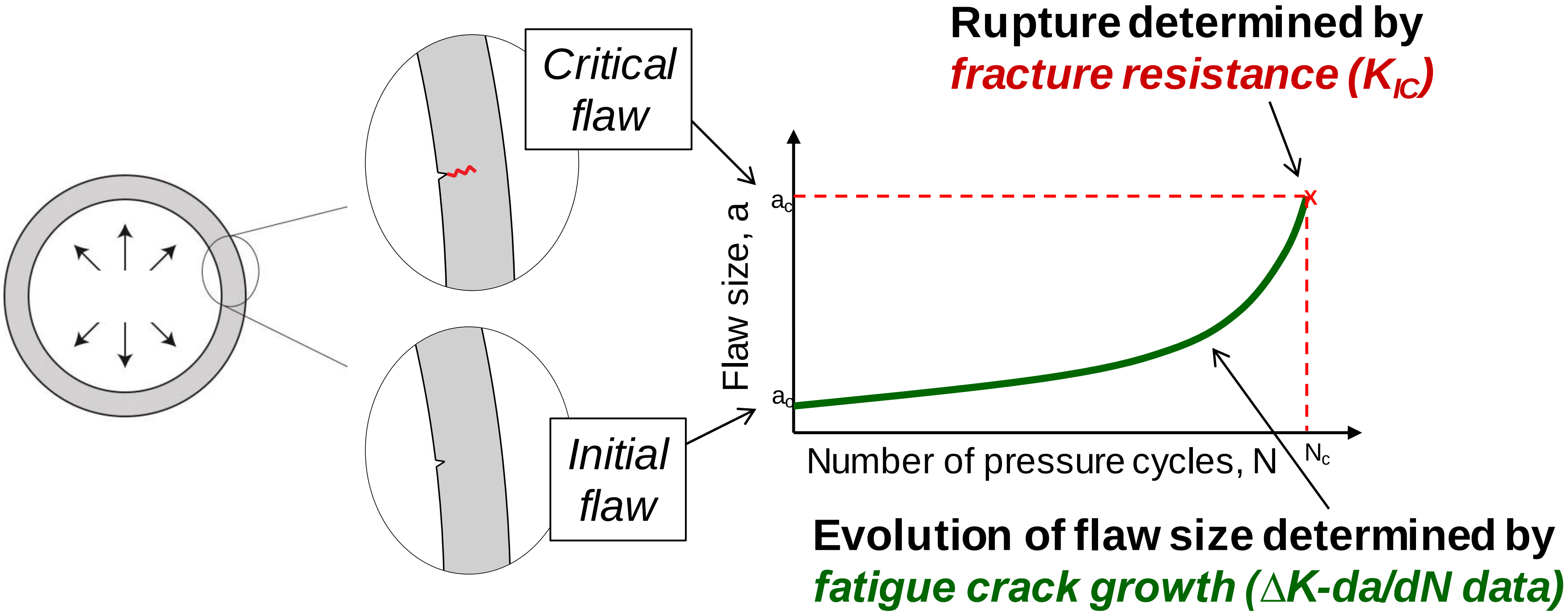


Materials

- Strength
- Microstructure and homogeneity

*Hydrogen embrittlement occurs in **materials** under the influence of **stress** in hydrogen **environments***

Testing motivation: structural integrity assessment utilizing fracture mechanics-based analysis



ASME B31.12 describes rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Division 3, Article KD-10

Background: stress intensity factor, *K*

What is this in the stress intensity factor, *K*?

$$K = \sigma\sqrt{\pi a} \times f(geometry)$$

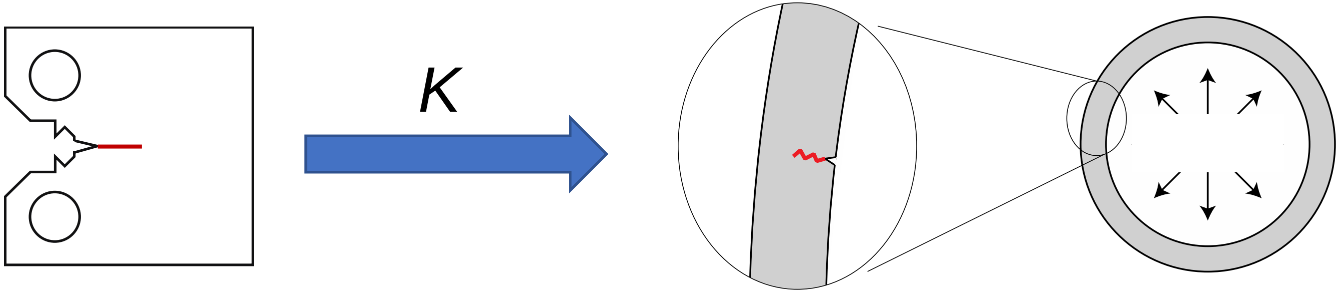
$\sigma = stress$

$a = crack\ size$

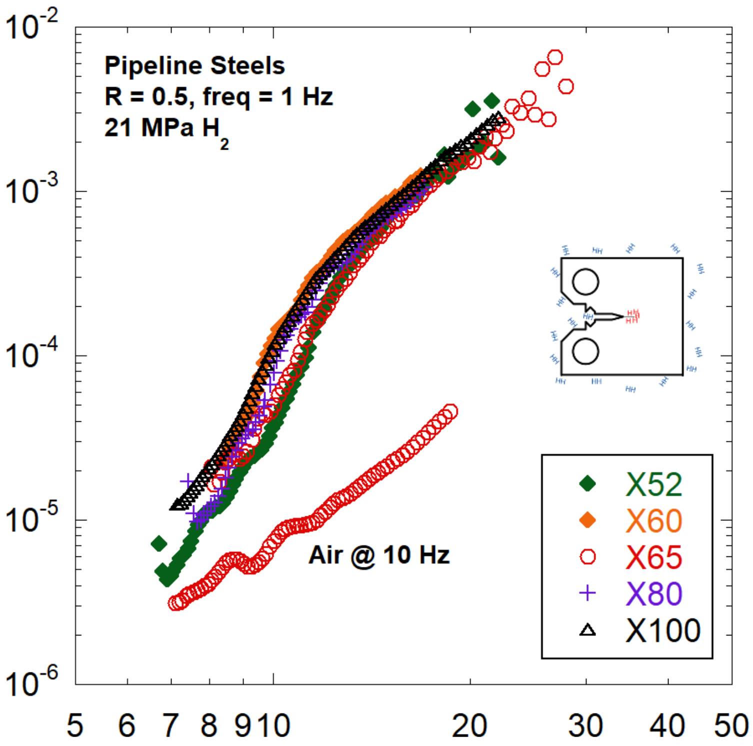
$$\Delta K = K_{max} - K_{min}$$

$$R = \frac{K_{min}}{K_{max}}$$

- ***K*** **characterizes the stress state at a crack tip**
  - analogous to the stress, but for the case of cracks in structures
- ***K*** **is a transferable parameter that is used to generalize the state of a crack and transfer information between one geometry and another**
  - for example between a laboratory test and a real-world application



API grade pipeline steels, representing a wide range of strength, show similar fatigue crack growth rates in gaseous hydrogen (GH2)

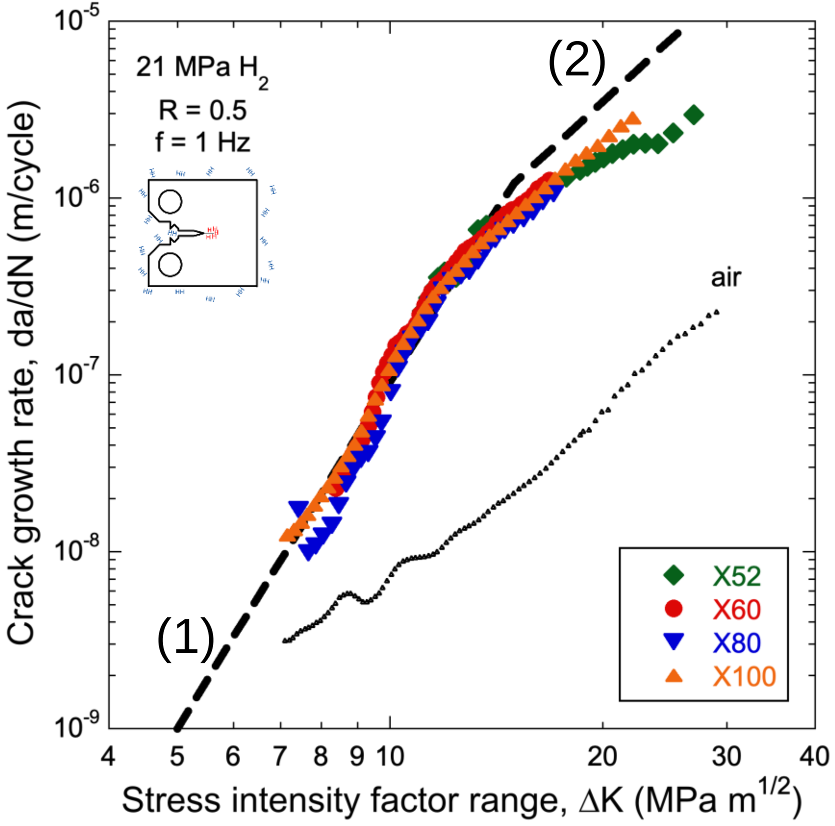


A wide variety of pipeline steels display nominally the same fatigue response in high-pressure GH2

Material	Microstructure	S_y (MPa)
X52	PF + pearlite	429
X60	PF	434
X65	banded ferrite + pearlite	478
X80 (B)	90% PF + 10% AF (coarse)	565
X80 (E)	AF (fine)	593
X80 (F)	70% AF + 30% PF	552
X100	Bainite + PF	732

Data generated at both SNL and NIST-Boulder, contained in various publications

The effects of GH2 on pipeline steels are captured by ASME CC2938 design curve for pressure vessels



CC2938 design curve was based on high pressure data

$$(2)\quad \frac{da}{dN} = C_3\left[\frac{1 + C_4 R}{1 - R}\right]\Delta K^{m_2}$$

$$(1)\quad \frac{da}{dN} = C_1\left[\frac{1 + C_2 R}{1 - R}\right]\Delta K^{m_1} f^{1/2}$$

Pressure compensation term not in CC2938

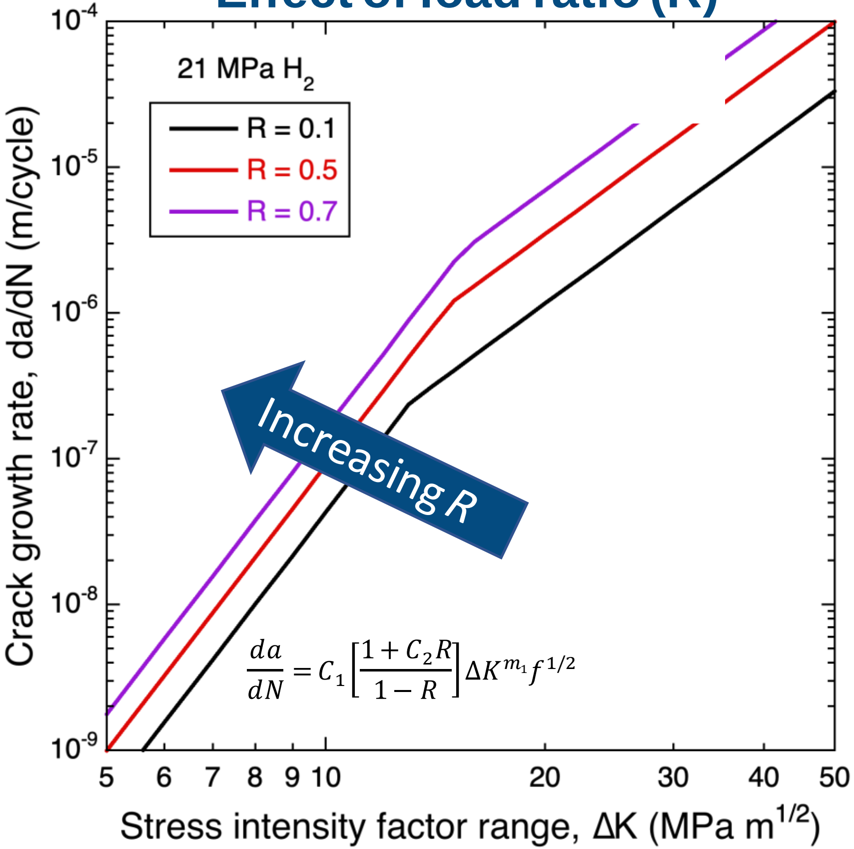
f is the thermodynamic pressure or fugacity

Ref: San Marchi et al, PVP2019-93803

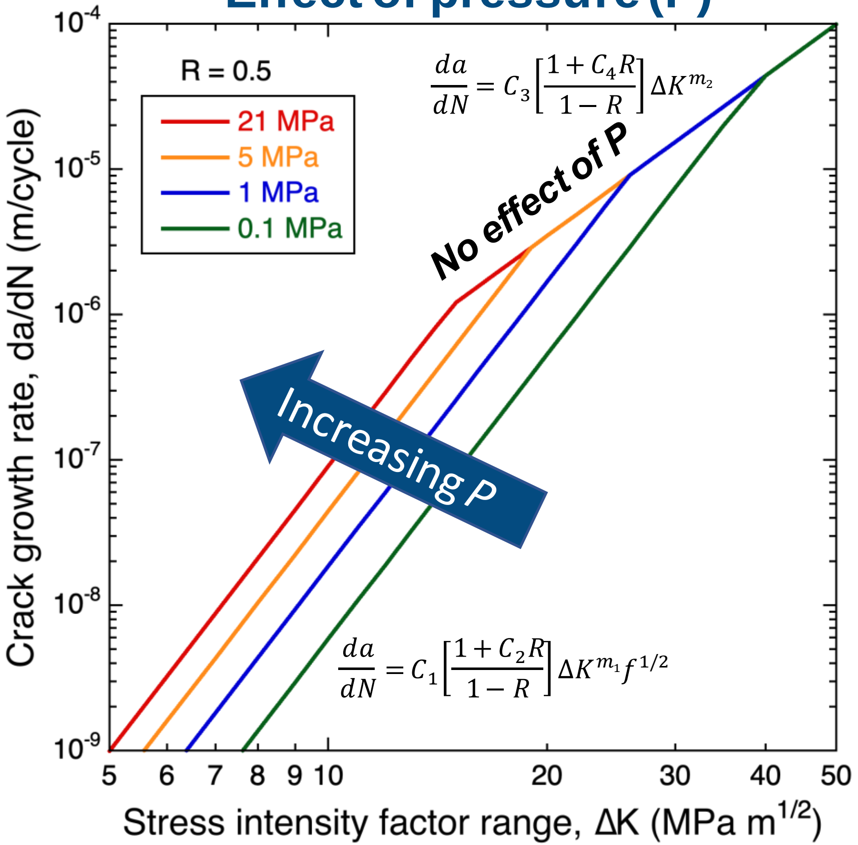
- **Does this design curve capture fatigue behavior of relevant pipeline steels at low pressure?**
- **What is the effect of pressure on fracture?**
- **What about welds?**

Design curves enable upper bound prediction for fatigue crack growth as function of loading and pressure

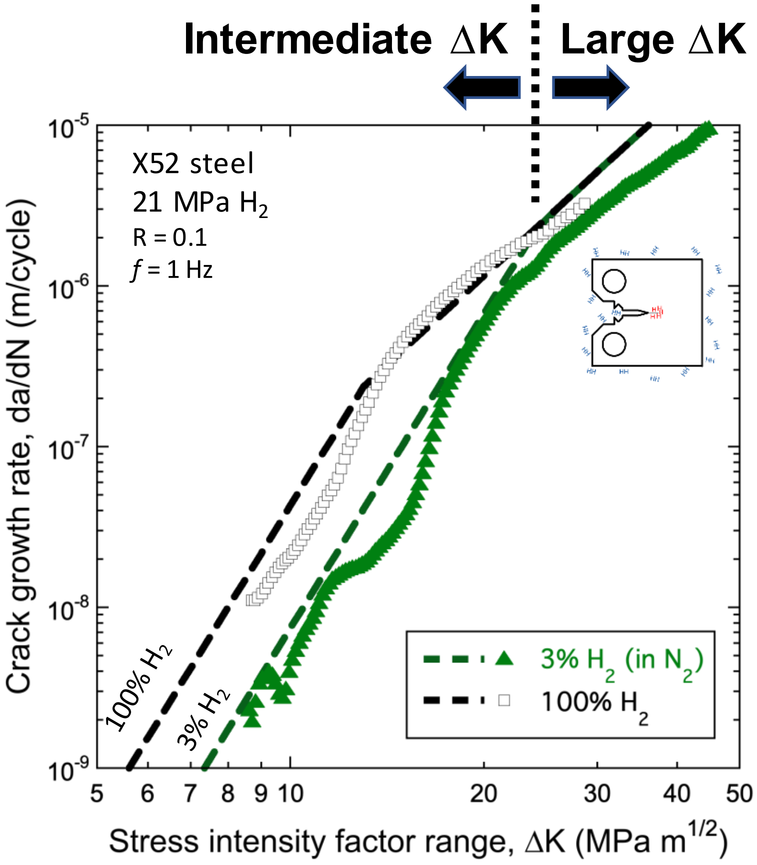
Effect of load ratio (R)



Effect of pressure (P)



Fatigue crack growth of X52: effect of Pressure



- **<u>Large ΔK</u>**
  FCG remains independent of pressure
  - **Fatigue crack growth rate in 3% H_2 is the <u>same</u> as in 100% H_2**
- **<u>Intermediate ΔK</u>**
  FCG is dependent on hydrogen partial pressure
  - **Fatigue crack growth rate is <u>slower</u> in 3% H_2 than in 100% H_2**

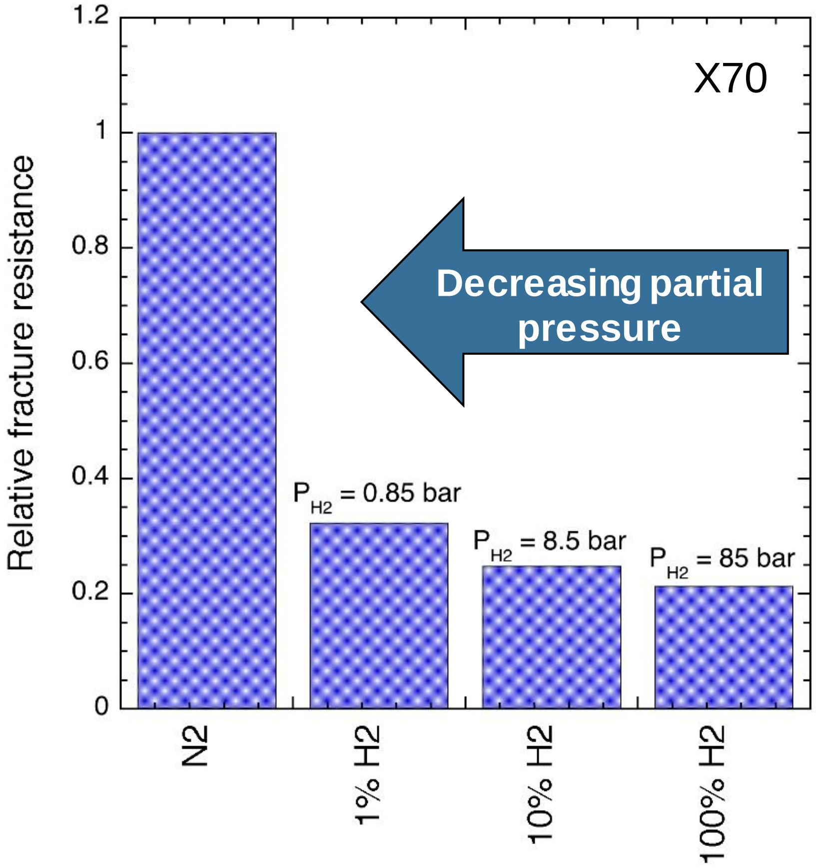
Design curves predict fatigue crack growth rates as a function of H_2 partial pressure (fugacity)

Ref: San Marchi et al, PVP2021-62045

Hydrogen-assisted fracture is apparent in low partial-pressure hydrogen

- **Measurements of fracture resistance in gaseous mixtures of H_2 and N_2 show substantial effects of H_2**
- **1% H_2 is only modestly different than 100% H_2**
- **Fracture resistance does not scale linearly with pressure/fugacity**

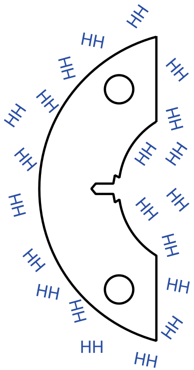
<1 bar of H_2 reduces fracture resistance



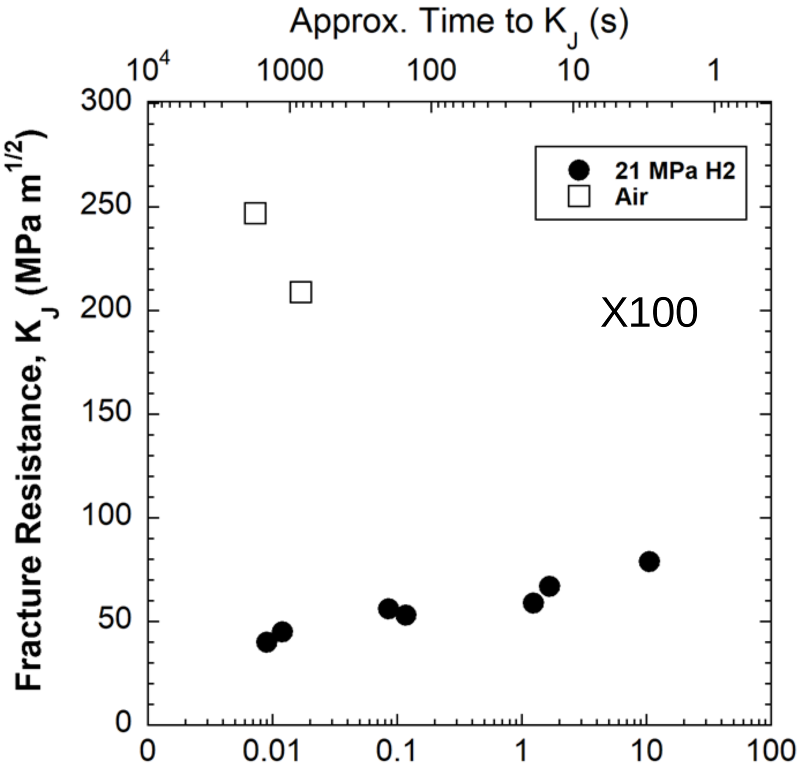
Ref.: Briottet et al, PVP2018-84658

GH2 affects fracture at high deformation rate

- **ASTM E1820 elastic-plastic fracture test (J-R curve) using arc geometry**
- **Estimate of strain rate:**
  - dε/dt ~ 1 EQPS/s for
  - dK/dt ~ 10 MPa $m^{1/2}$ s^{-1}

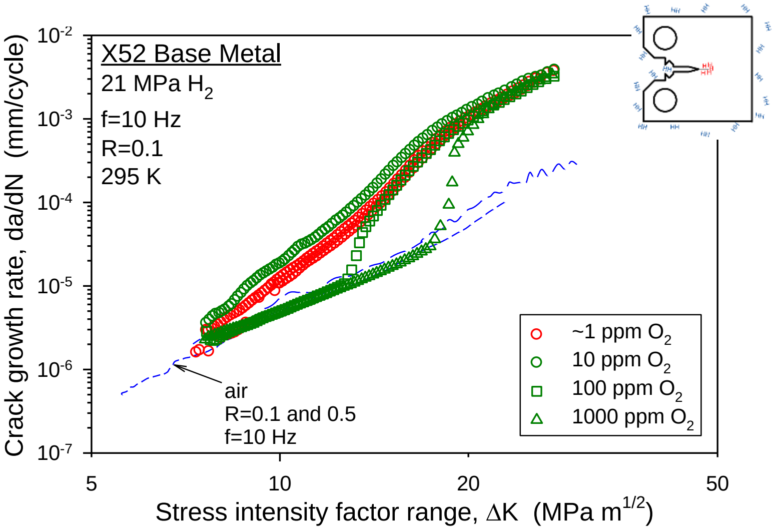


Effect of H_2 on fracture at high rate is more significant than commonly assumed



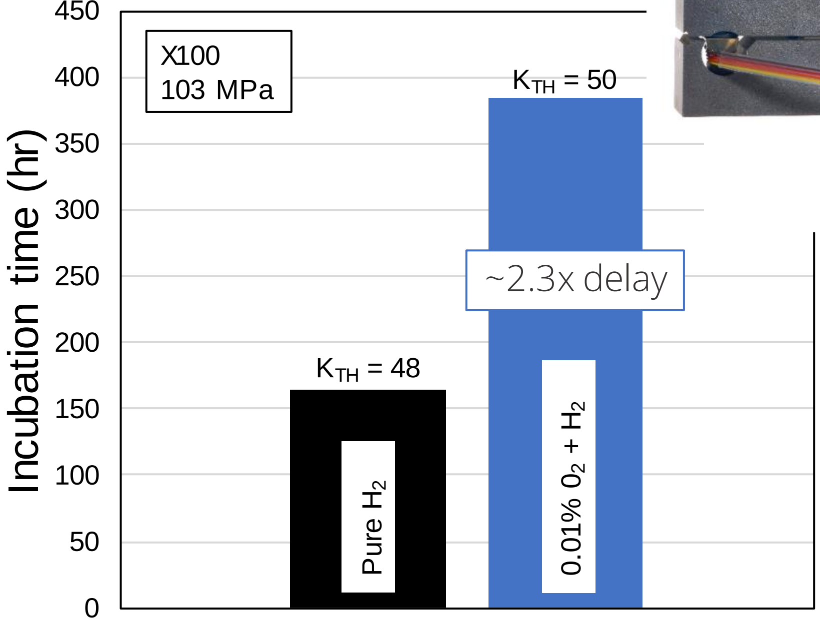
Ref.: Ronevich, San Marchi (unpublished).

Gas impurities can influence laboratory measurements…



Laboratory testing shows O_2 can mitigate some effects of H_2, but O_2 does <u>not</u> prevent H_2-assisted cracking

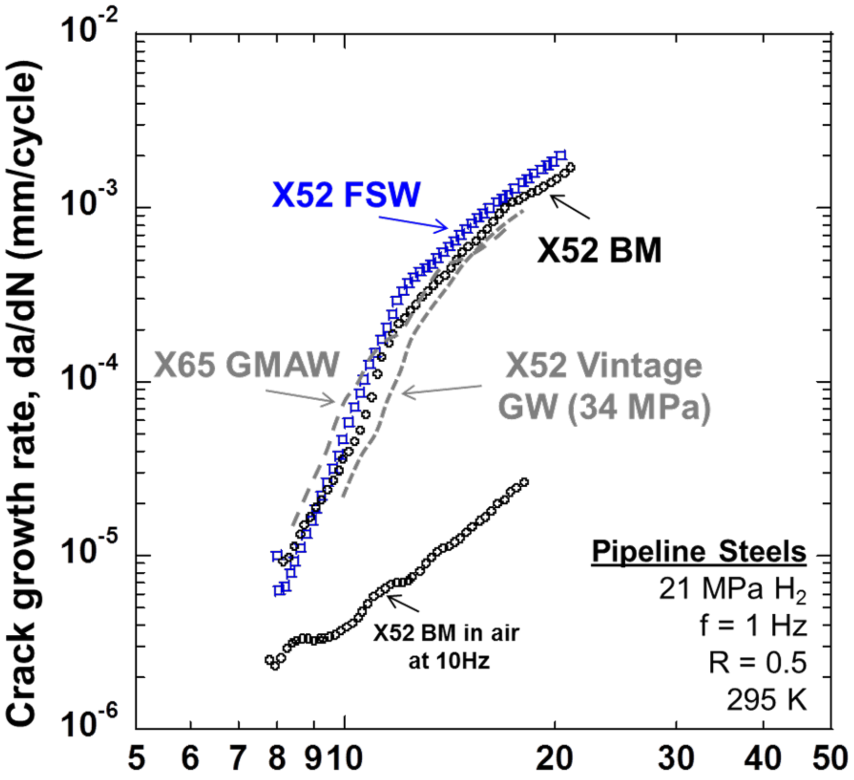
Constant displacement fracture tests



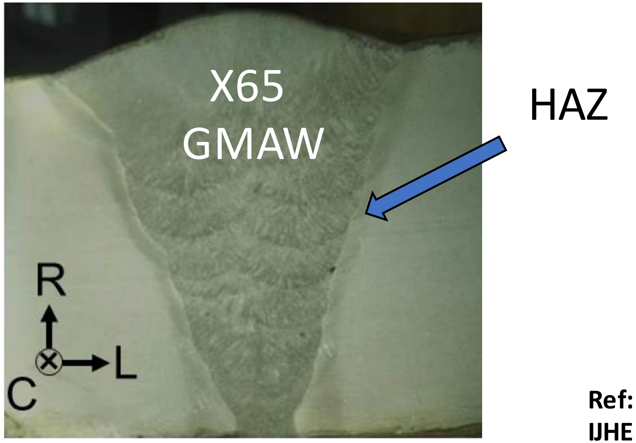
Ref.: Wheeler, Ronevich, San Marchi (unpublished).

… but challenging to transfer to service conditions

Welds and base materials behave similarly

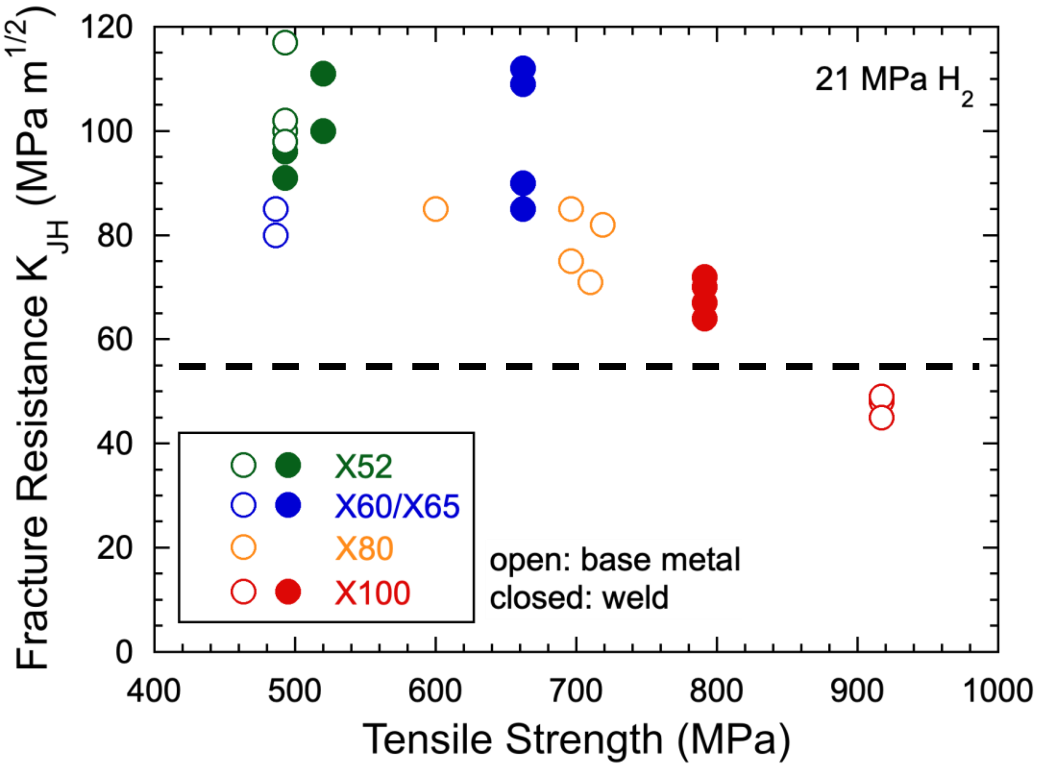


- To first order and if residual stress is considered, welds show similar fatigue and fracture behavior in gaseous H_2 as the base metals
- Similar trends have been observed for a variety of weld processes



Ref: Ronevich et al. IJHE 42 (2017)

Fracture resistance trends for welds and base metals are similar in GH2



- **Fracture resistance in H_2 decreases with increasing strength**
- **Welds behave nominally the same as base metals for same strength/hardness**
- **K_{JH} is generally greater than 55 MPa m$^{1/2}$**

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

Summary of *materials* behavior in GH2 (established)

- **How does gaseous hydrogen affect fatigue and fracture of pipeline steels?**
  - *Fatigue is accelerated by >10x*
  - *Fracture resistance is reduced by >50%*

- **Does the magnitude of pressure affect fatigue and fracture and is there a threshold below which hydrogen effects can be ignored?**
  - *Fatigue and fracture are affected by the magnitude of pressure*
  - *Even small amounts of hydrogen have large effects*

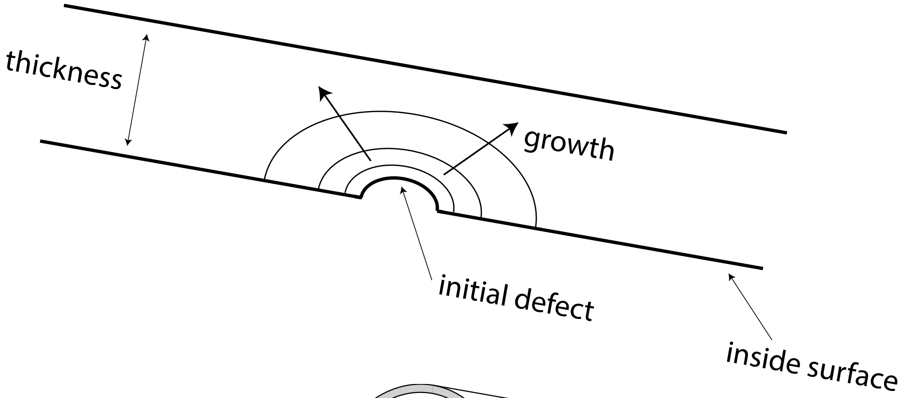
- **What materials variables influence the fatigue and fracture in GH2?**
  - *Materials pedigree has surprisingly little effect on FCG*
  - *Hydrogen-assisted fracture is influenced by strength*

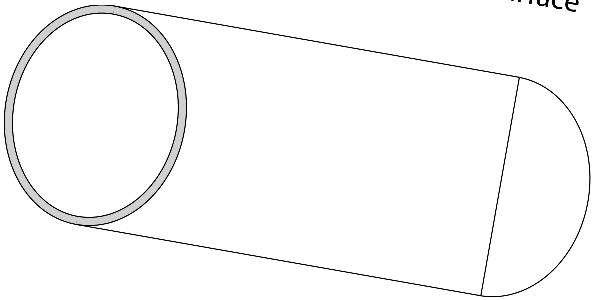
Summary of *materials* behavior in GH2 (emerging)

- **Are welds more susceptible to hydrogen than base metal?**
  - ***Welds (of comparable strength) have similar performance to base metals when residual stresses are accounted for***
- **Do high deformation rates preclude influence of GH2 on fracture?**
  - ***Large reduction in fracture resistance is maintained at high fracture rates***
- **Can oxygen (and other impurities) mitigate the effects of GH2?**
  - ***Under some circumstances in accelerated testing, O_2 can mitigate effects of GH2***
  - ***In long-term testing, O_2 appears less effective at mitigating effects of GH2***

Application of materials behavior to structural integrity analysis (simple example)

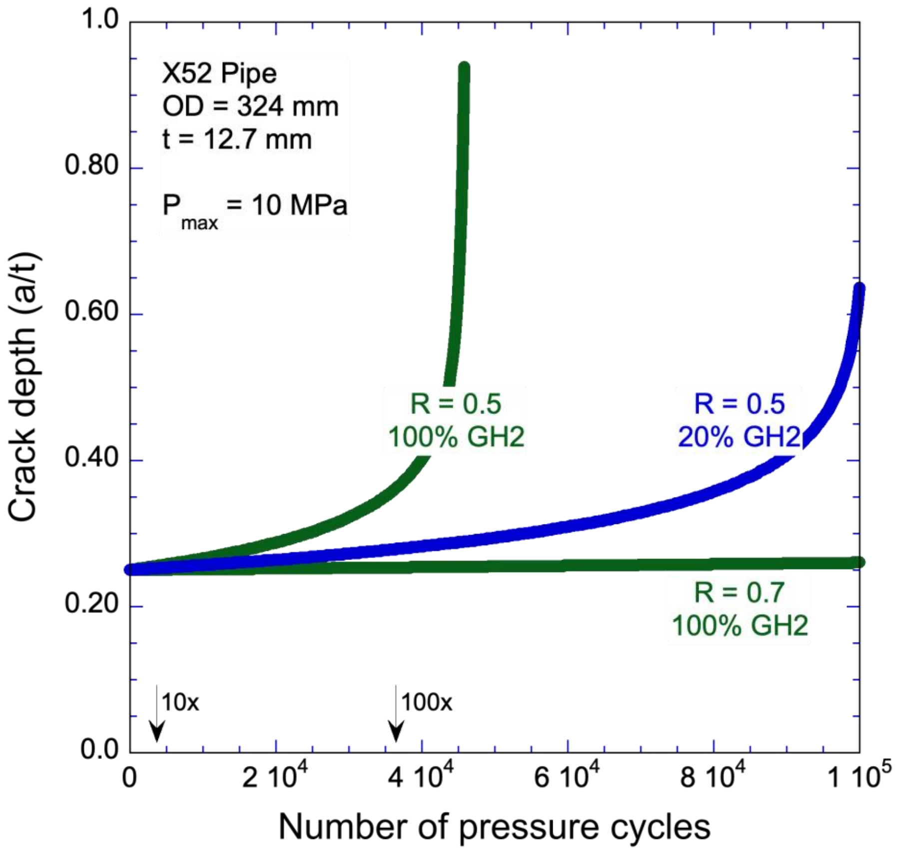
- ***Material***:
  - API grade X52 pipe
  - OD = 324 mm
  - t = 12.7 mm
- ***Environment***:
  - Pressure = 10 MPa, 20 MPa
  - GH2 = 20%, 100%
- ***Stress***:
  - Hoop stress: 34% SMYS, 68% SMYS
  - Cyclic pressure: $R = P_{min}/P_{max} = 0.5, 0.7$
  - Flaw
    - depth: 25% of wall thickness (a/t =0.25)
    - length: 40 mm (2c = 40mm) – propagate with constant aspect ratio





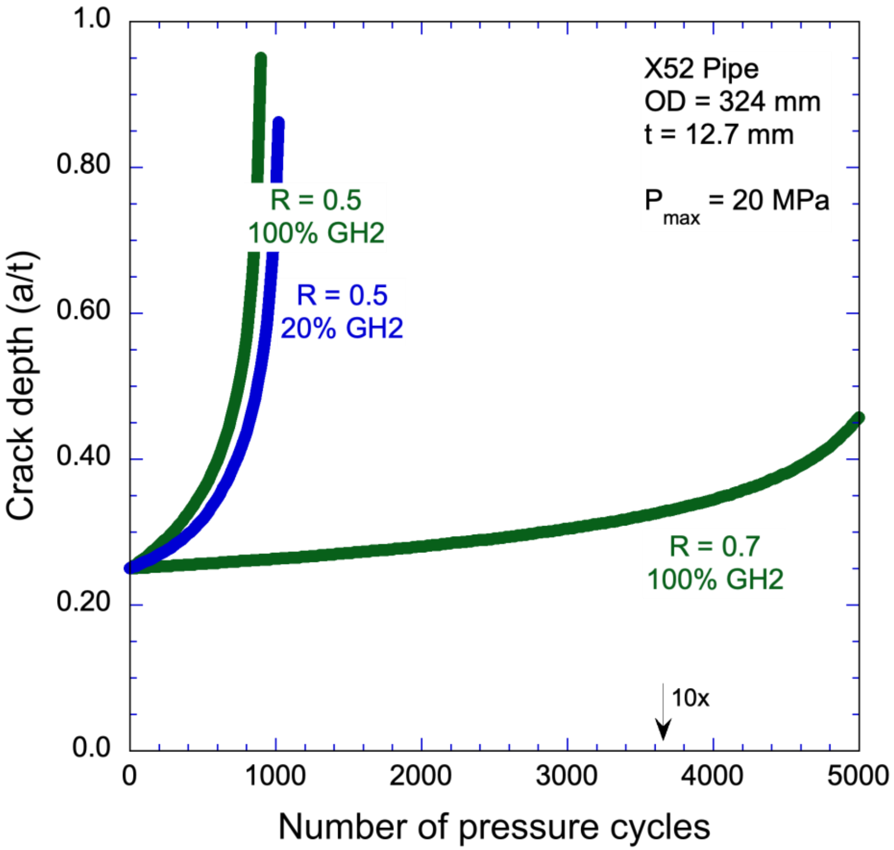
Analysis of transmission pipe structure (simple example)

- Stress is rather modest in this example
  - P_{max} = 10 MPa
  - σ_{hoop} ~ 34% SMYS
- Initial crack/flaw: a/t = 0.25
  - $K_{applied}$ = 16.5 MPa $m^{1/2}$
- The blending ratio has a non-proportional effect on crack evolution
- The pressure cycle has a much larger effect on crack evolution than the blending ratio: $\Delta P = (1 - R)P_{max}$
- Crack depth: a/t = 0.80
  - $K_{applied}$ = 50 MPa $m^{1/2}$
  - $K_{material}$ > 55 MPa $m^{1/2}$



Analysis of transmission pipe structure (simple example)

- **Stress is <u>large</u> in this example**
  - **P_{max} = 20 MPa**
  - **σ_{hoop} ~ 68% SMYS**
- **Initial crack/flaw: a/t = 0.25**
  - **$K_{applied}$ = 33 MPa $m^{1/2}$**
- **The blending ratio has no effect on fatigue response (for R = 0.5)**
- **The pressure cycle dominates**
- **Crack depth: a/t = 0.80**
  - **$K_{applied}$ = 99 MPa $m^{1/2}$**
  - **$K_{material}$ > 55 MPa $m^{1/2}$**



Summary of *structural* behavior with GH2

- **Can GH2 be safely injected into natural gas transmission pipe?**

It depends…

- ***Structural integrity depends sensitively on the pipe dimensions, the pipe condition and operating conditions***
- ***For given pipe dimensions and operating conditions, the base material is a secondary consideration***
- ***Blending ratio will not be the principal concern in most cases***
- ***Pressure cycling will likely need to be managed***
- ***Hard spots could be problematic (e.g., vintage welds)***
- ***External loading and the condition of the asset (e.g., defects) will likely dominate overall risk exposure***

Acknowledgements

H-Mat R&D and the HyBlend projects are being funded by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy's Hydrogen and Fuel Cell Technologies Office

The HyBlend Pipeline Blending CRADA is additionally being cost shared by >30 stakeholders from across industry, academia, and states.

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

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.

Thank You!

Chris San Marchi
cwsanma@sandia.gov

Joe Ronevich
jaronev@sandia.gov

https://h-mat.org/

https://www.sandia.gov/matlsTechRef/

https://granta-mi.sandia.gov/

Special thanks to Sandia's Safety, Codes and Standards team, H-Mat team and HyBlend team:

James McNair
Brendan Davis
Jeff Campbell
Robert Wheeler
Rakish Shrestha
Jay Foulk
Chris LaFleur
Brian Ehrhart
Ethan Hecht
Remi Dingreville
Khalid Hattar
Coleman Alleman
Vince Pericoli
Xiaowang Zhou
Chris Nowak
Mark Wilson
Nalini Menon
Norm Bartelt
Kathryn Small
Matthew Brownell
Brian Kagay
Amalie Frischknecht
Brandon Talamini
Ben Schroeder
Austin Glover

Informational resources

- **Technical Reference for Hydrogen Compatibility of Materials**
  - **https://www.sandia.gov/matlsTechRef/**
  - Report no. SAND2012-7321 (Technical Reference v.2)
  - Report no. SAND2013-8904 (polymers)
- **Technical Database for Hydrogen Compatibility of Materials**
  - **https://granta-mi.sandia.gov/**
- **Study Group on Materials Testing and Qualification for Hydrogen Service**
  - Annual topical discussion group: international and industrial participation
- **ASME Pressure Vessels and Piping Division Annual Conference (2005 - current)**
  - *Materials for Hydrogen Service*: session organization (2014-current)
- **Expanded resources under development at**
  - **Including H-Mat DataHUB (https://h-mat.org)**

Background: thermodynamics (origin of fugacity)

H in metals: $\mu^{H} = \mu_{o}^{H} + RT \ln c_{H}$

Gas phase: $\mu^{HH} = \mu_{o}^{HH} + RT \ln f_{HH}$

At equilibrium: $\frac{1}{2}H_2 \leftrightarrow [H]$

$$\frac{1}{2}\mu^{HH} = \mu^{H}$$

$$\frac{\frac{1}{2}\mu_{o}^{HH} - \mu_{o}^{H}}{RT} = \ln \frac{c_H}{(f_{HH})^{1/2}}$$

General form of Sieverts' Law $K = \frac{c_H}{(f_{HH})^{1/2}}$

Equation of state for H_2
Abel-Noble formulation

$$V_m = \frac{RT}{P_{HH}} + b$$

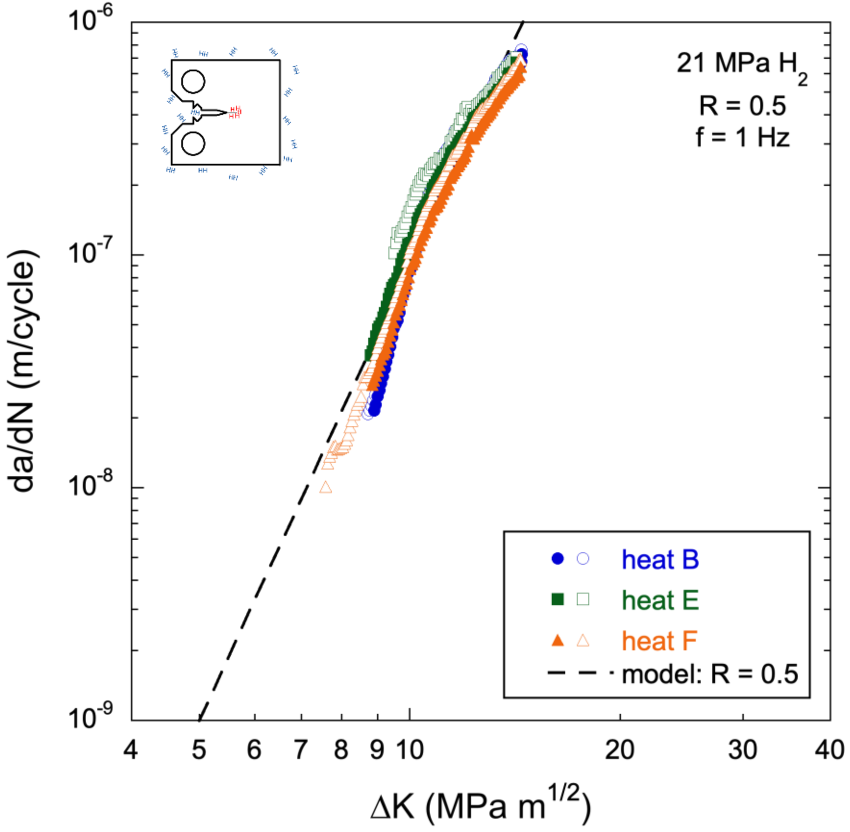
Pure gaseous H_2:

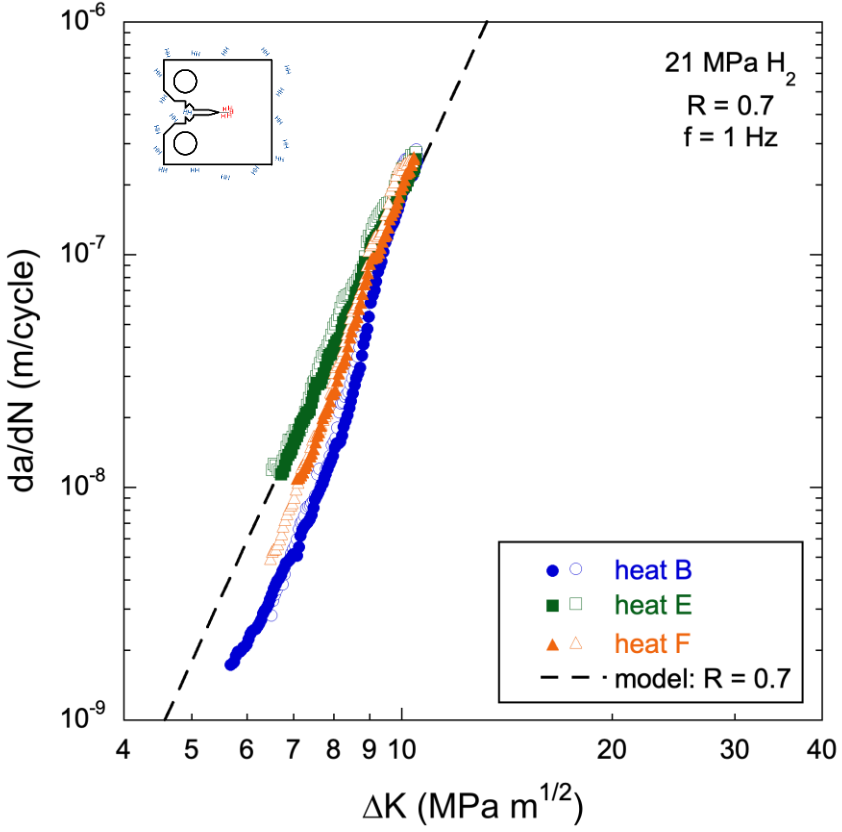
$$f_{HH} = P_{HH} \exp\left(\frac{bP_{HH}}{RT}\right)$$

Blended H_2:

$$f_{HH} = P_{HH} \exp\left(\frac{bP_{total}}{RT}\right)$$

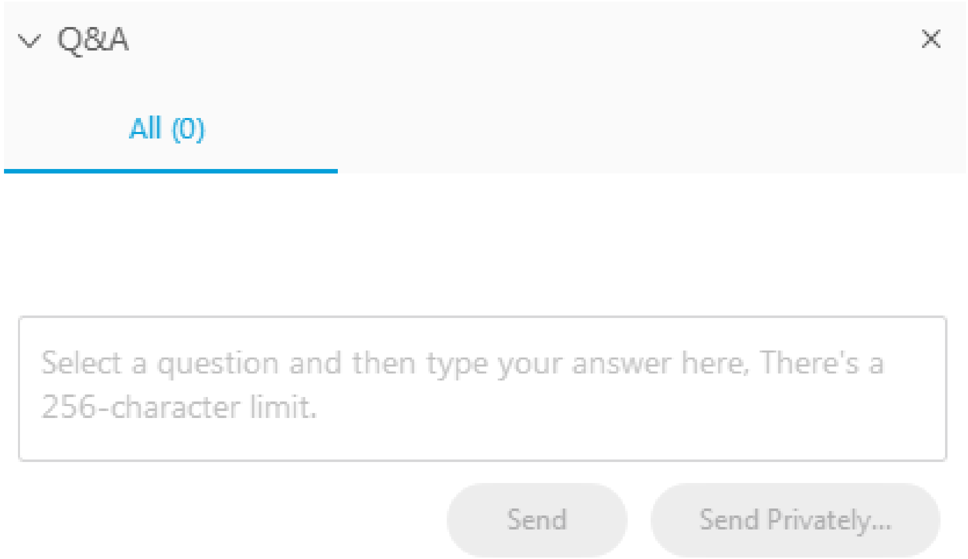
Fatigue crack growth of X80: effect of R





The #H2IQ Hour Q&A

Please type your questions into the **Q&A Box**



The #H2IQ Hour

Thank you for your participation!

Learn more:

energy.gov/fuelcells
hydrogen.energy.gov