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Hydrogen-assisted fatigue and fracture of pipeline materials in natural gas infrastructure: trends and implications on structural integrity

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Motivation

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

Challenge

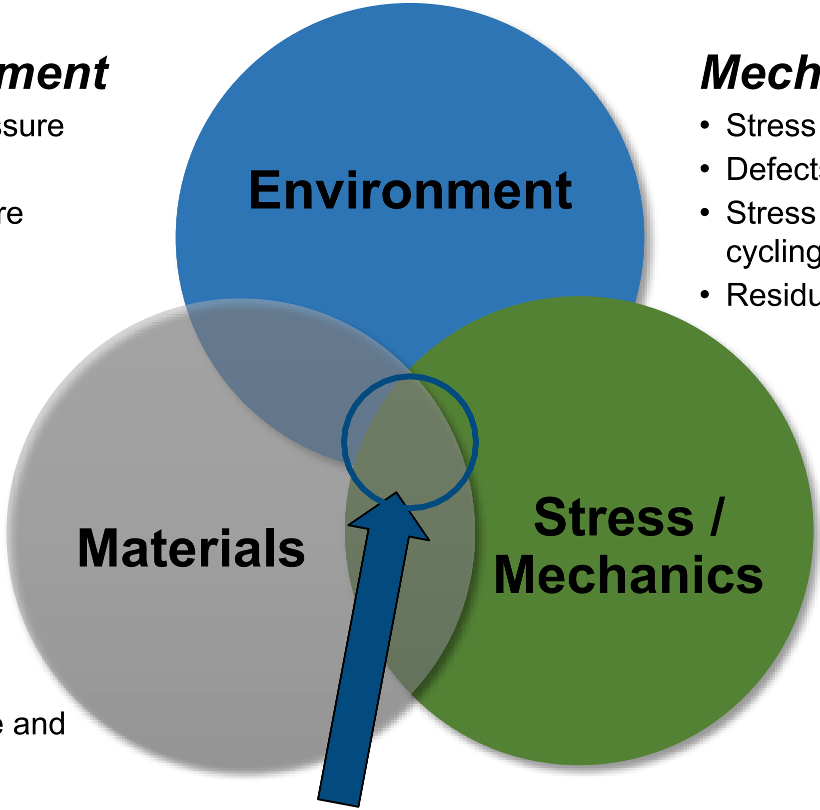
Hydrogen degrades fatigue and fracture resistance of steels, and the effects on pressure vessel and line pipe steels are significant

Environment

- Partial pressure
- Impurities
- Temperature

Mechanics

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

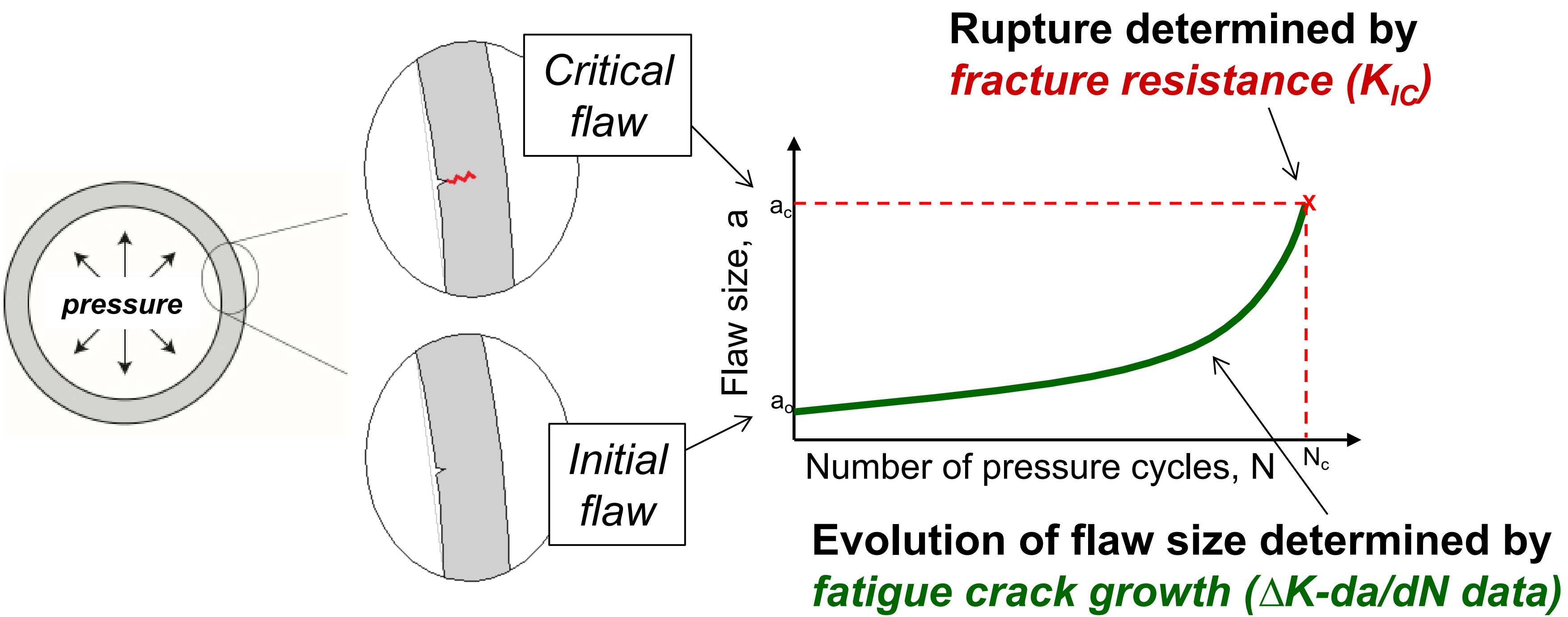


Materials

- Strength
- Microstructure and homogeneity

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

Structural integrity assessment: Basic requirements



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

Outline

- Materials variables
  - Microstructure and Welds
- Environmental variables
  - Pressure
- ~~Mechanics variables~~
- Application of knowledge to structural integrity assessments for hydrogen service

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→ Structural performance

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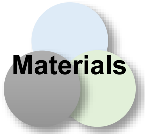

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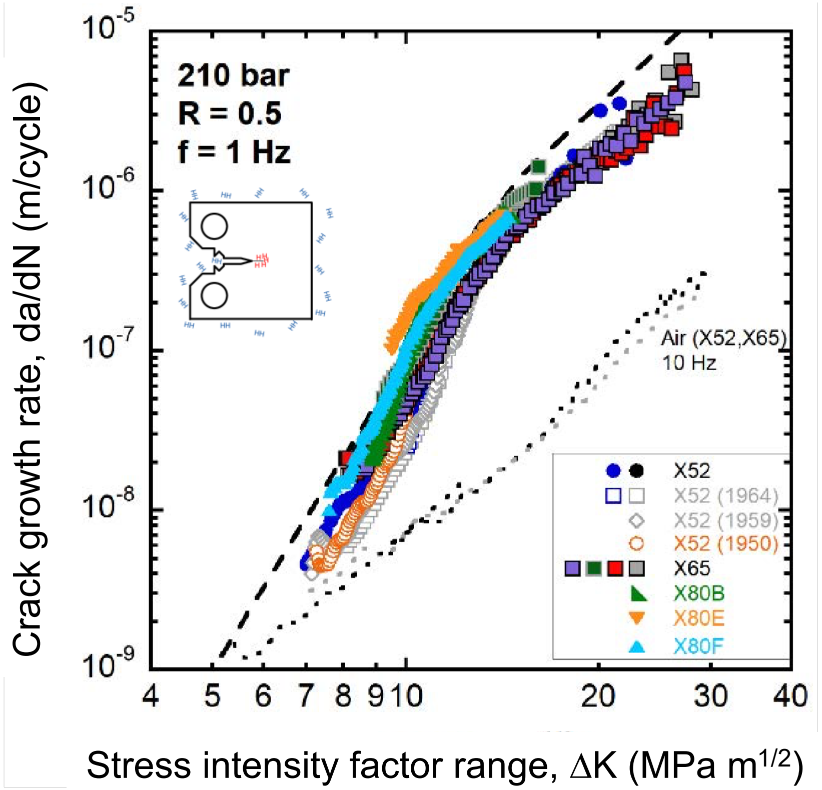
Materials performance

Fatigue crack growth rates in gaseous hydrogen (GH2) similar for all grades of API pipeline steels



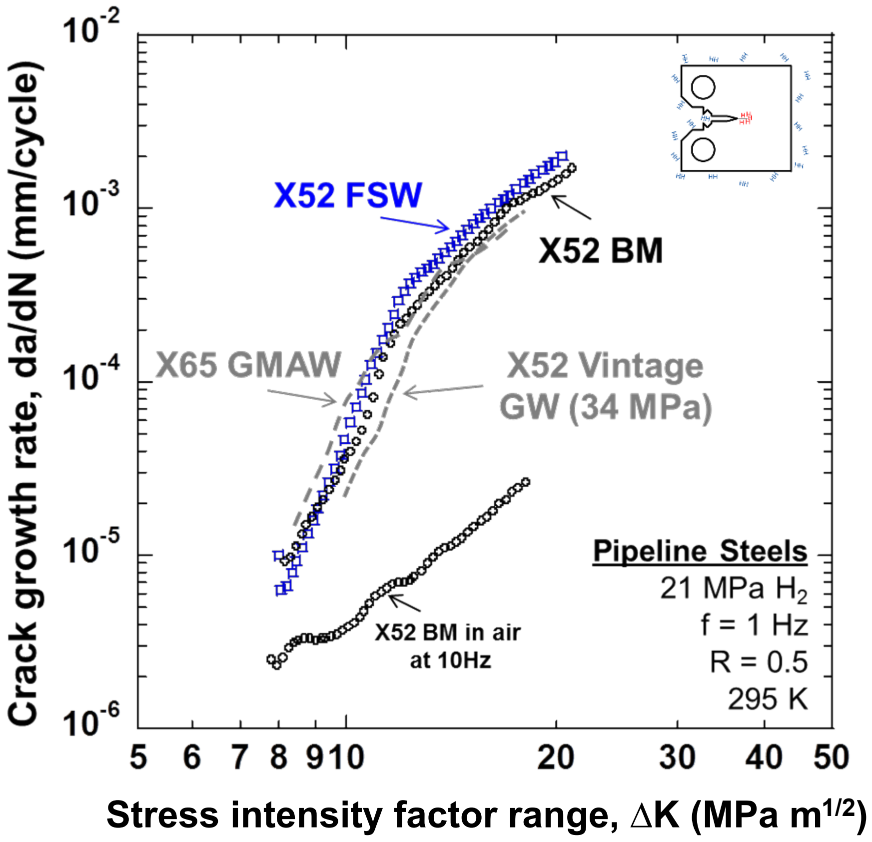
A wide variety of steel microstructures display nominally the same fatigue response in high-pressure GH2

Material	Microstructure	S_y (MPa)
X52	PF + pearlite	334-490
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

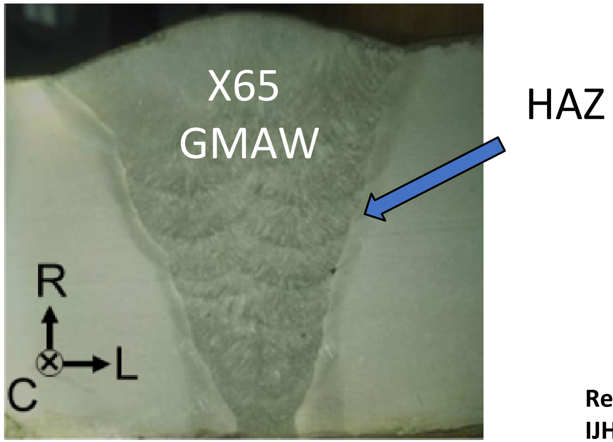
Data generated at both SNL and NIST-Boulder, contained in various publications

Welds and base materials behave similarly in GH2

Materials



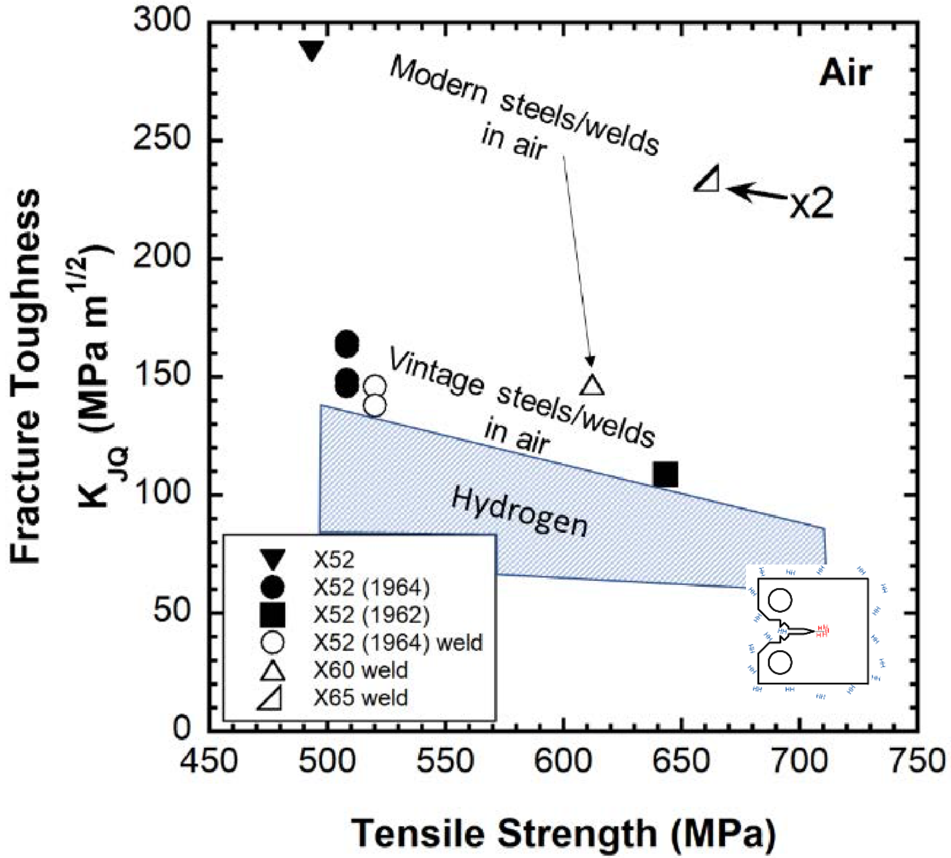
- To first order and if residual stress is considered, welds and HAZ show similar fatigue behavior in gaseous H_2 as the base metals
- Similar trends have been observed for a variety of weld processes



Ref: Ronevich et al. IJHE 42 (2017)

Fracture toughness of API grade pipeline steels depends on steel vintage and strength

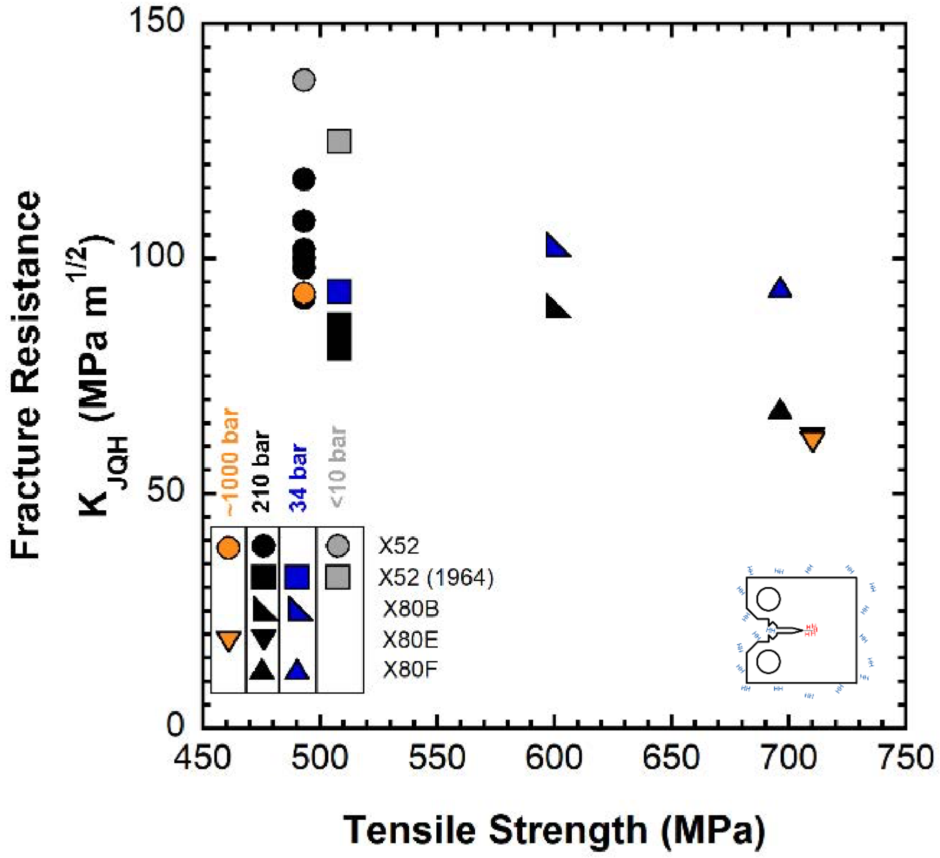
Materials

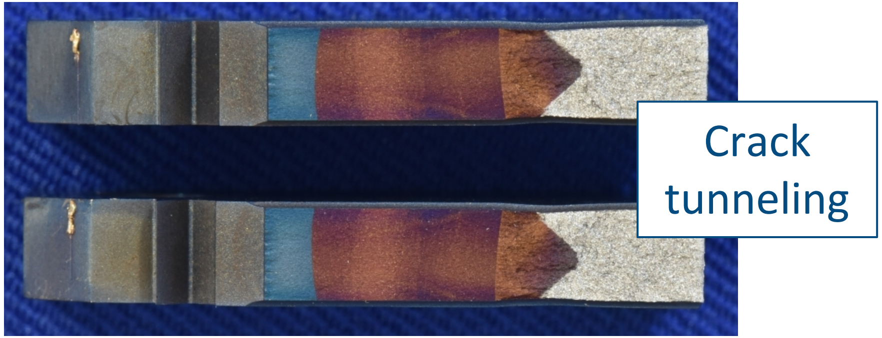


- **In general, modern steels have very high fracture toughness in air**
- **Modest trend with tensile strength in air:**
  higher strength →
  lower fracture toughness
- **Hydrogen 'equalizes' the fracture behavior**

Ref.: Ronevich et al, Intern Conf Metals and Hydrogen (2022)

Fracture resistance in GH2 does not necessarily reflect the fracture toughness in air





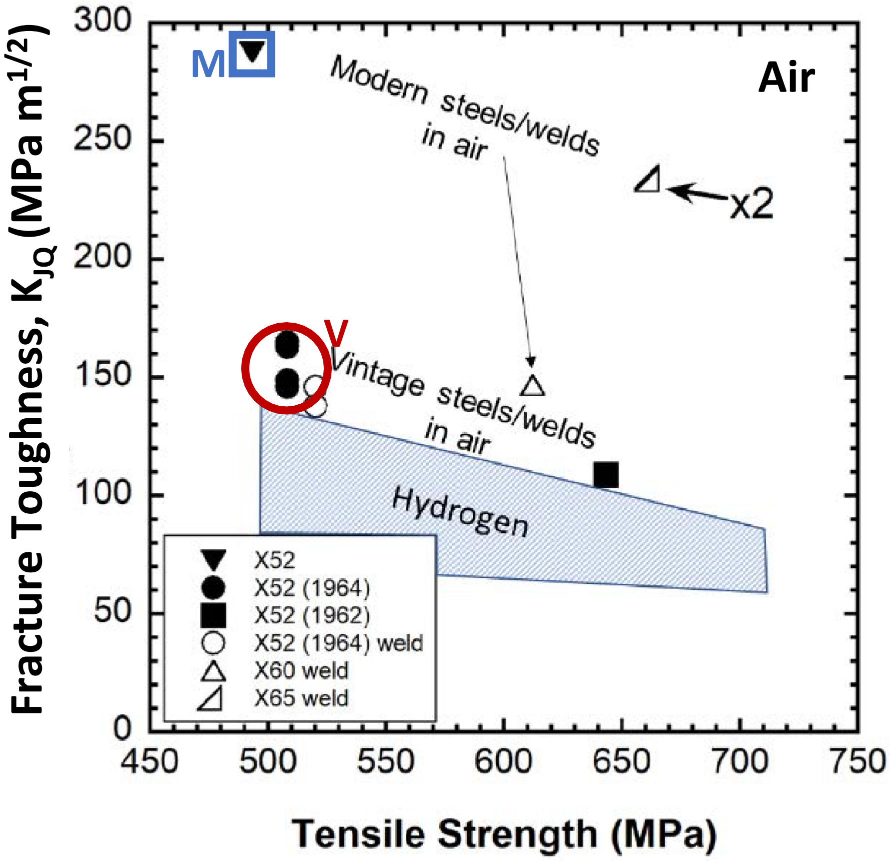
- **In GH2 (as in air)**

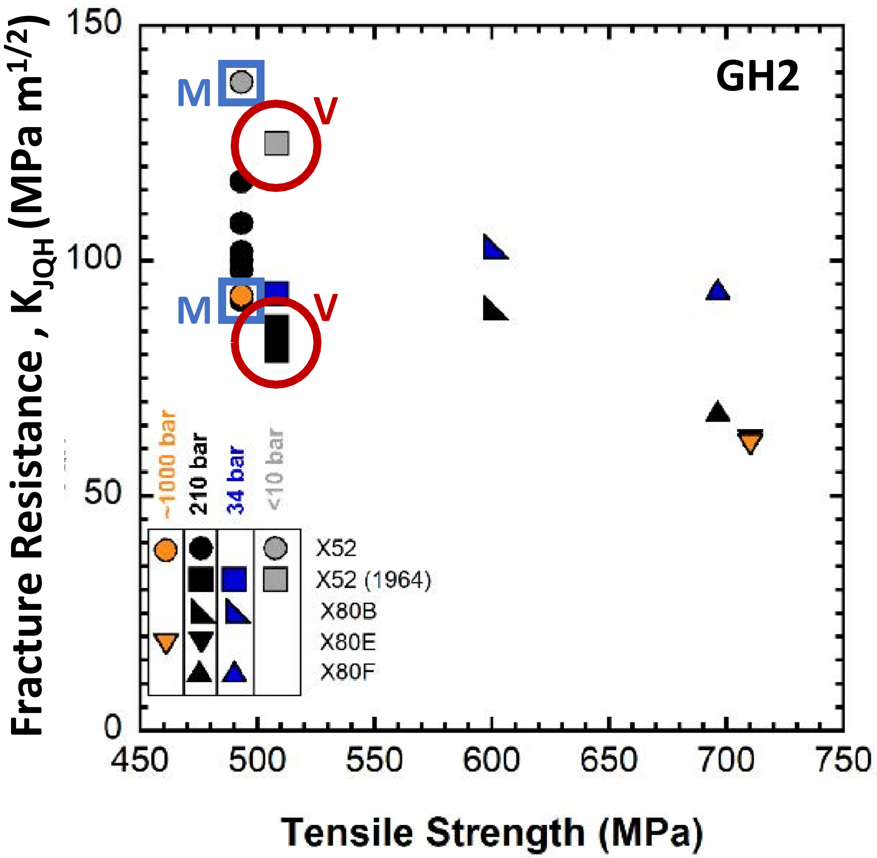
  higher strength → lower fracture resistance

- **K_{JQH} is generally greater than 55 MPa m$^{1/2}$**

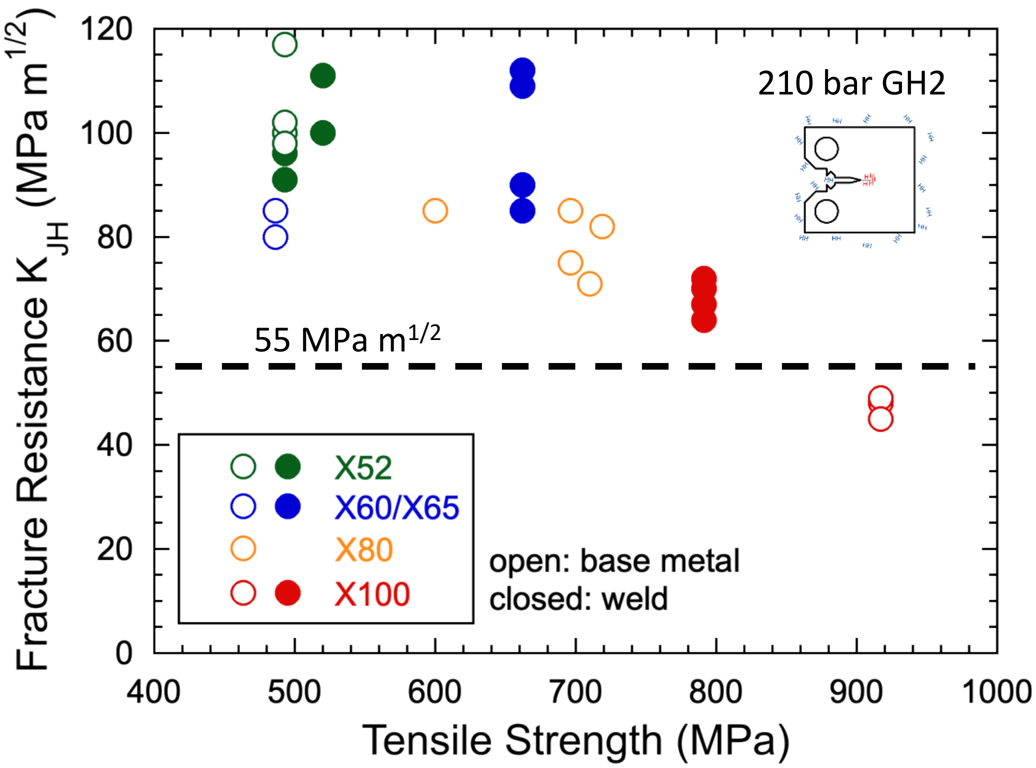
Ref.: Ronevich et al, Intern Conf Metals and Hydrogen (2022)

Hydrogen '*equalizes*' the fracture behavior





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



- **Fracture resistance trends are similar for welds and base metals**
- **One should consider the influence of residual stresses**
- **Hardness is an important factor**
    - **Local hard spots can be detrimental in GH2**

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

Outline

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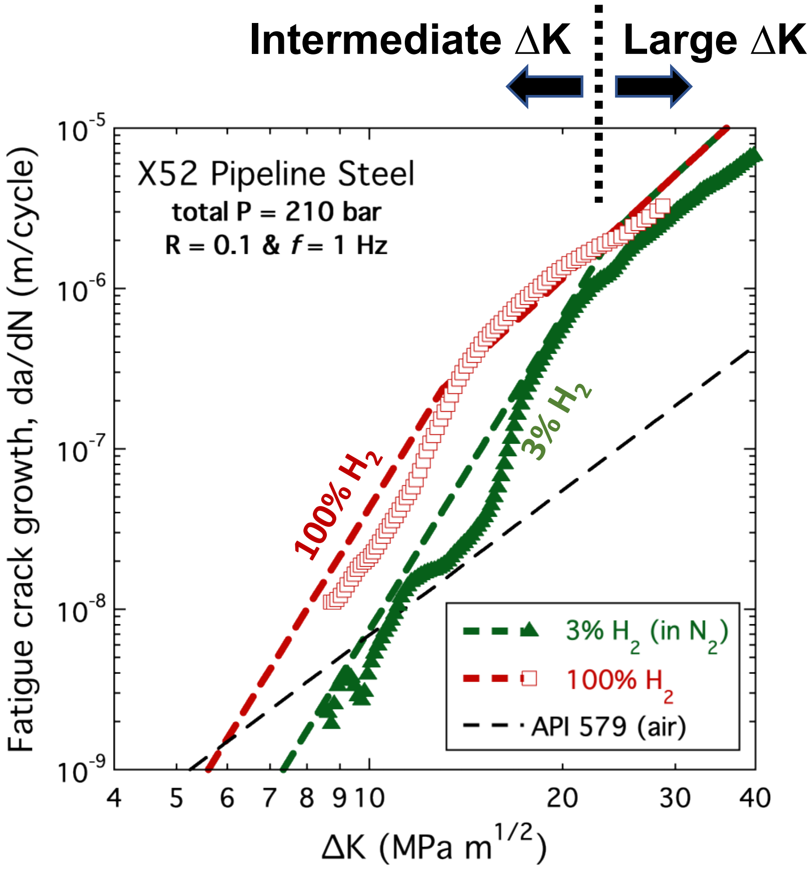
Materials performance

Low hydrogen pressure = large effect on fatigue

Environment



- <u>Large ΔK</u>
  FCG is 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

Dashed lines represent design curves that can be used to bound fatigue crack growth rates

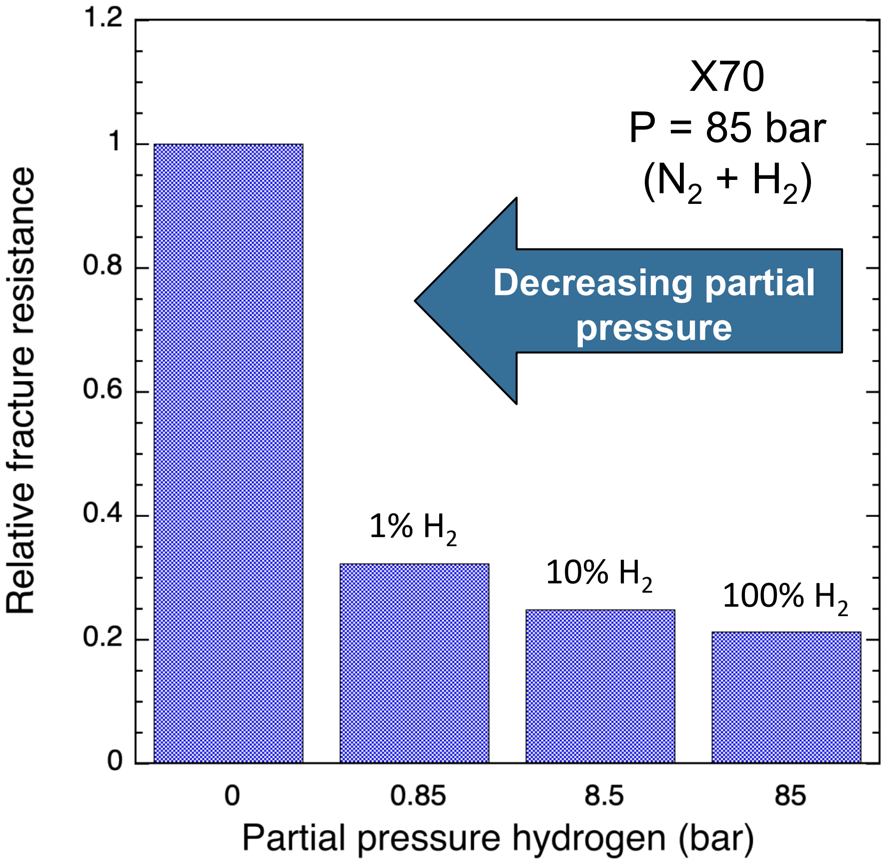
Ref.: San Marchi et al, PVP2021-62045

Low hydrogen pressure = large effect on fracture

Environment

- 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 substantially reduces fracture resistance



Ref.: Briottet et al, PVP2018-84658

Summary of *materials performance* in GH2

- How does GH2 affect fatigue and fracture of pipeline steels?
  - *Fatigue is accelerated by >10x*
  - *Fracture resistance is reduced by >50%*
- Does pressure affect fatigue and fracture?
  - *Fatigue and fracture are affected by pressure and there's no obvious threshold (low pressure can 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*
  - *Welds (of comparable strength) have similar performance to base metals*

Outline

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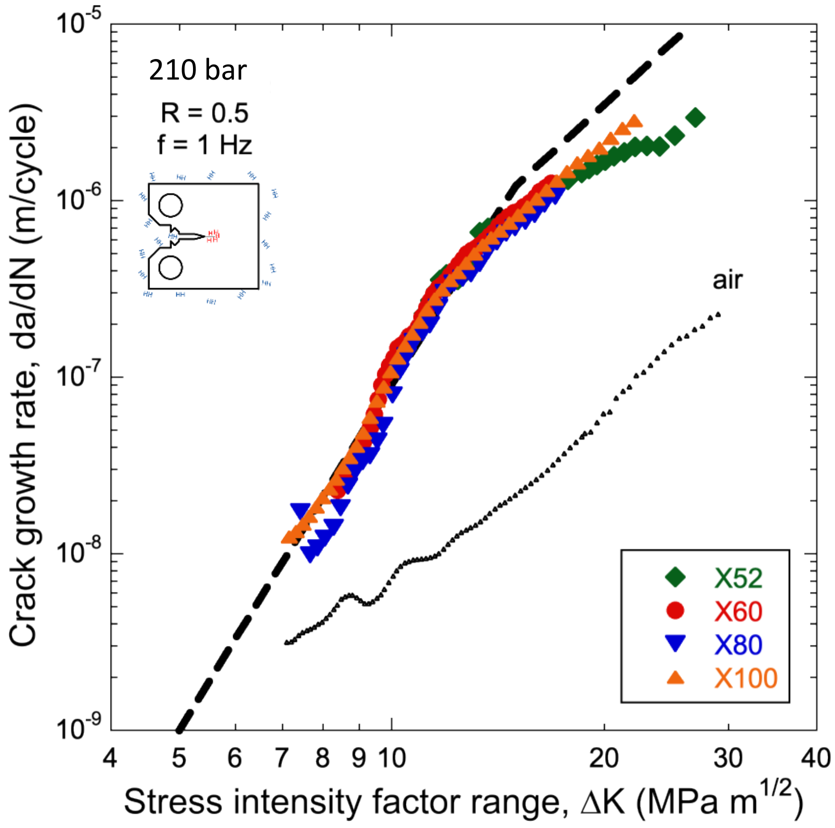
- **Application of knowledge to structural integrity assessments for hydrogen service** → **Structural performance**

General bounding (design) curve captures the behavior of pipeline steels in GH2



Master design curve formulation

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

Low ΔK: $$\frac{da}{dN} = 7.6x10^{-16}\left[\frac{1+0.4286R}{1-R}\right]\Delta K^{6.5} f^{1/2}$$

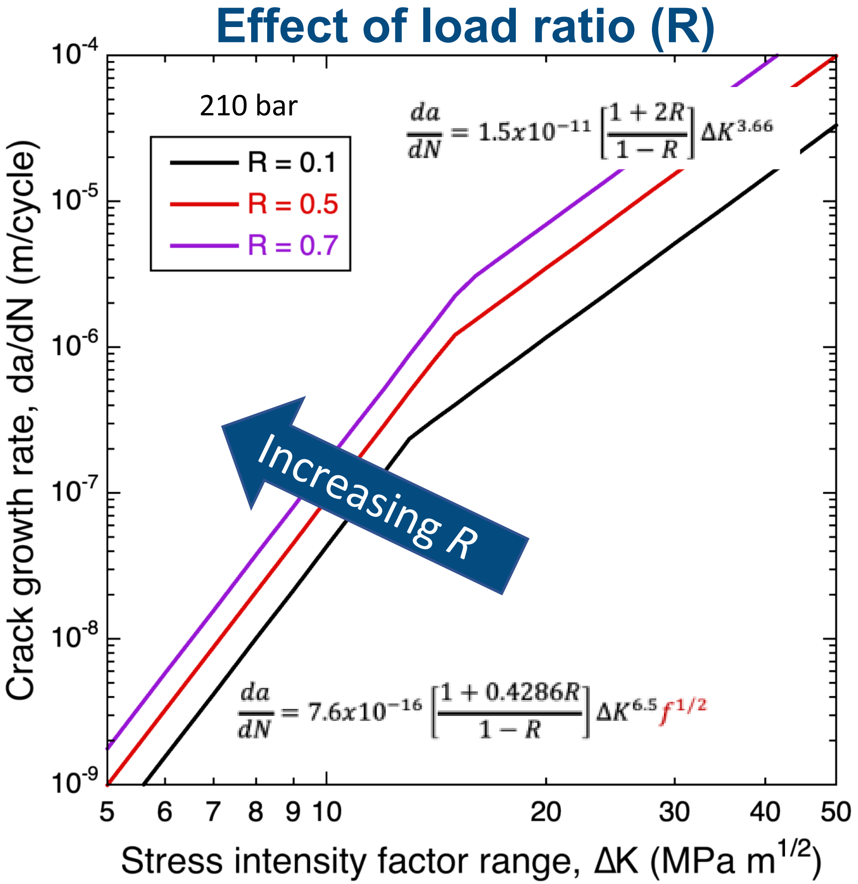
Pressure term

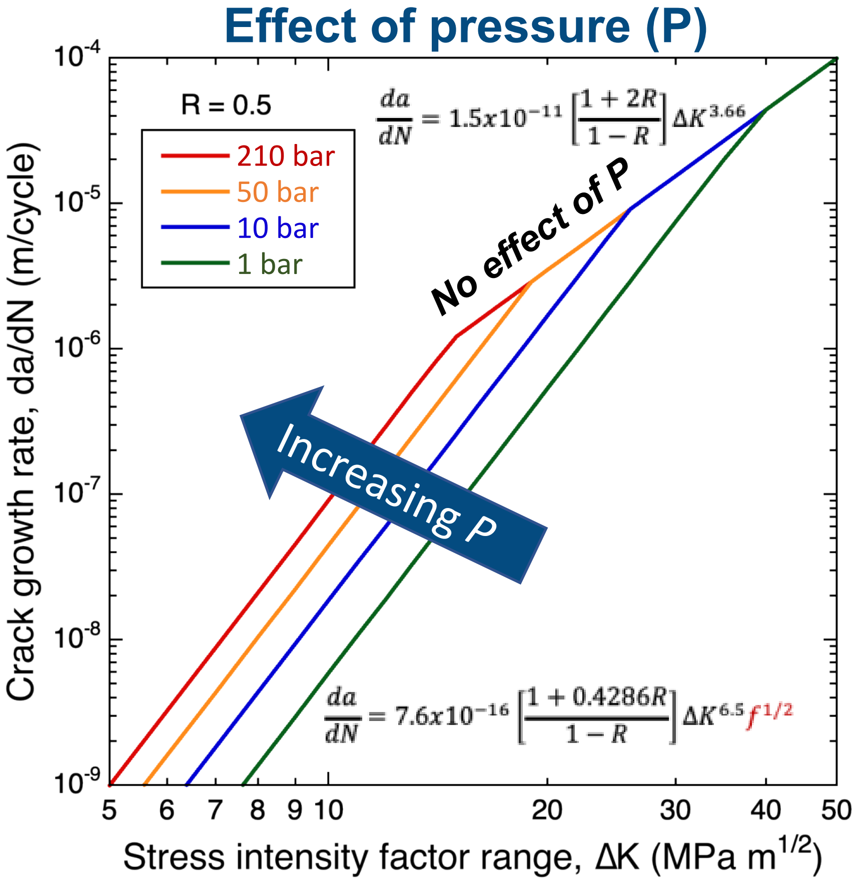
f is the thermodynamic pressure or fugacity

Refs: San Marchi et al, PVP2019-93803
San Marchi et al, PVP2021-62045
San Marchi et al, PVP2022-84757

- **Units are important!**
- **In the above formulation:**
  - *fugacity* is in units of < bar >
  - da/dN: < m/cycle >
  - ΔK: < MPa $m^{1/2}$ >

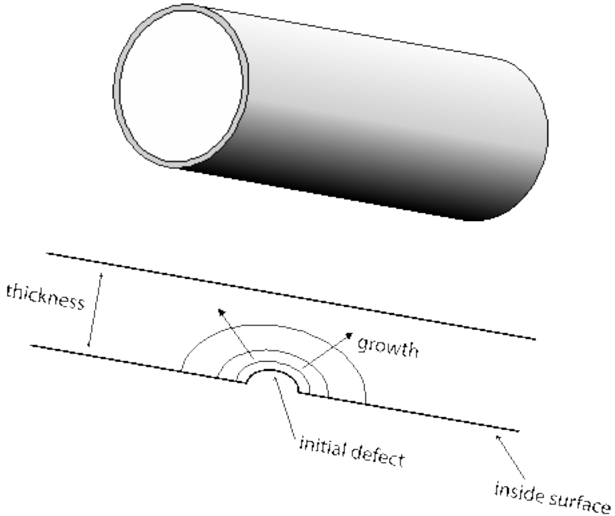
Design curves enable upper bound prediction for fatigue crack growth as function of loading and pressure





Application of materials behavior to structural integrity analysis: Blends

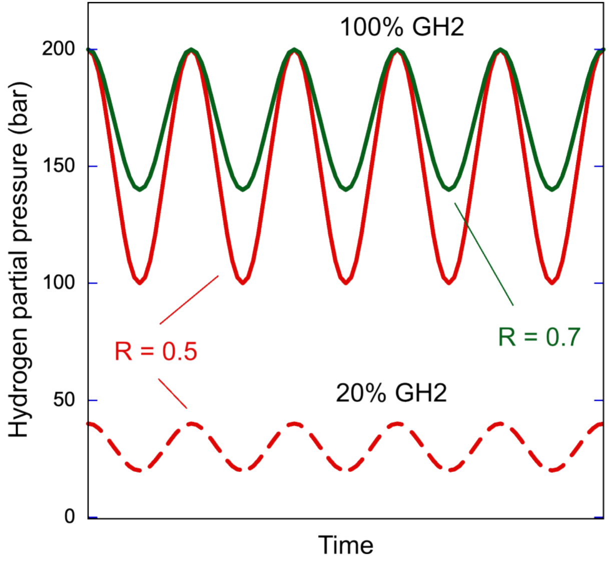
- ***Material***:
  - API grade X52 pipe
  - OD = 324 mm
  - t = 12.7 mm
- ***Environment***:
  - Pressure = 200 bar
  - GH2 = 20%, 100%
- ***Stress***:
  - Hoop stress: 68% SMYS
  - Cyclic pressure: $R = P_{min}/P_{max} = 0.5, 0.7$
  - Flaw
    - depth: 25% of wall thickness (a/t =0.25)
    - length: 40 mm (2c = 40mm) – propagate with constant aspect ratio



Reminders

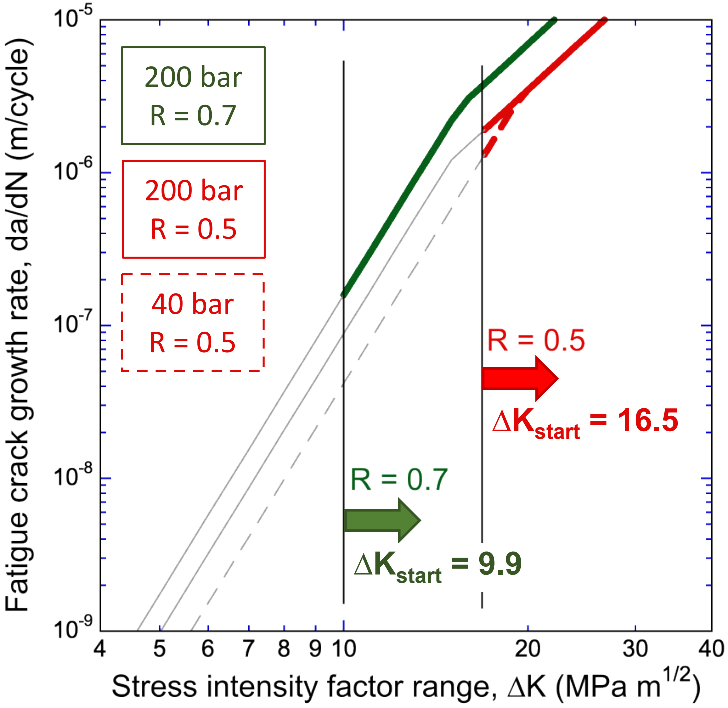
$$\sigma \rightarrow P_{total}$$

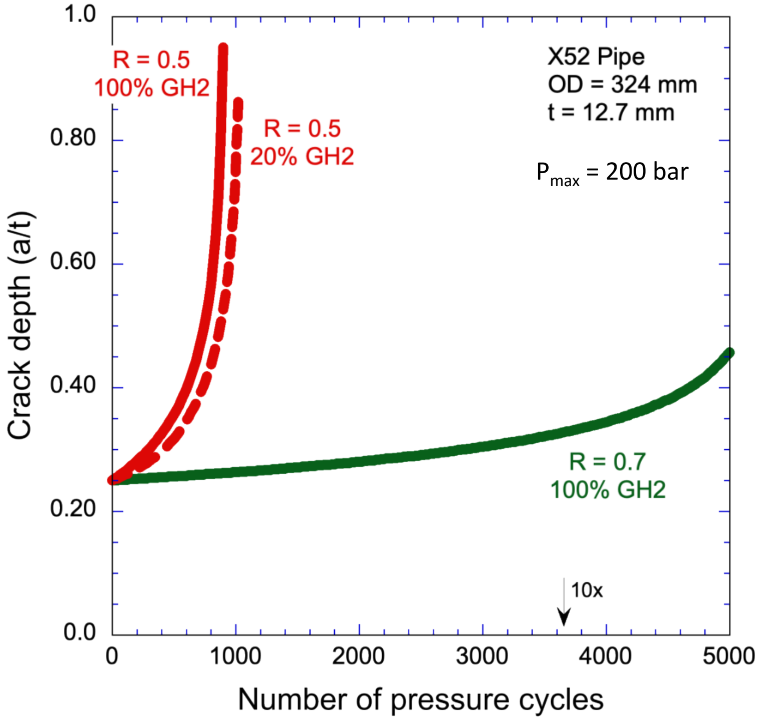
$$\frac{f}{P_{HH}} \rightarrow P_{total}$$



Analysis of transmission pipe structure: Blends

- **Initial crack/flaw: 40 x 3.2 mm**
  - **At start: K_{max} = 33 MPa m$^{1/2}$**





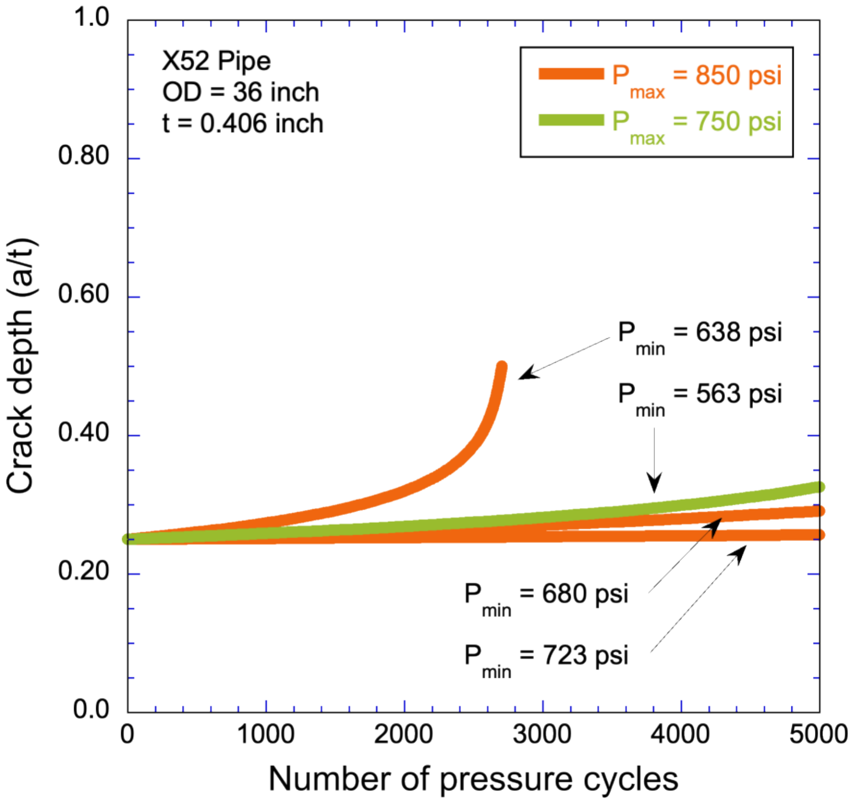
The blending ratio has no effect on fatigue response (for R = 0.5)

Analysis: ‘Real-world’ example (100% GH2)

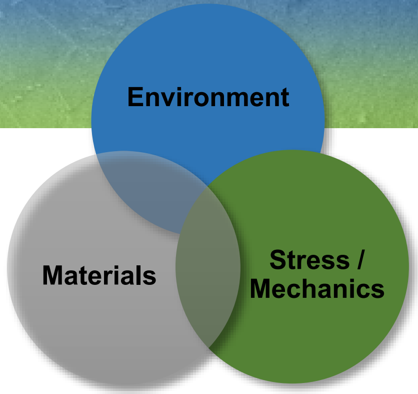
- ***Material***:
  - X52
  - OD = 36 inch
  - t = 0.406 inch
- ***Environment***:
  - GH2 = 100%
- **Flaw**
  - depth: a/t =0.25
  - length: 40mm

Analysis of pipeline operating data:
nominally 24-hour cycles over one year

- P_{max} < 700 psi
- Maximum hoop stress < 60% SMYS
- R > 0.9



Summary of *structural performance* 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*
  - *External loading and the condition of the asset (e.g., defects) will likely dominate overall risk exposure*
  - *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)*

Thank You!

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https://h-mat.org/

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

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

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Brandon Owens
Remi Dingreville
Ben Schroeder
Khalid Hattar
Kathryn Small
Matthew Brownell

And the many former contributors to the work on pipeline steels

Informational resources

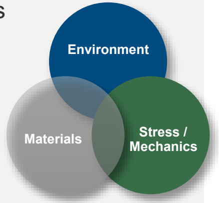
- **Technical Reference for Hydrogen Compatibility of Materials**
  - **https://www.sandia.gov/matlsTechRef/**
  - Report no. SAND2012-7321 (Technical Reference v.2)
  - Report no. SAND2013-8904 (polymers)
- **Technical Database for Hydrogen Compatibility of Materials**
  - **https://granta-mi.sandia.gov/**
- **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)**

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

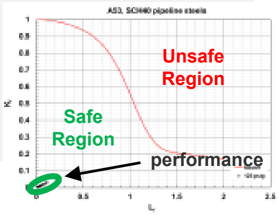
- Assessment of critical parameters determining materials response in hydrogen environments
- Survey of critical materials in ancillary equipment (e.g., pumping stations)
- Long-duration aging of polymers in piping systems
- Evaluation of vintage materials in existing infrastructure



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



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

Guidance on operating conditions

+ partners

Industry-focused probabilistic framework for risk assessment

PRCI EPRI gti

State-of-the-art characterization

H-Mat

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

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:

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

Background: stress intensity factor, *K*

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

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

=

=

$\Delta \;=\; -$

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

- ***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