SAND2024-13546C

HYDROGEN & FUEL CELL WEEK

OCTOBER 7–11, 2024

#FuelCellsNow #HydrogenNow

U.S. DEPARTMENT OF **ENERGY**

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Sandia National Laboratories

Exceptional service in the national interest

SAND2024-13546C

Fatigue and fracture of structural steels in gaseous hydrogen environments

Chris San Marchi, Milan Agnani,
Rob Wheeler, Fernando Leon-Cazares,
Brendan Davis, Joe Ronevich

Sandia National Laboratories
Livermore CA

MS&T24 Technical Meeting and Exhibition **6-9 October 2024**

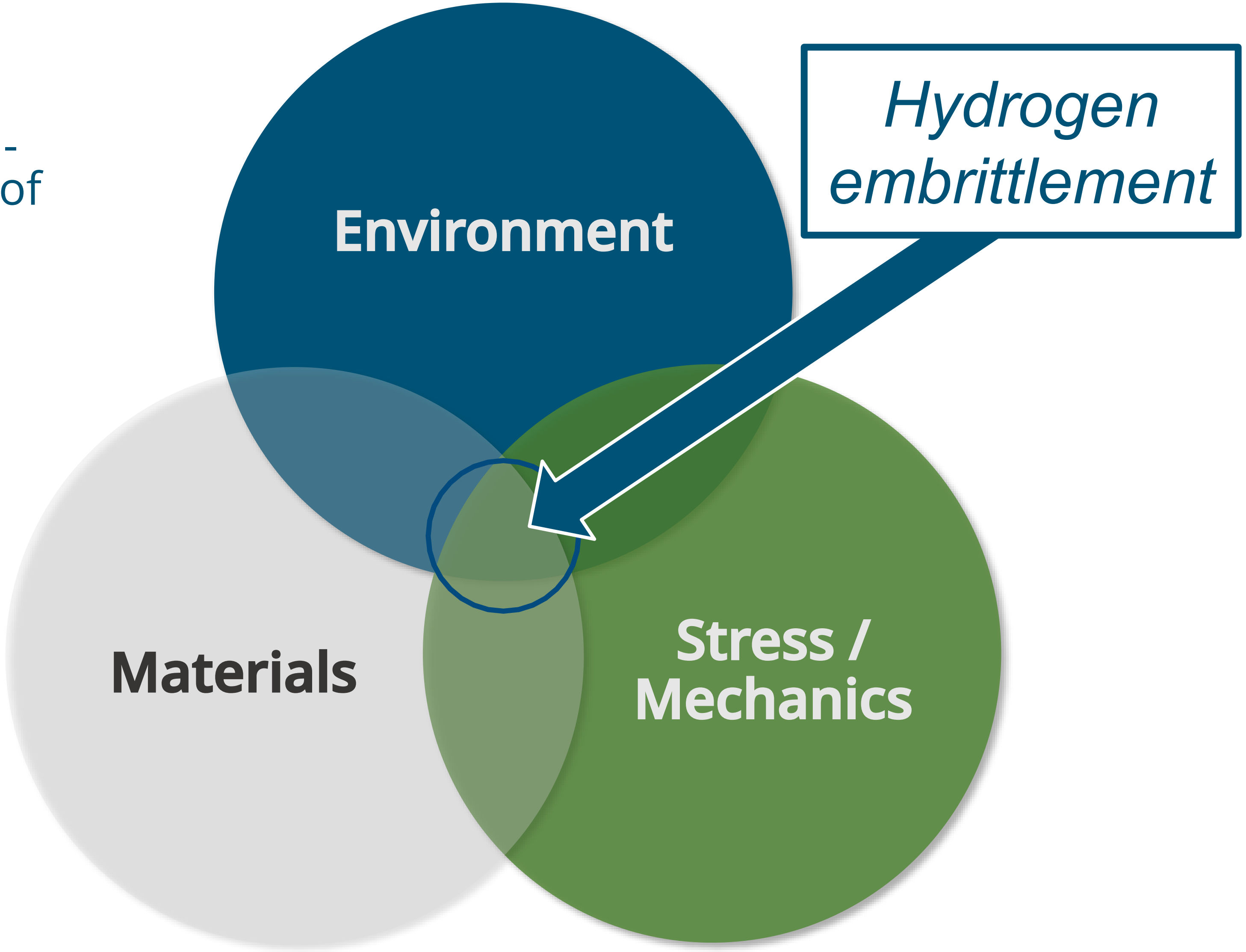
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

Hydrogen-assisted fatigue and fracture is sensitive to environmental, mechanical and materials variables

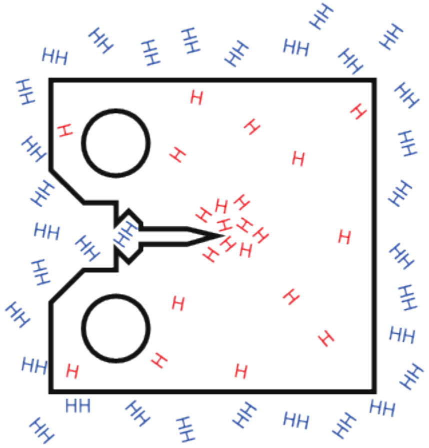
Presentation scope:

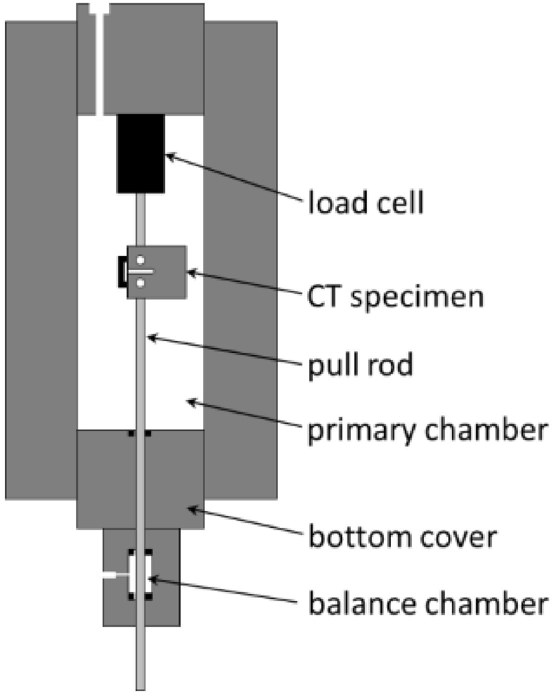
Overview of key aspects of hydrogen-assisted fatigue and fracture testing of pressure vessel and pipeline steels

- ***Environment***
  - Hydrogen partial pressure
  - Impurities – oxygen/oxides
- ***Mechanics***
  - Stress ratio (fatigue)
  - Fatigue frequency
  - Fracture rate
- ***Materials***
  - Strength



Fatigue and fracture testing performed in gaseous H_2





Instrumentation

- Internal Load cell
- Clip gauge
- Direct Current Potential Difference (DCPD)

Fatigue crack growth: ASTM E647

- K-controlled testing
- Frequency can be varied
- Crack extension by compliance

Fracture: ASTM E1820 (J-integral)

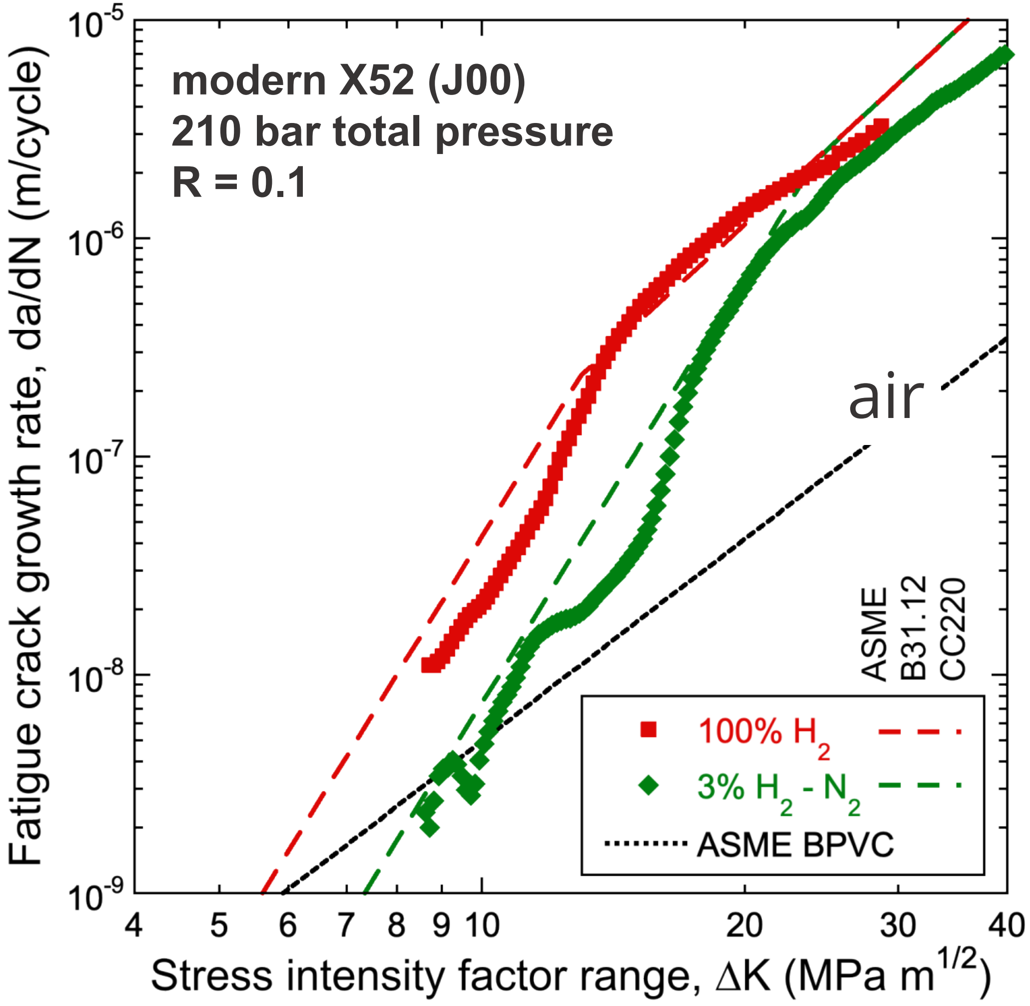
- Loading rates can be varied
- Crack extension by DCPD

Environment

- gaseous H_2 (GH2) and gas mixtures
  - Pressure up to ~1,400 bar GH2
- Monitoring for oxygen and moisture

Environment

Environmental variables: H-assisted fatigue crack growth depends on hydrogen partial pressure for intermediate ΔK



Ref.: San Marchi et al, PVP2021-62045

- Thermodynamically, pressure effects should be characterized by the hydrogen fugacity (real gas behavior)
  - For intermediate ΔK, fatigue crack growth is proportional to $f^{1/2}$ (f is hydrogen fugacity – also called thermodynamic pressure)
  - At high ΔK, H-assisted fatigue crack growth is independent of fugacity

Abel-Noble EOS
Pure gas

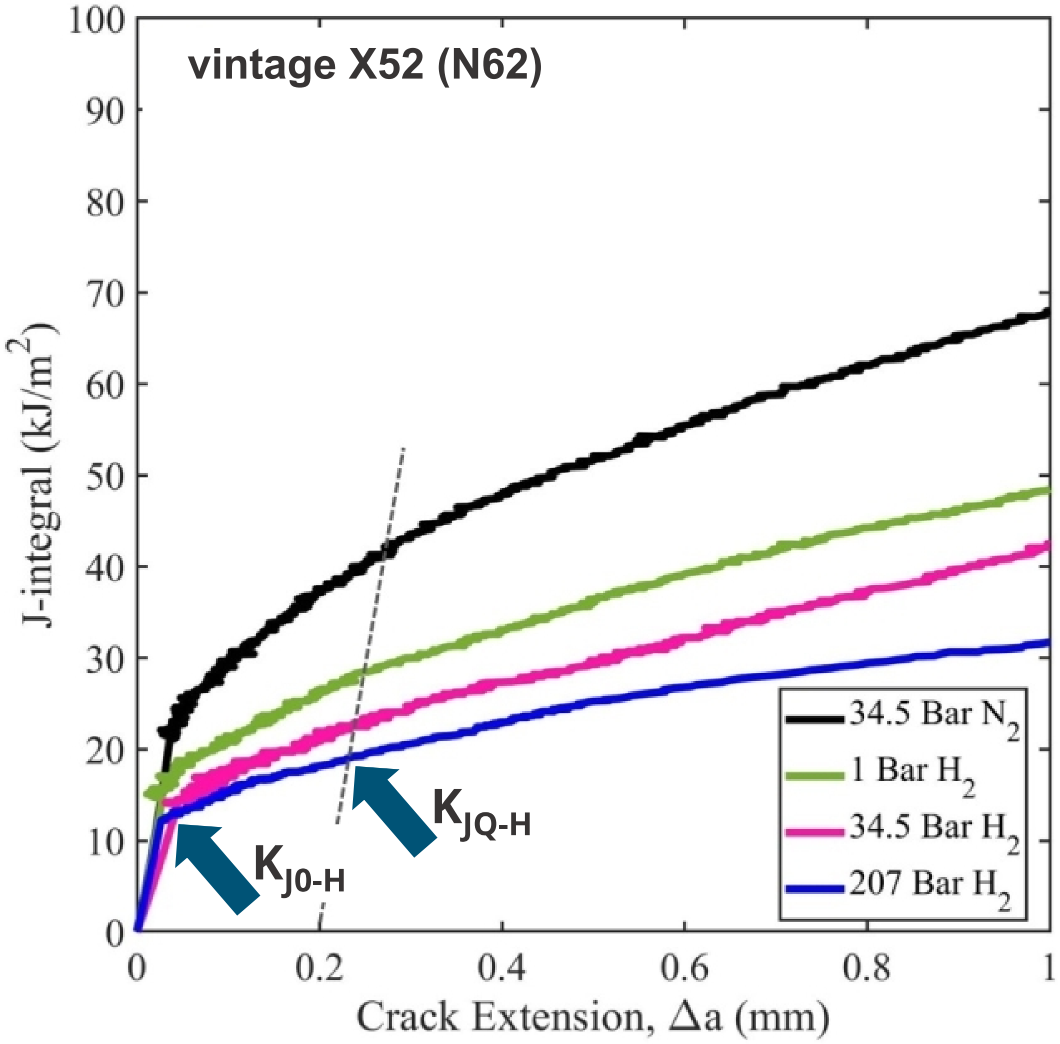
$$\frac{f}{P_H} = exp\left(\frac{P_H b}{RT}\right)$$

Regular solution model
Mixed gas

$$\frac{f}{P_H} = exp\left(\frac{P_t b}{RT}\right)$$

Ref.: San Marchi et al., ASME PVP2024-122529

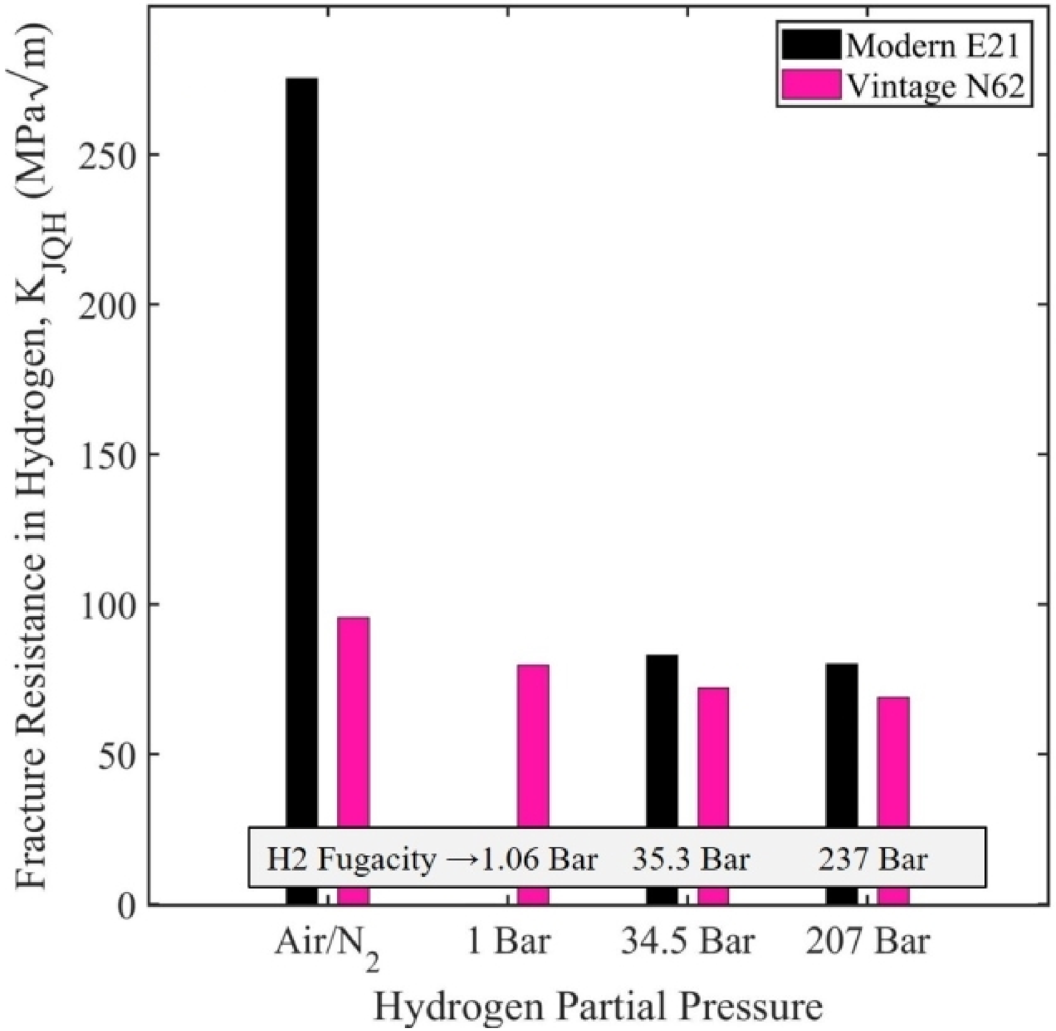
Environmental variables: H-assisted fracture degrades significantly in hydrogen partial pressure of 1 bar



- H-assisted fracture depends on the hydrogen partial pressure
  - Hydrogen partial pressure as low as 1 bar substantially reduces the fracture resistance
  - Fracture resistance continues to degrade for higher pressure, but relationship is non-linear
- Steels remain ductile in high-pressure GH2 (>200 bar), displaying elastic-plastic fracture behavior

Ref.: Agnani et al, PVP2024-123477

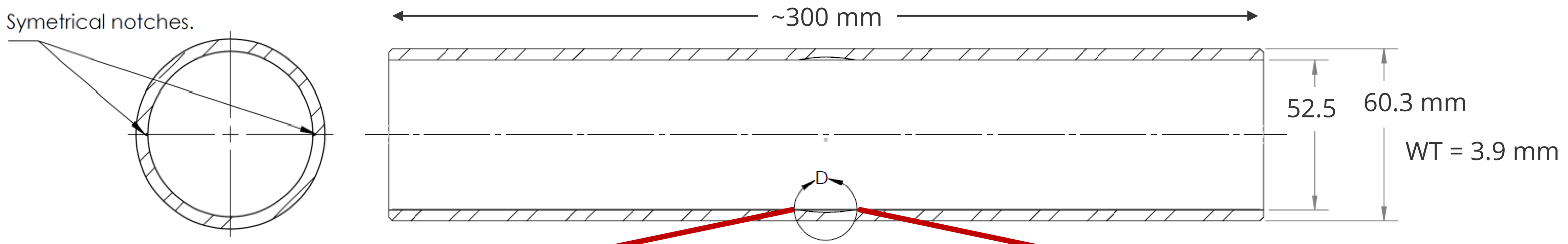
Environmental variables: H-assisted fracture of modern steels shows greater relative reduction than vintage steels

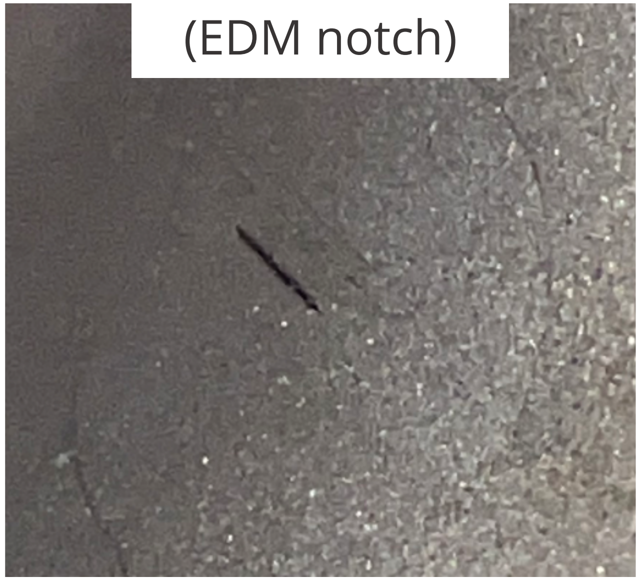


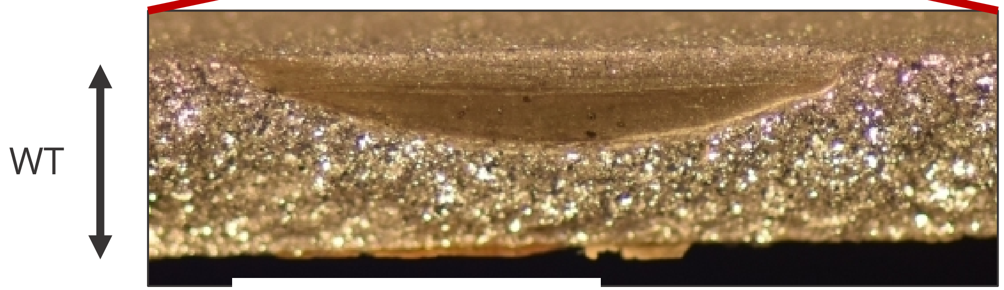
- In air, fracture toughness of modern steels is 2-4x greater than vintage steels
- In GH2, relative reduction of fracture resistance for modern steels is much greater than for vintage steels
- In high pressure GH2, the fracture resistance of modern and vintage steels is comparable
  - Similar trend with pressure for modern and vintage steels

Ref.: Agnani et al, PVP2024-123477

Environmental variables: What is the role of the surface condition, oxides and oxygen on influence of hydrogen?

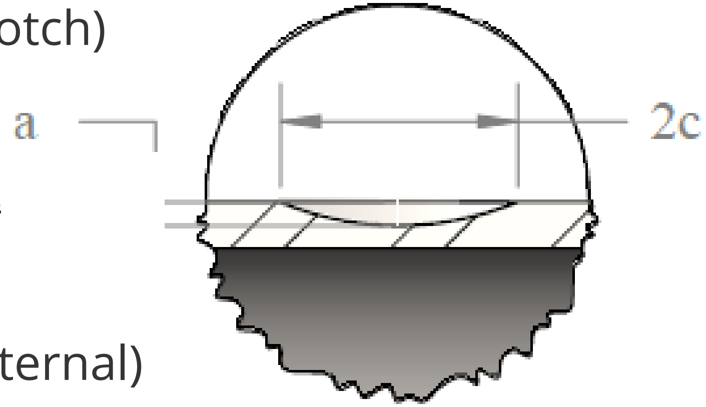



External defect
(EDM notch)

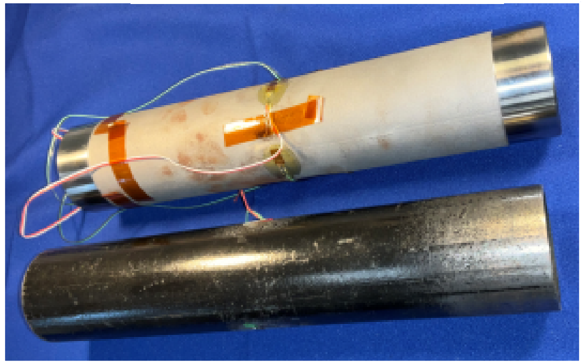


Internal defect
(EDM notch)

<u>Nominal defect</u>
a = 2 mm
2c = 40 mm
(both internal and external)



NPS 2, Schedule 40



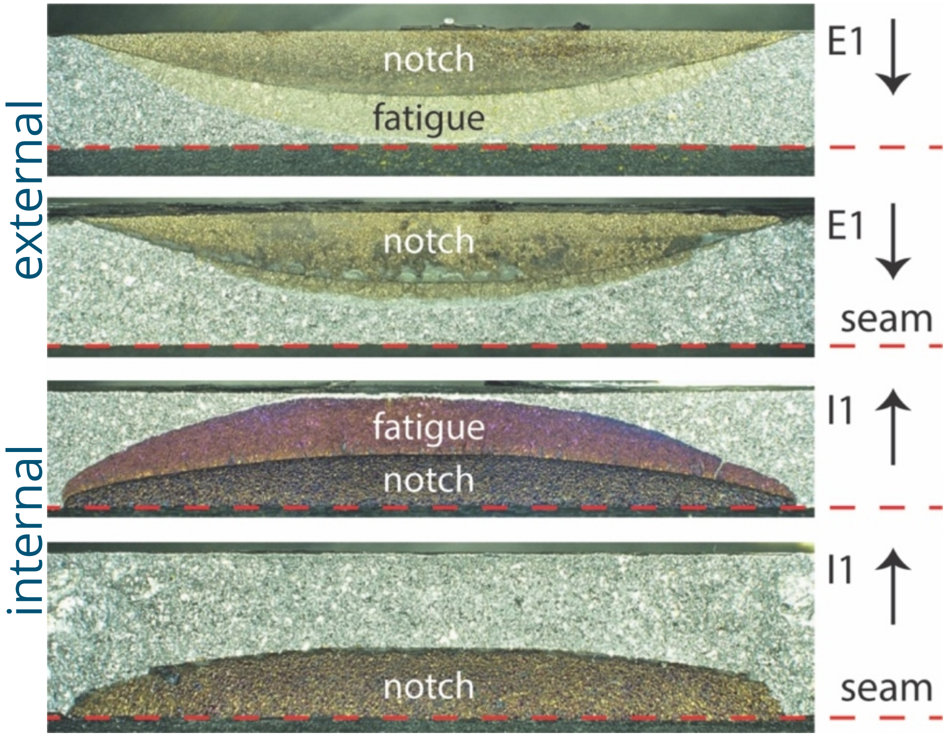
Black pipe
ASTM A53

SMYS = 205 MPa
Meas. YS ~ 260 MPa

Environmental variables**:** Can surface oxides prevent hydrogen-assisted fatigue and fracture?

Experimental plan: compare influence of internal and external (engineered) defects on fatigue failure during pressure cycling of pipe

Specimen	**Measured cycles to Failure**	
	Hydrogen	**Nitrogen**
Internal	636	18,880
External	1,097 - 1,191	13,356



Dashed line = inside surface

—

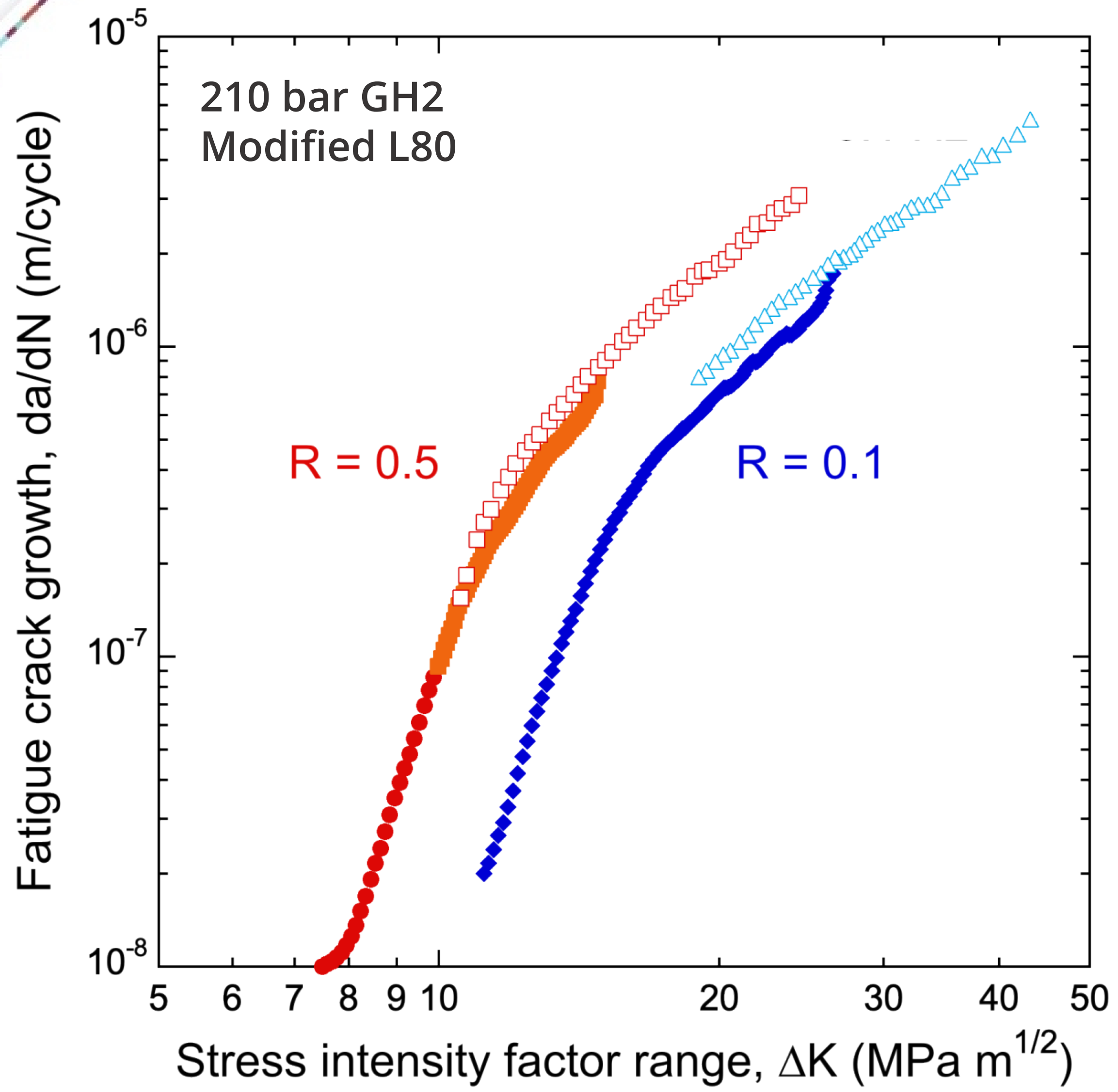
Arrow = direction of crack

- **Surface oxides on inner pipe surface do NOT prevent H-assisted fracture**
- **Oxygen? Stick around for talk in ~30 minutes**

Ref.: San Marchi et al, IPC2024-134173

Mechanics

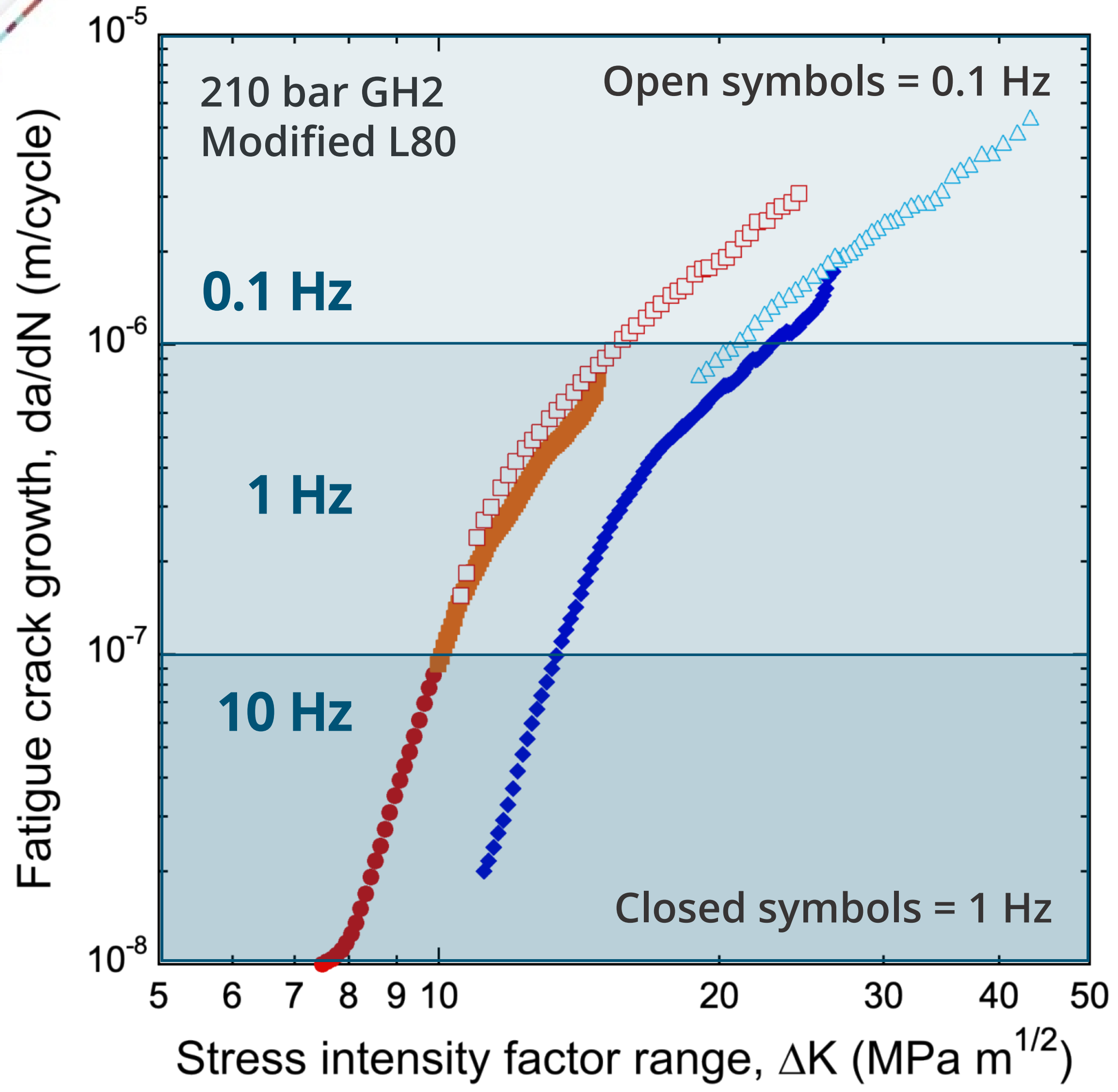
Mechanics variables: Stress ratio (R) has a significant influence on H-assisted fatigue crack growth



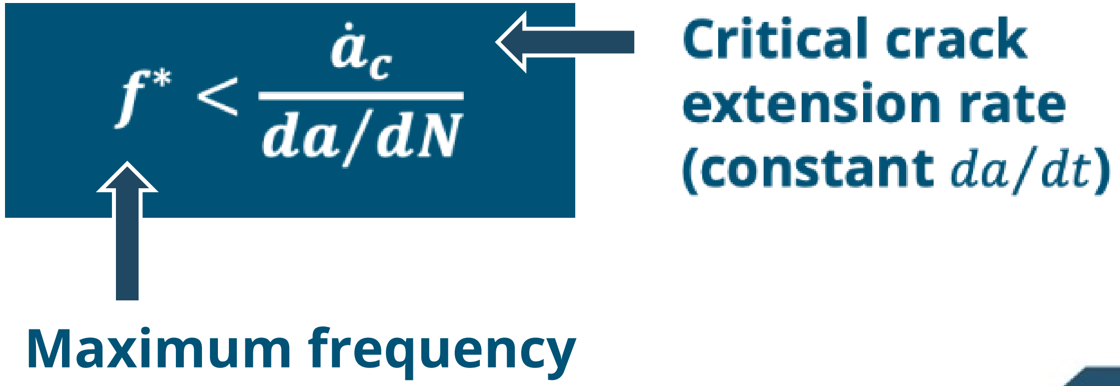
- H-assisted fatigue crack growth is more sensitive to stress ratio than fatigue in air
  - Likely related to the influence of strength on hydrogen effects
- H-assisted fatigue crack growth is characterized by a two-part power law relationship

$$\frac{da}{dN} = \underset{\textit{constant}}{C}\ \underbrace{f(R_k)}_{\textit{stress ratio dependence}}\ \underbrace{\Delta K^m}_{\textit{power law}}$$

Mechanics variables: Appropriate frequency for hydrogen testing depends on the crack growth rate



- **If fatigue crack growth rates are related to hydrogen transport ahead of the crack tip, then frequency dependence will depend on the growth rate regime**
  - **In other words, if the crack is growing slowly, then the frequency can be higher to achieve the same da/dt**



$$f^* < \frac{\dot{a}_c}{da/dN}$$

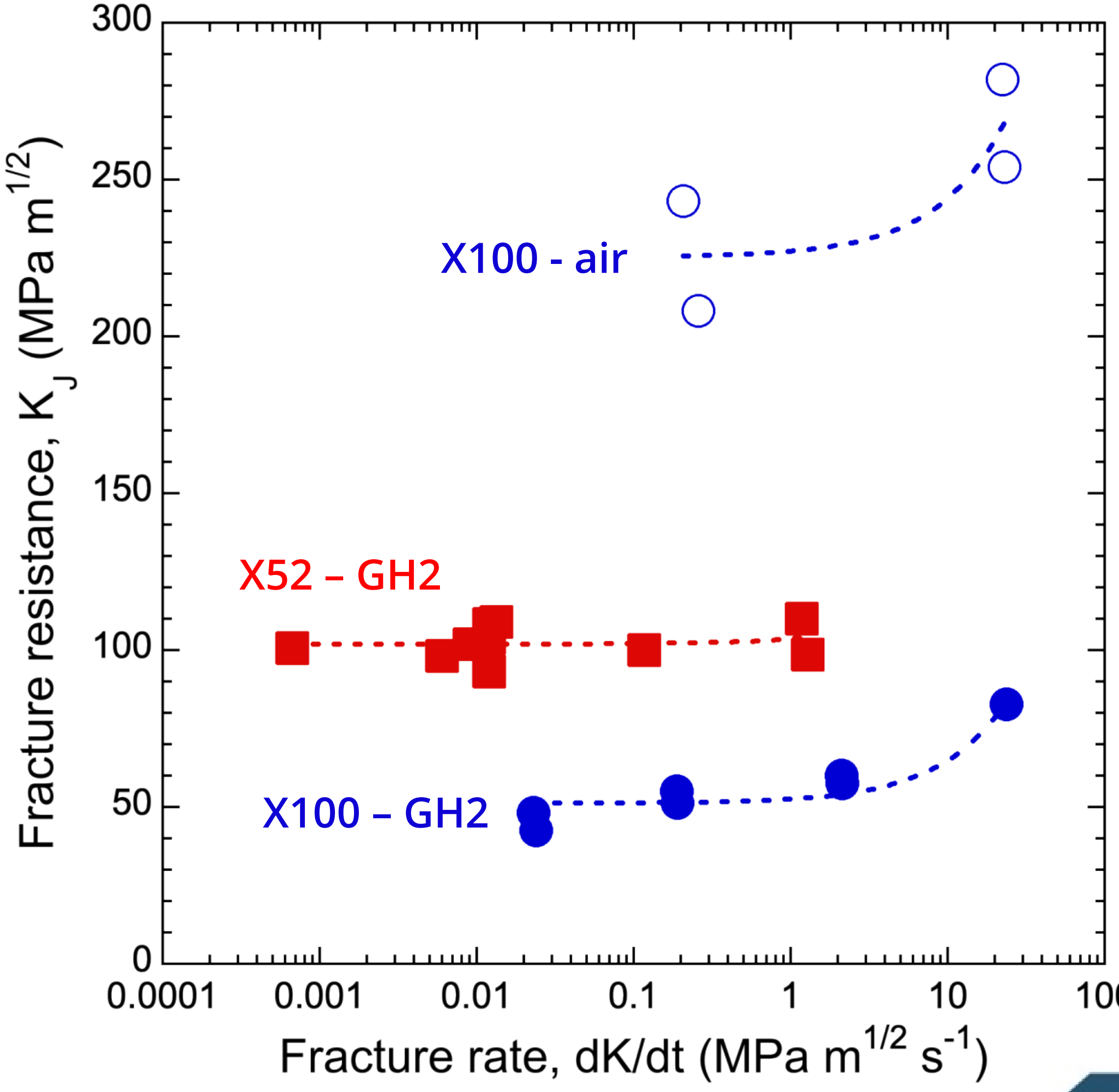
Critical crack extension rate (constant da/dt)

Maximum frequency

Mechanics variables: Testing rate is an important parameter in measurement of H-assisted fracture

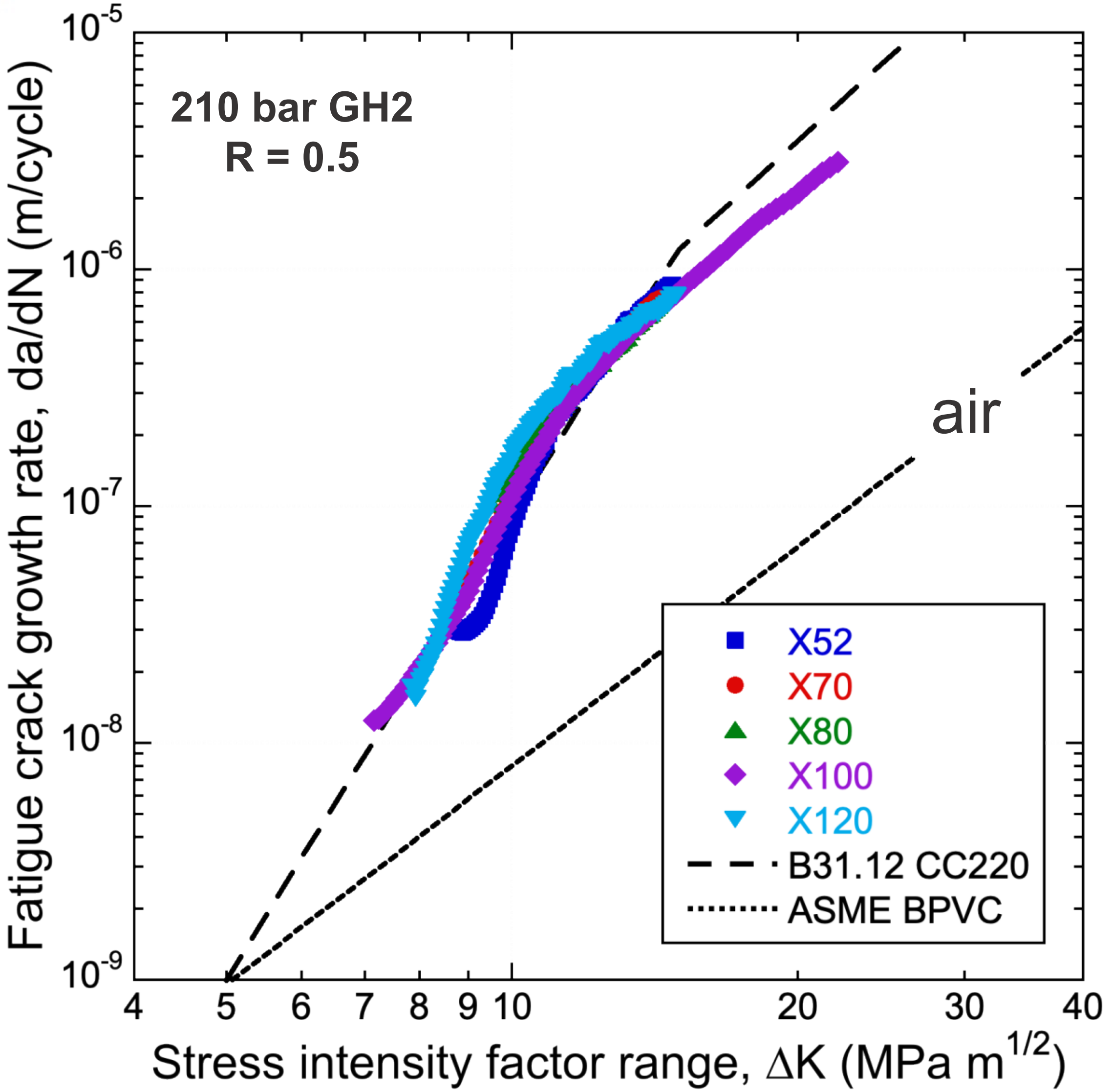
- Fracture measurements can be sensitive to rate both in air and GH2
  - Substantial influence of hydrogen is evident, even when fracture test is performed rapidly (seconds)
  - Rate effects in air and GH2 show similar trend

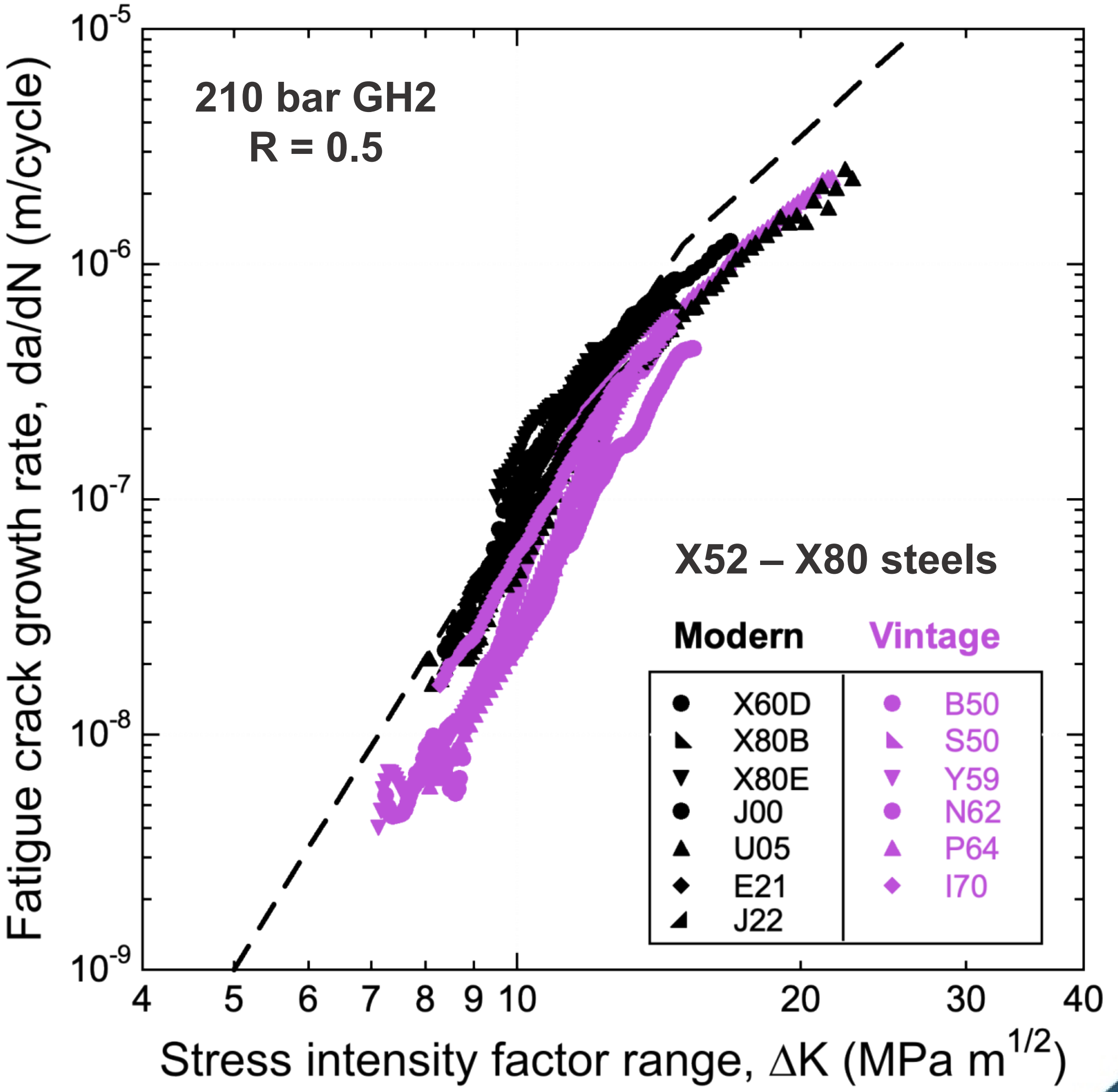
Exceptionally slow fracture testing is generally not necessary



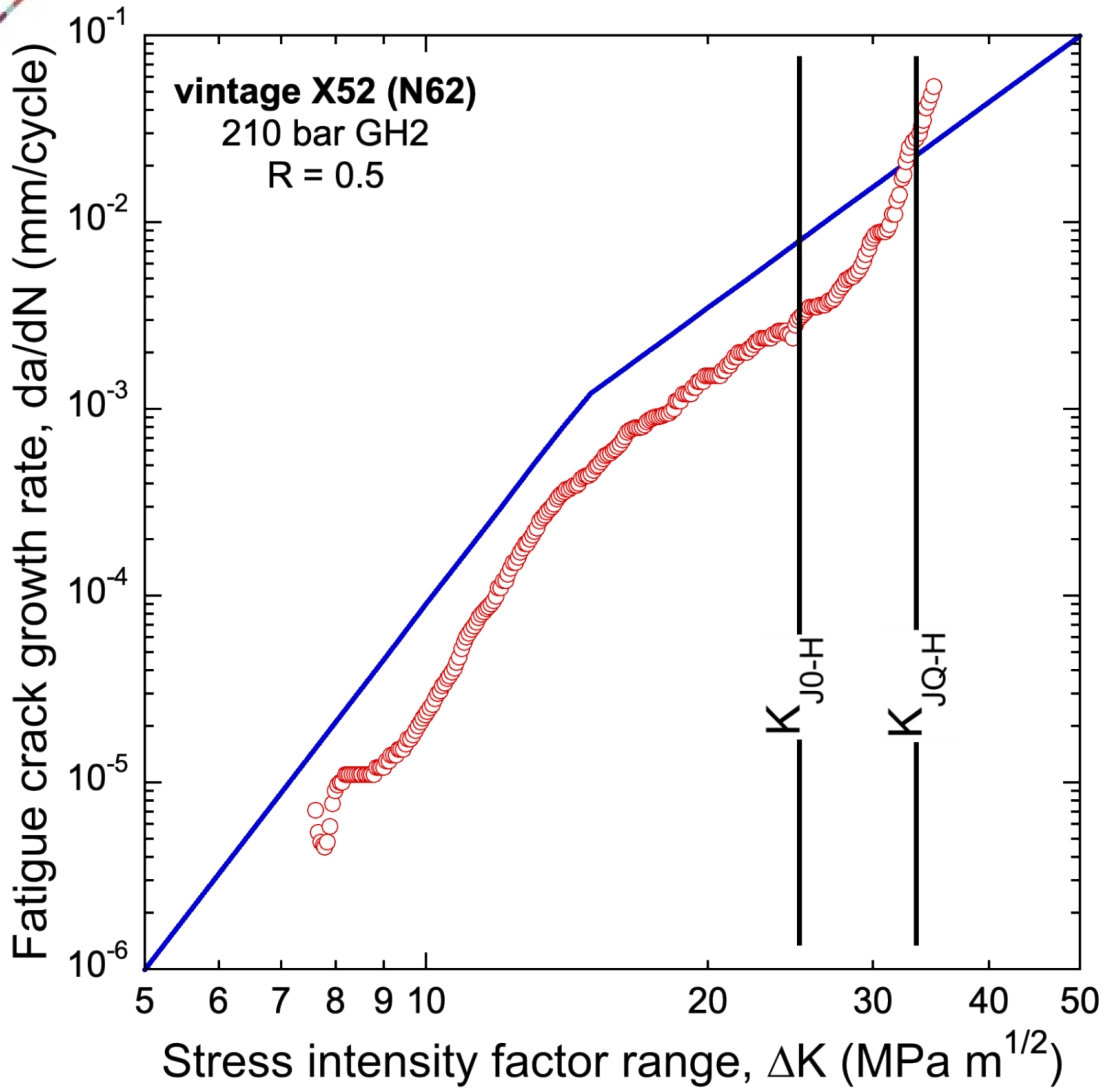
Materials

Materials variables: H-assisted fatigue crack growth does not degrade as strength increases





Caution: H-assisted fatigue can be influenced by the onset of fracture

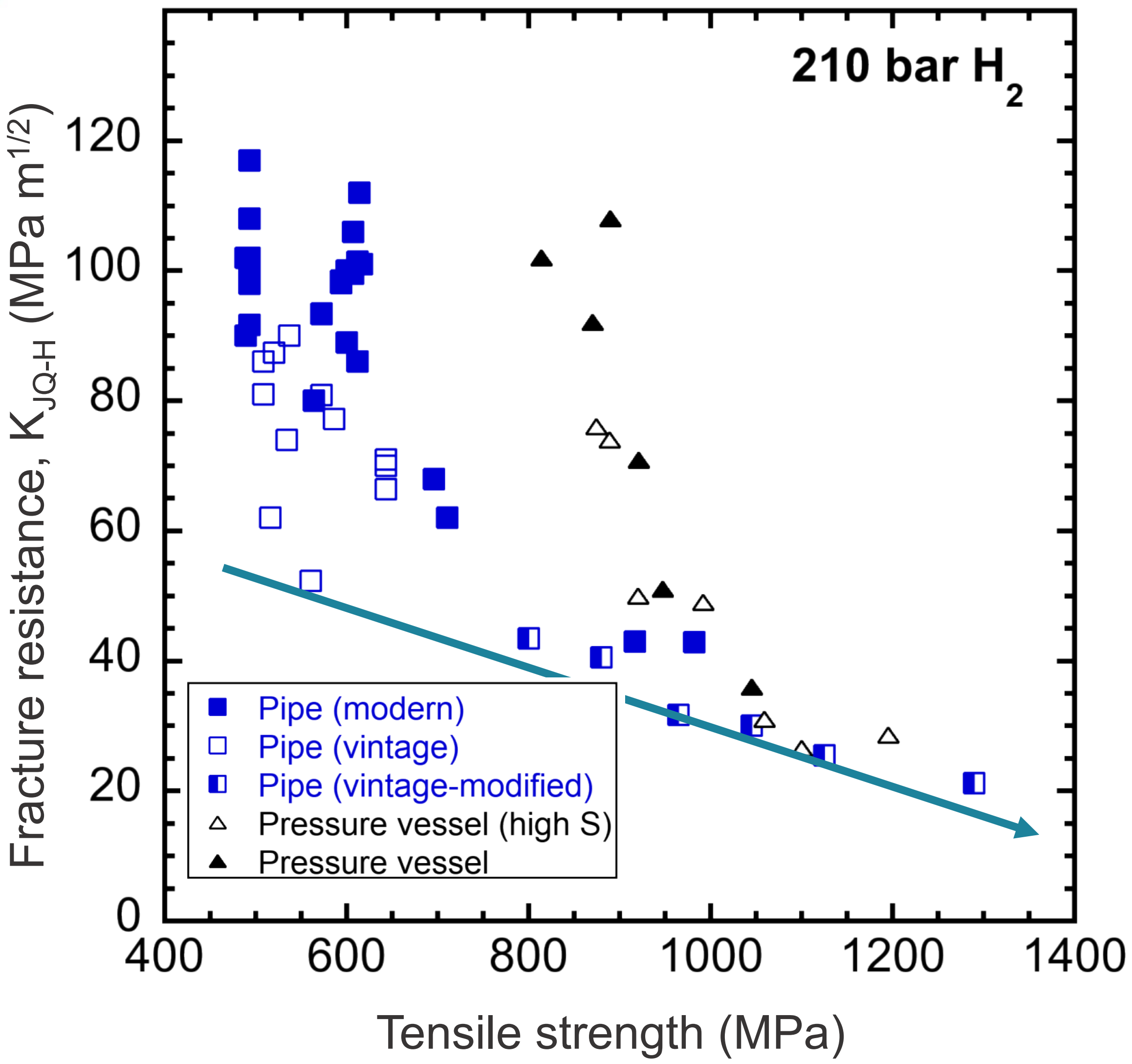


- Hydrogen-assisted fracture must be considered when testing at large ΔK
  - Stable crack extension can be observed for:

$$K_{max}\text{ (fatigue)} > K_{J0\text{-}H}\text{ (fracture)}$$

  - However, crack extension in this region is rate sensitive
- High-strength steels will be rate sensitive (i.e., frequency dependent) at low ΔK

Materials variables: H-assisted fracture resistance degrades with strength



- Fracture resistance shows a decreasing lower bound as strength increases
  - Similar to basic trends in air
  - As a rule-of-thumb, materials with tensile strength >900-950 MPa should be avoided in hydrogen service
- High hardness in welds, and potentially hard spots in base metals, will limit fracture resistance
  - Critical size of hard zones remains an open question
- Modern steels tend to have modestly higher fracture resistance than vintage
  - Compared to very large differences in air (not shown)

Conclusions – H-assisted fatigue and fracture of structural steels

- Hydrogen-assisted fatigue
  - Crack growth scales non-linearly with hydrogen fugacity: $da/dN \propto f^{1/2}$
  - Stress ratio (R) has greater effect on FCGR in hydrogen than in air
  - Frequency should be considered in context of crack growth rate
  - Strength has little effect on H-assisted fatigue crack growth
- Hydrogen-assisted fracture
  - “first molecule is the worst molecule” – fracture is weak function of pressure
  - Slow testing rates ($\frac{dK}{dt} < 0.1\ \mathrm{MPa\ m}^{1/2}$) may not be necessary
  - Steels with tensile strength > 900-950 MPa should be avoided in hydrogen service (or used with caution)

Thank you for your attention!

Chris San Marchi
cwsanma@sandia.gov

Joe Ronevich
jaronev@sandia.gov

Hydrogen Effects on Materials Laboratory

Milan Agnani (now at GTI Energy)
Rob Wheeler
Fernando Leon-Cazares

Brendan Davis
James McNair
Keri McArthur
Tanner McDonnell

Additional resources

https://h-mat.org/

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

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

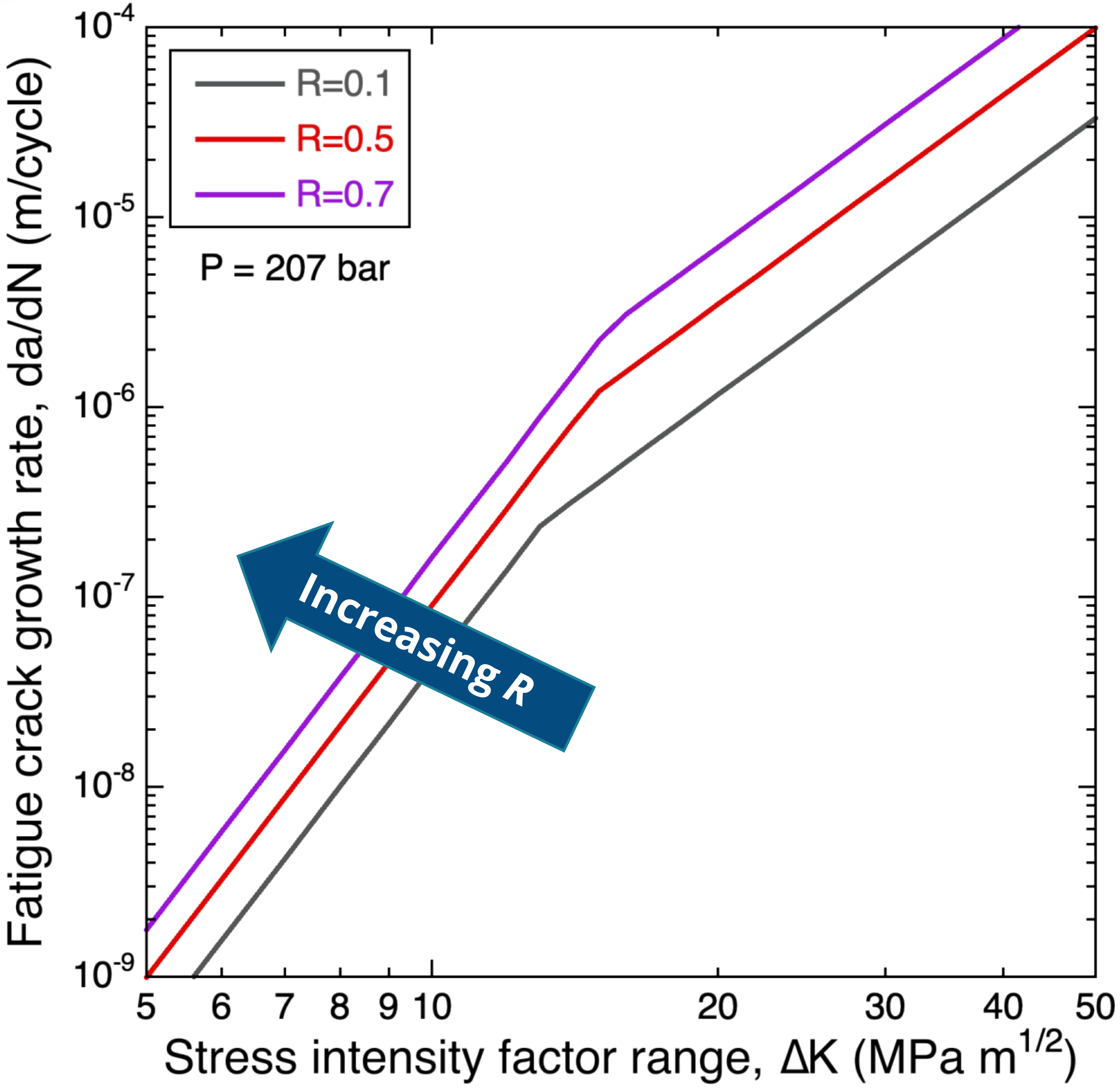
https://helpr.sandia.gov/

For details on HyBlend, email:
<HyBlend_CRADA@nrel.gov>

Acknowledgement:

Sandia's Hydrogen Effects on Materials Laboratory (HEML) gratefully acknowledges sustained support from the Office of Energy Efficiency and Renewable Energy's (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO) within the U.S. Department of Energy (DOE). Any subjective views or opinions that might be expressed in the presentation do not necessarily represent the views of the U.S. Department of Energy or the United States Government

Mechanics variables: H-assisted fatigue is sensitive to stress ratio (R) and stress intensity factor range (ΔK)



- Based on extensive data, ASME adopted generic fatigue design curves for hydrogen, featuring:
  - Two-part power law formulation analogous to form in ASME codes
  - Single formulation for pressure vessel and linepipe steels (similar to existing design curves)
  - “pressure” term proportional to the square root of the hydrogen fugacity

$$\frac{da}{dN} = \underbrace{C\ f(R_k)\ \Delta K^m}_{\textit{basic ASME form}}\ \boxed{f(P)}$$

Pressure term