SAND2023-03962C

Sandia National Laboratories

Exceptional service in the national interest

Fatigue and Fracture Behavior of Line Pipe Steels in Pressurized Gaseous Hydrogen

Joe Ronevich, Milan Agnani, Chris San Marchi

Sandia National Laboratories

Livermore, CA

HyBlend

U.S. DEPARTMENT OF ENERGY

Emerging Fuels Symposium

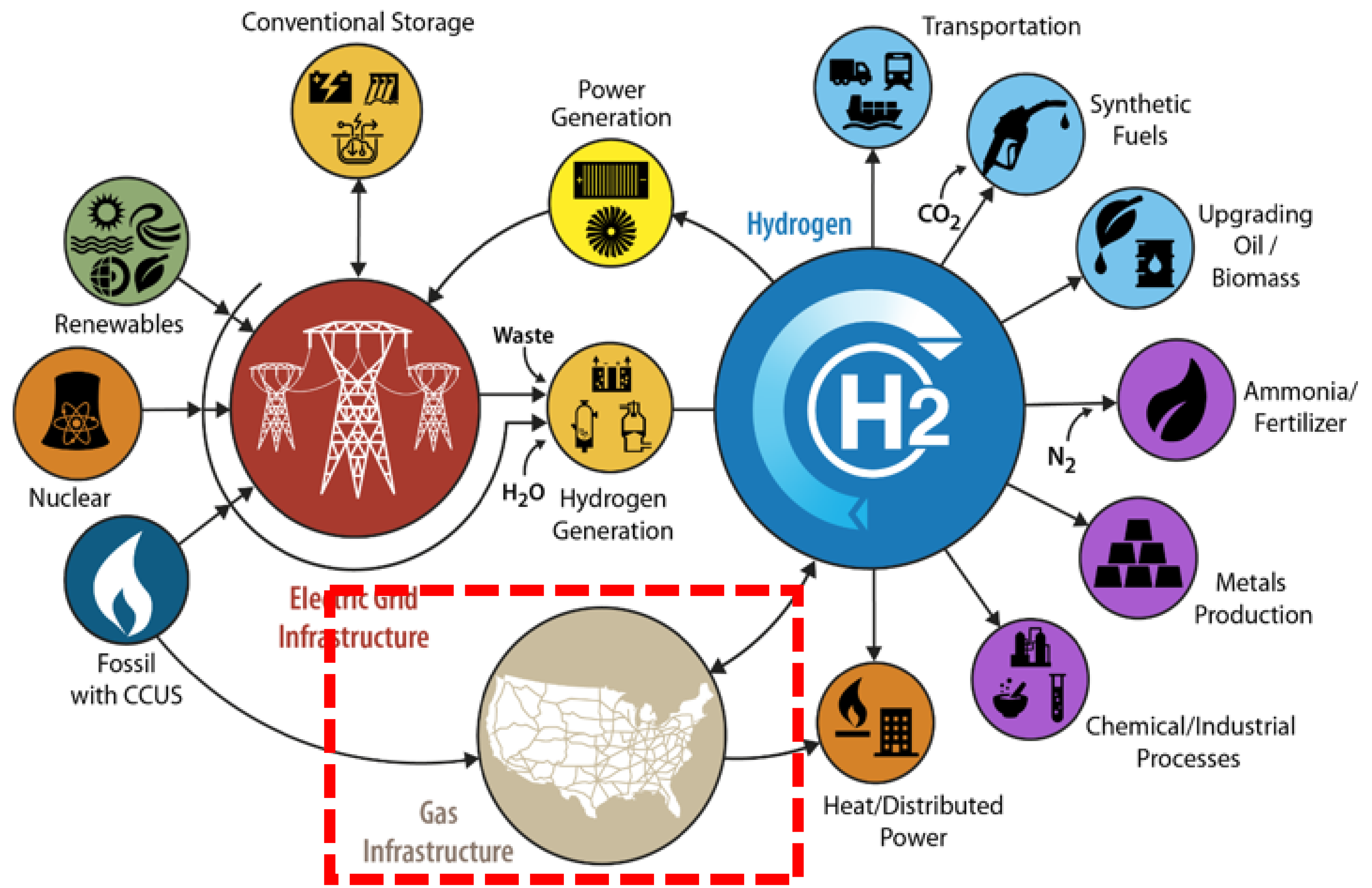
Orlando, FL June 5-8th, 2023

SAND2023-XXXX

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and ... wholly owned subsidiary of Honeywell International Inc. for the U.S. ...onal Nuclear Security Administration under contract DE-NA0003525.

Hydrogen has broad potential for decarbonization

H2@Scale is an enabler for deep decarbonization across sectors



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

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

1 **H** 1.008 =

- **simple**
- **clean**
- **flexible**

Pipeline Blending CRADA

Objective - Provide scientific framework that enables blending of hydrogen into NG infrastructure

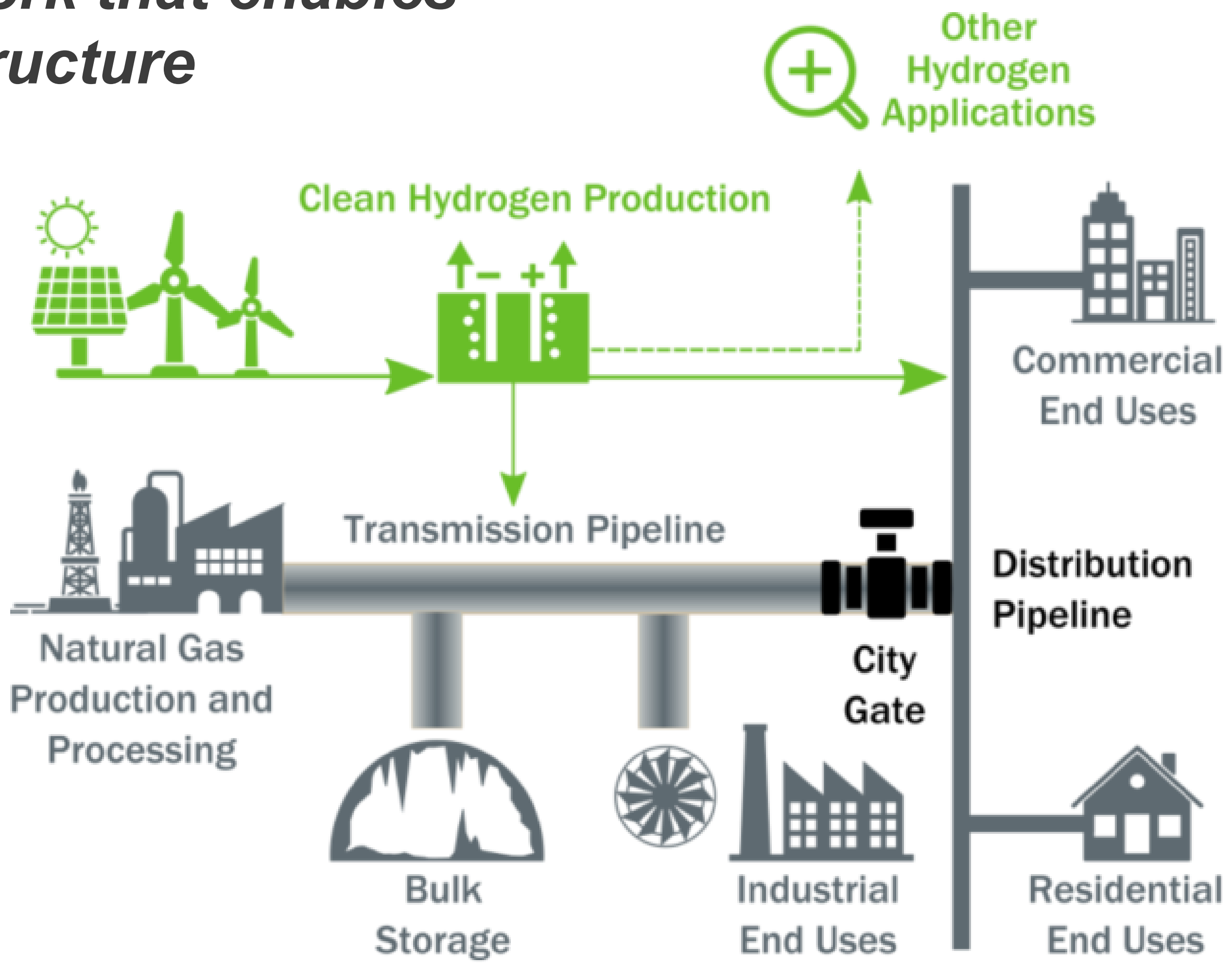
4 national laboratories

26 total industry, academia, and consortium partners :

- 5 international partners
- 3 consortiums
- 2 oil majors

Tasks:

1) **Structural Materials**
2) Technoeconomic Analysis (TEA)
3) Life Cycle Analysis (LCA)



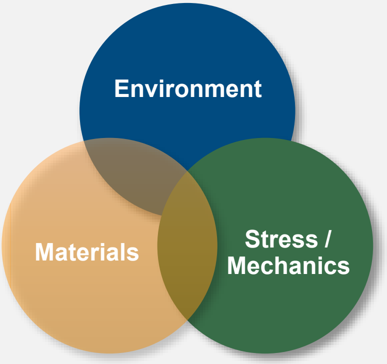
Oct 2021 – Sept 2023 (2 yr project)

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

Assess structural integrity of infrastructure with hydrogen

Develop Database of design properties for NG assets with hydrogen

- Fracture mechanics based measurements
- Evaluate vintage and modern pipes
- Welds / HAZ
- Effects of:
  - Pressure
  - Microstructure
  - Hardness



Guidance on operating conditions

+ partners

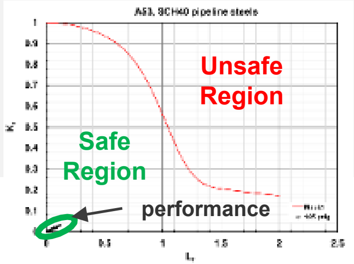
Structural risk to assets with blended hydrogen

Pipeline Structural Integrity Tool

HELPR – Hydrogen Extremely Low Probability of Rupture

- Employ probabilistic fracture mechanics
- Initial
- Expa
- Sens … s for syste

Ben Schroeder will present this work (049)



Industry-focused probabilistic framework for risk assessment

PRCI EPRI gti

Formulate mechanistic models into predictions

Physics-based mechanisms of hydrogen embrittlement relevant to NG assets

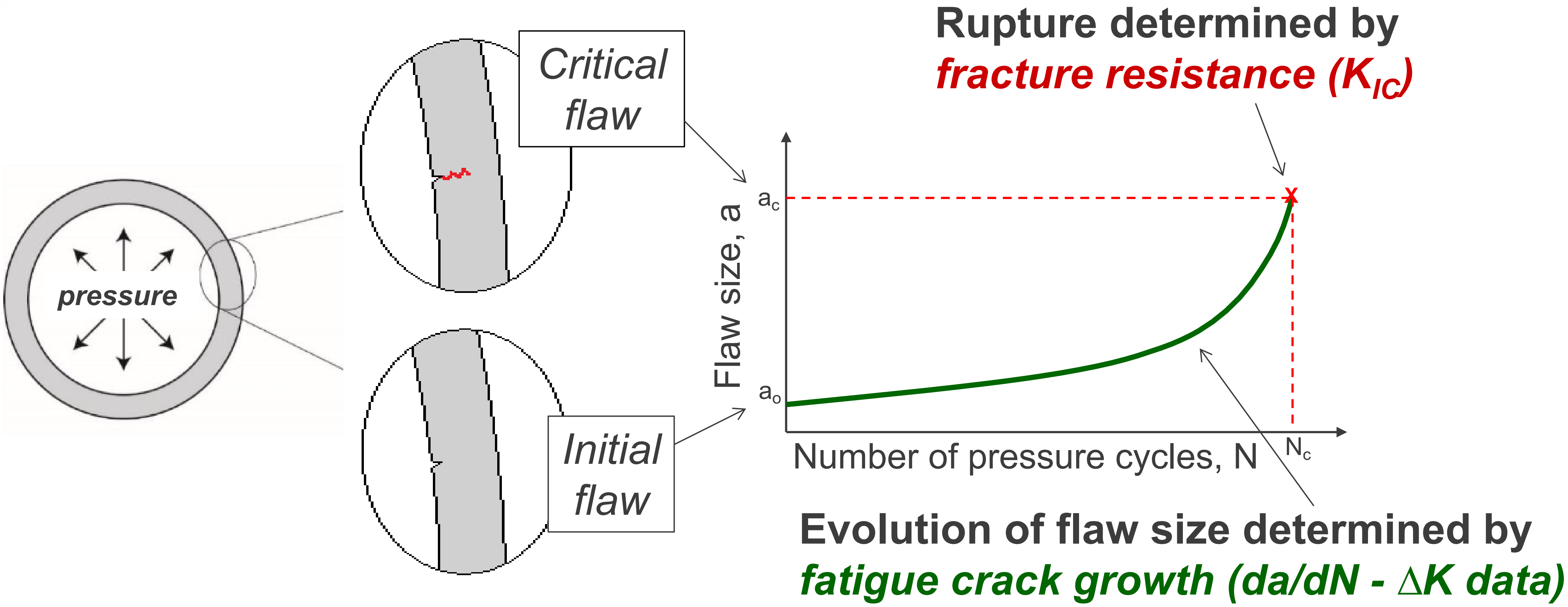
- Utilize advanced microscopy to understand degradation mechanisms
- Establish models and framework for implementing physical phenomena into structural integrity tool
- Inform materials selection guidance and establish basis for potential future materials development activity

State-of-the-art characterization

H-Mat

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

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 stress intensity factor, *K*?

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

$\sigma = stress$

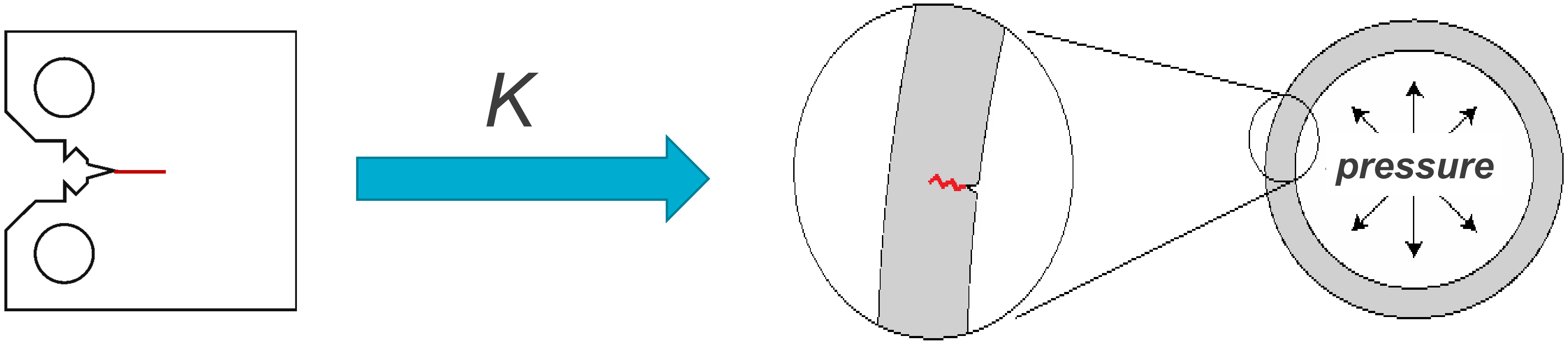
$a = crack\ size$

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

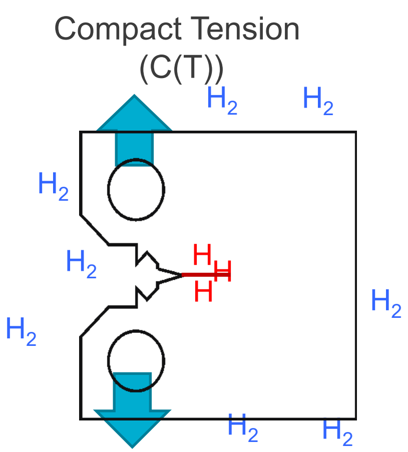
$$R = \frac{K_{min}}{K_{max}}$$

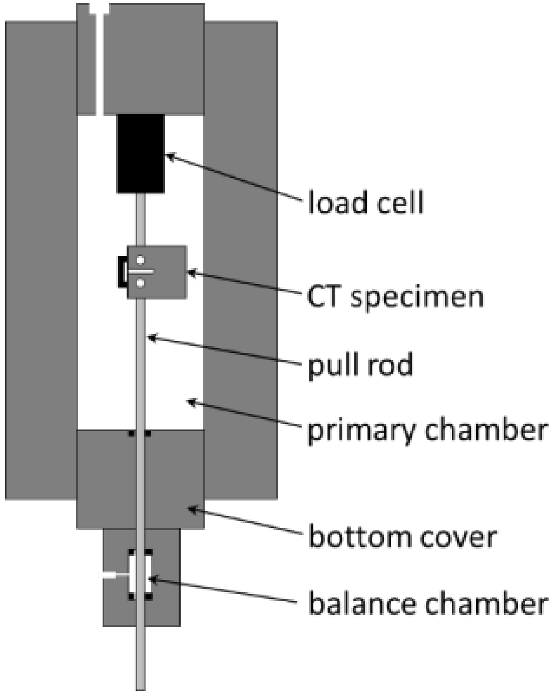
- ***K*** **characterizes the stress state at a crack tip**

- ***K*** **is a transferable parameter between geometries**
  - **For example between a laboratory test & crack in wall of pipe**



Fatigue/Fracture tests performed in high-pressure gaseous H_2





Instrumentation

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

Fatigue: ASTM E647

- Load ratios (R) 0.1 to 0.8
- Frequency: 0.01 → 10 Hz
- Constant load or K-control

Fracture: ASTM E1820 (Elastic-Plastic)

Environment

- Air
- Pure H_2
- Gas blends, e.g. N_2 – 3%H_2
- Gas impurity mixtures:

  e.g. H_2 + 10-1000 ppm O_2

Pipeline Materials

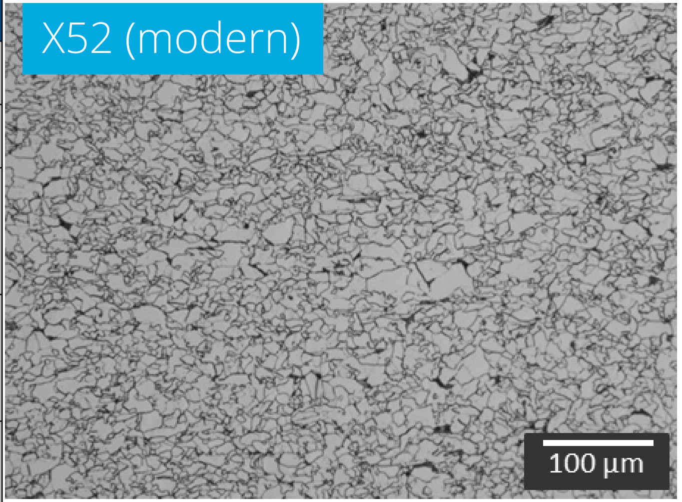
Pipeline steels examined have range of microstructures, strengths, ages

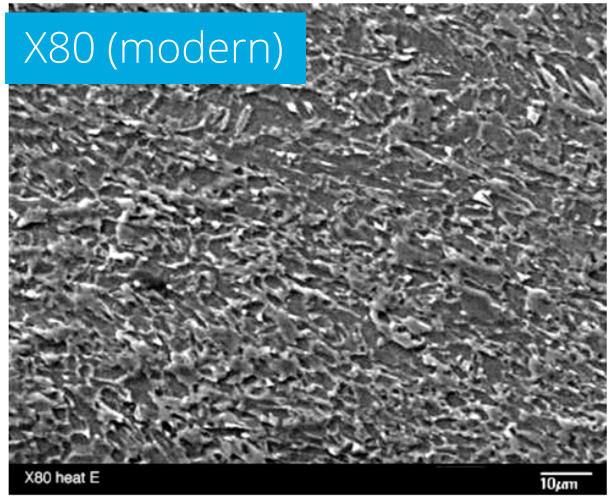
Modern

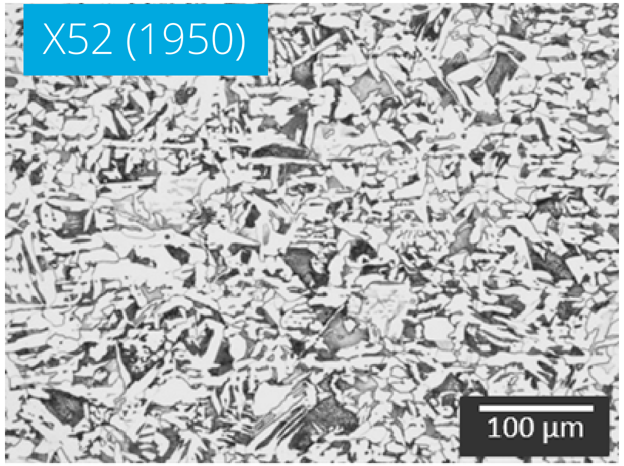
Vintage

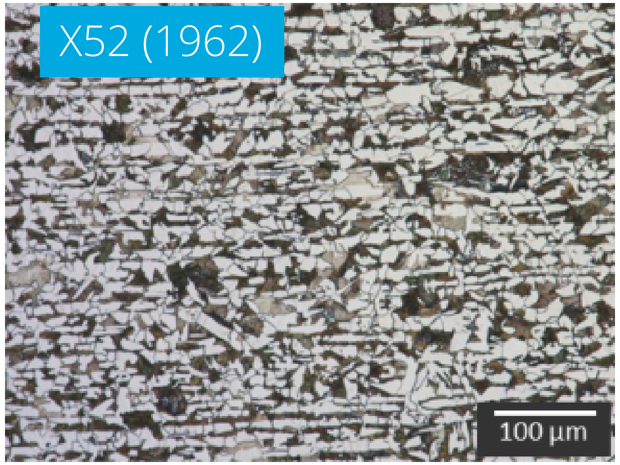
Material	Microstructure	σ_{ys} (MPa)
X52	Ferrite / pearlite	429
X65	Banded ferrite / pearlite	478
X65 (E18)	Awaiting characterization	517
X65 (J22)	Awaiting characterization	558
X80 (B)	90% PF + 10% AF (coarse)	565
X80 (E)	AF (fine)	593
X80 (F)	70% AF + 30% PF	552
X52 (1950)	Ferrite / pearlite	416
X52 (1952)	Ferrite / pearlite	424
X52 (1959)	Ferrite / pearlite	424
X52 (1962)	Banded Ferrite / pearlite	490
X52 (1964)	Ferrite / pearlite	334

AF = acicular ferrite: PF = polygonal ferrite







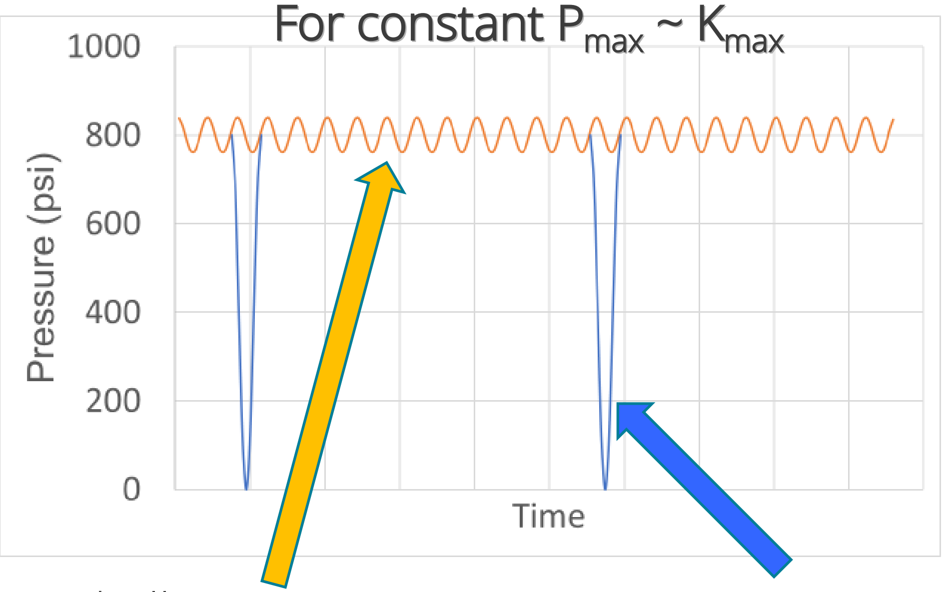


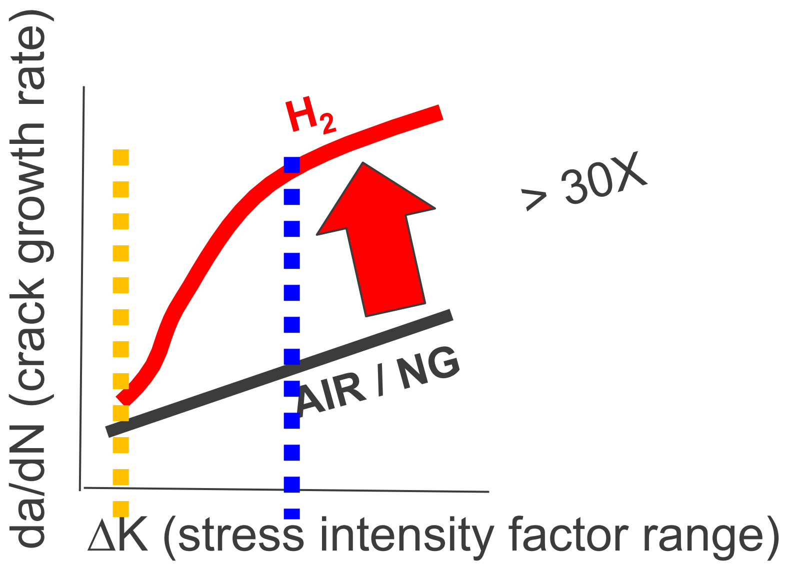
Higher carbon, higher sulfur

Trends in Fatigue Crack Growth Rates in H_2

Background: Hydrogen Assisted Fatigue

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

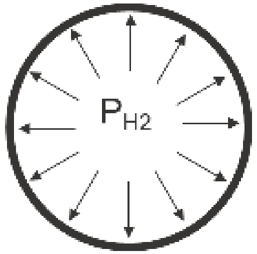




Shallow pressure cycles (high R, low ΔK)

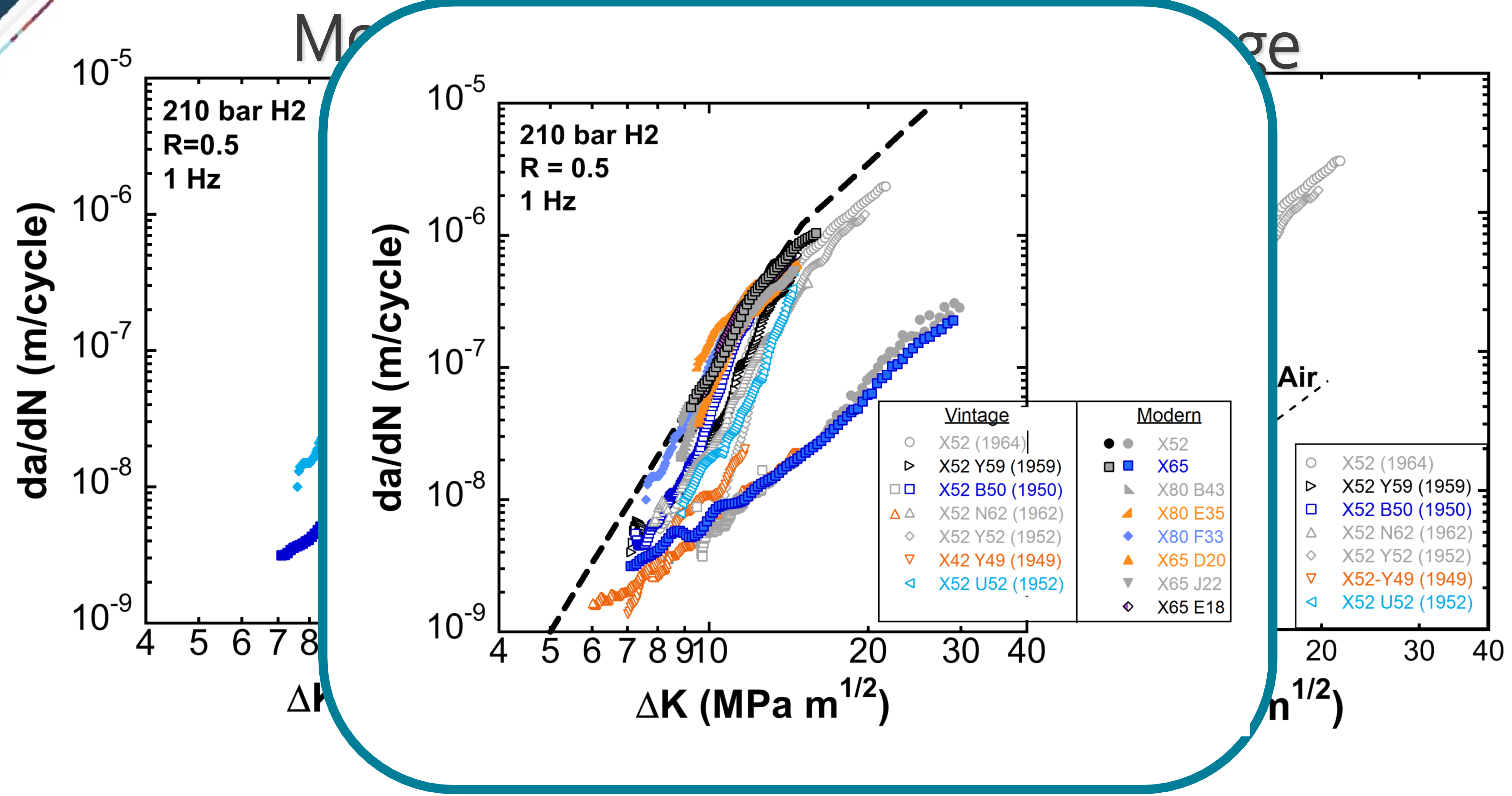
Deep pressure cycles (low R, high ΔK)

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



HA-FCG does not preclude material from use but necessitates proper design.

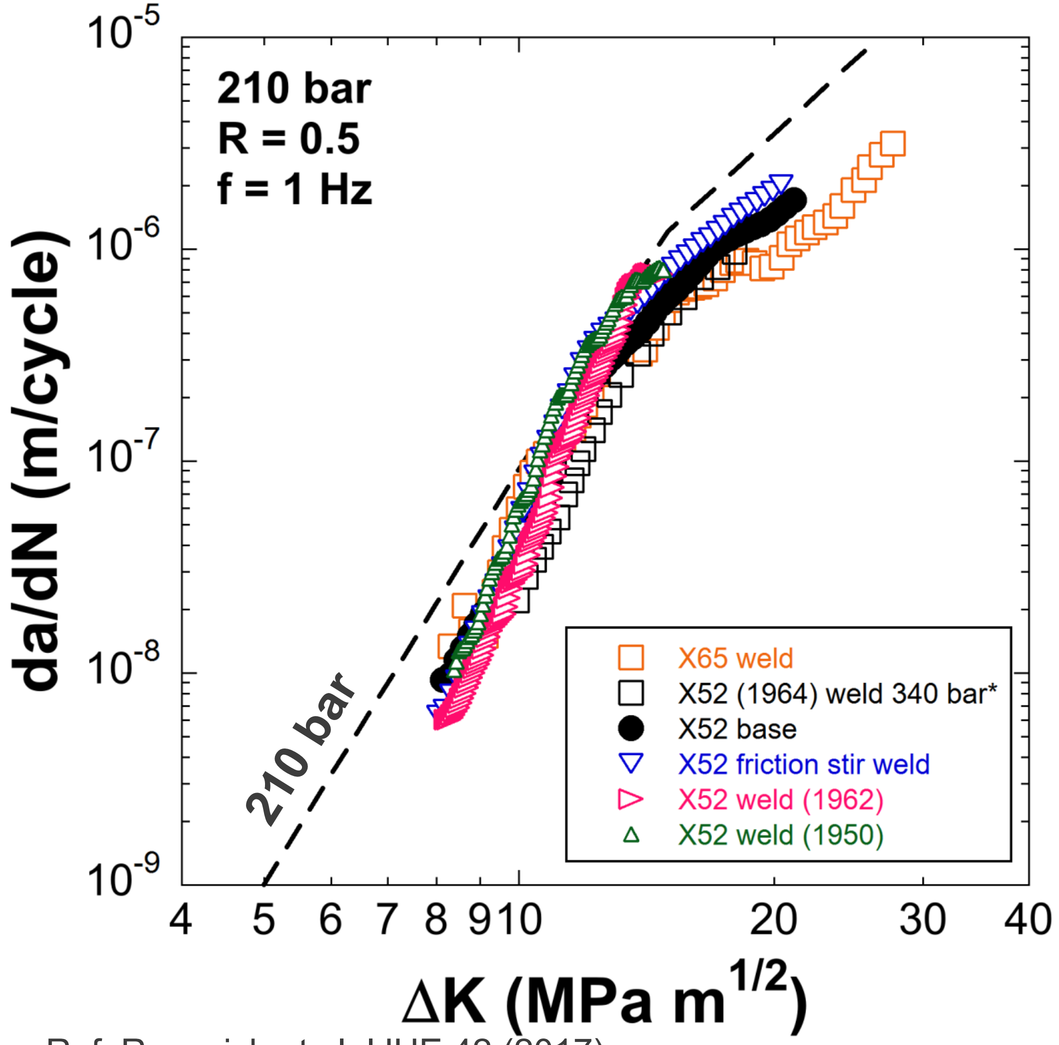
Variety of grades show similar behavior in gaseous H2

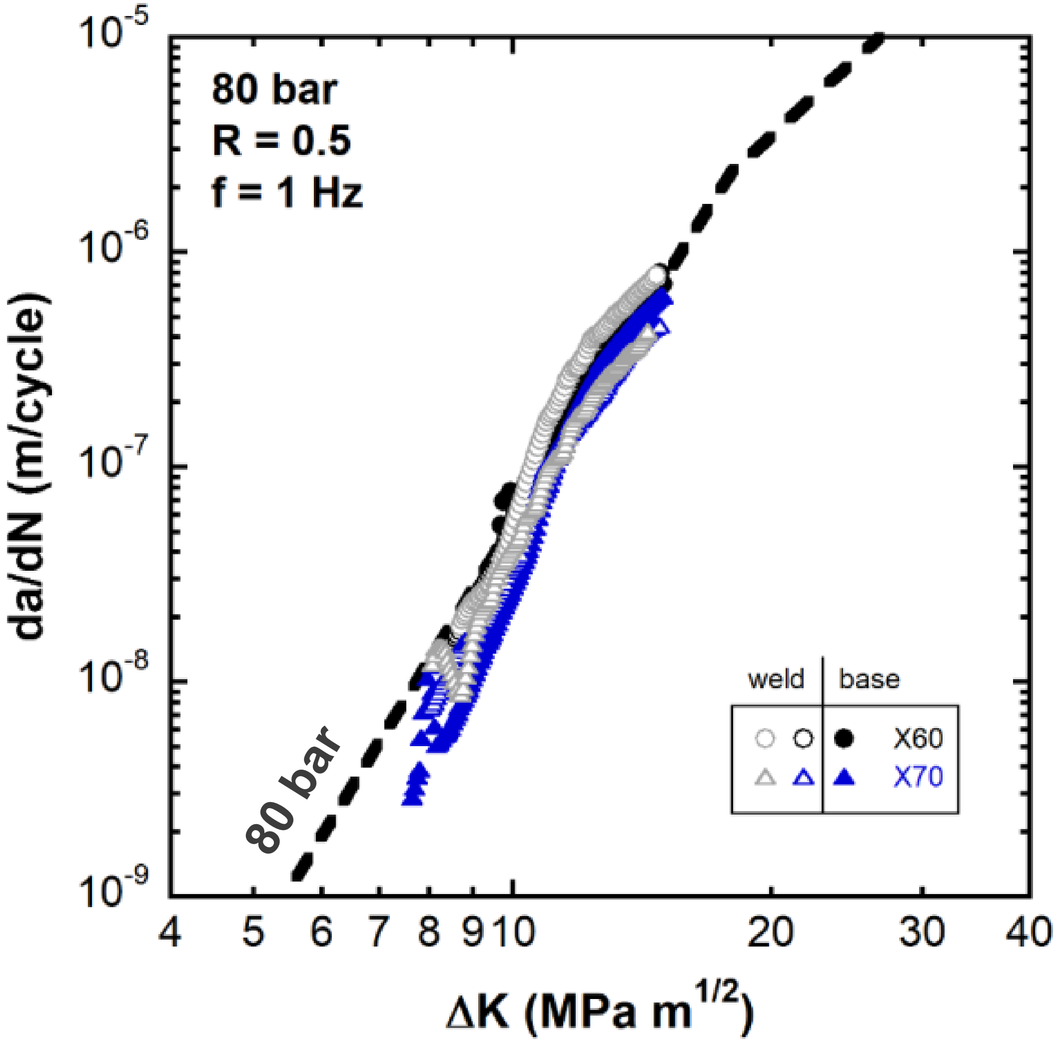


Welds and base materials behave similarly

Similar trends have been observed for a variety of weld processes

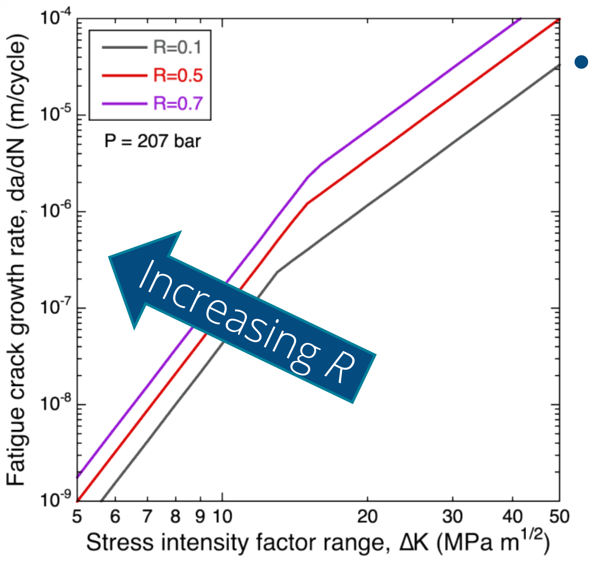
→ Design curves bound behavior

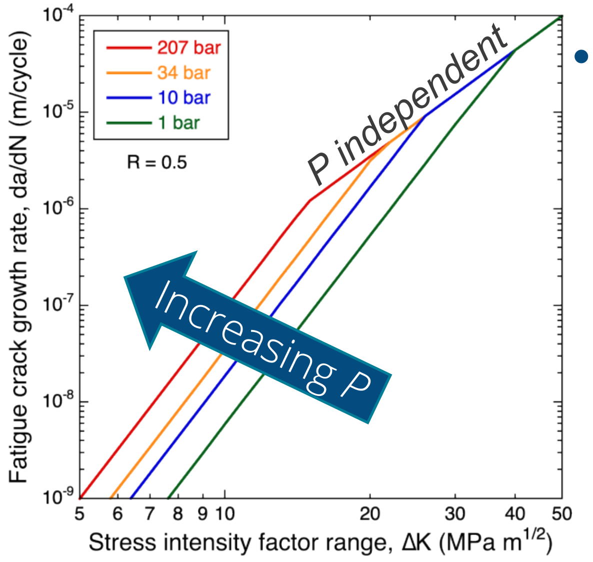




Ref: Ronevich et al. IJHE 42 (2017)
Slifka, PVP2015-45242

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





- **The effects of pressure and load ratio on fatigue crack growth are captured in conventional power law formulation :**

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

-At low ΔK $$\frac{da}{dN} = 3.5x10^{-14}\left[\frac{1+0.4286R}{1-R}\right]\Delta K^{6.5} g(P)$$

From 0 to 210 bar: $g(P) = 0.071P^{0.51}$ units in MPa

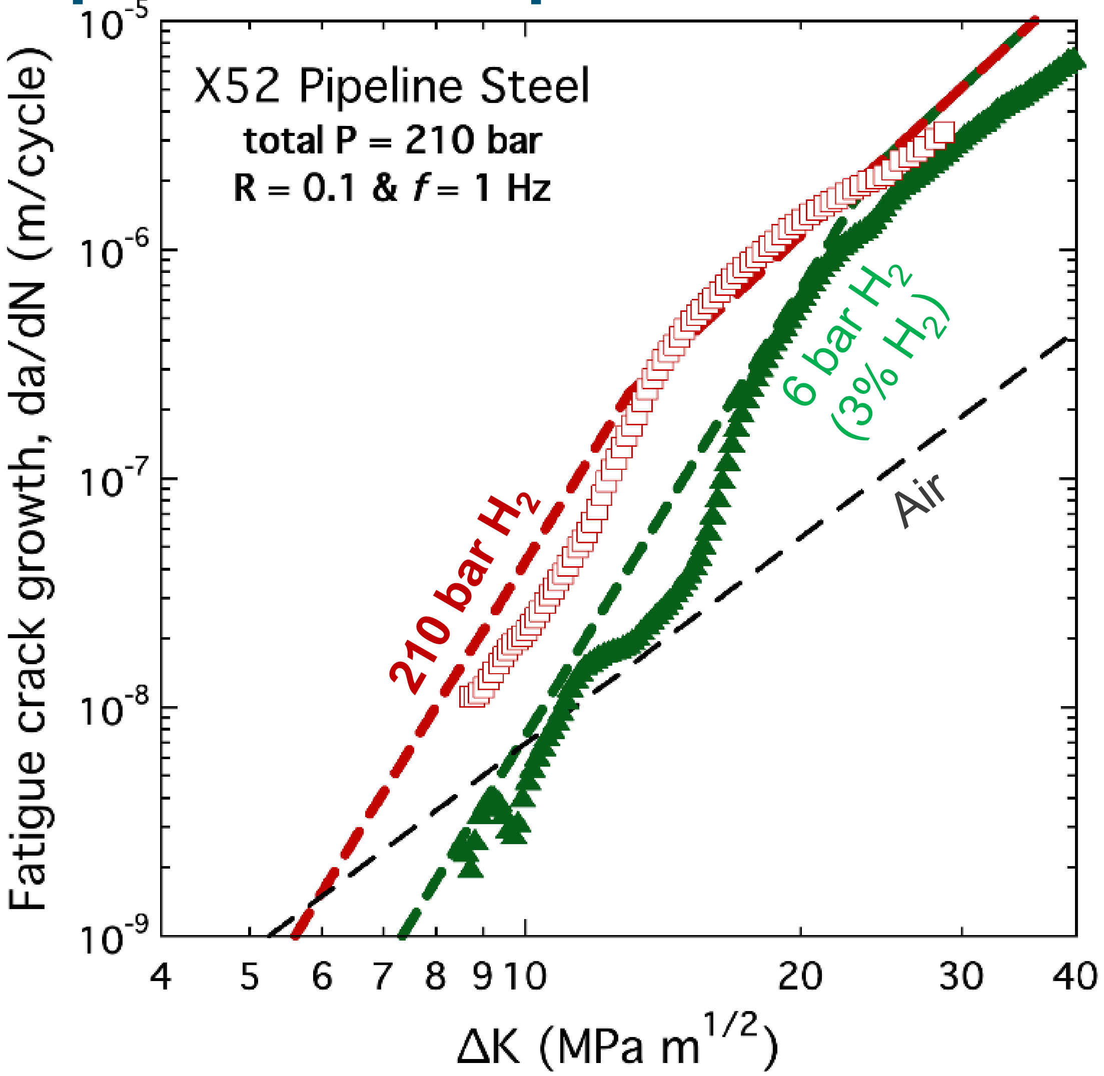
- **Master Design Curves appear to be effective for a wide range of construction steels**

Ref.: San Marchi et al., PVP2019-93907

<u>Outcome</u>:

- **Master Design Curves provide a simple framework to bound the fatigue crack growth of steels in gaseous H_2**

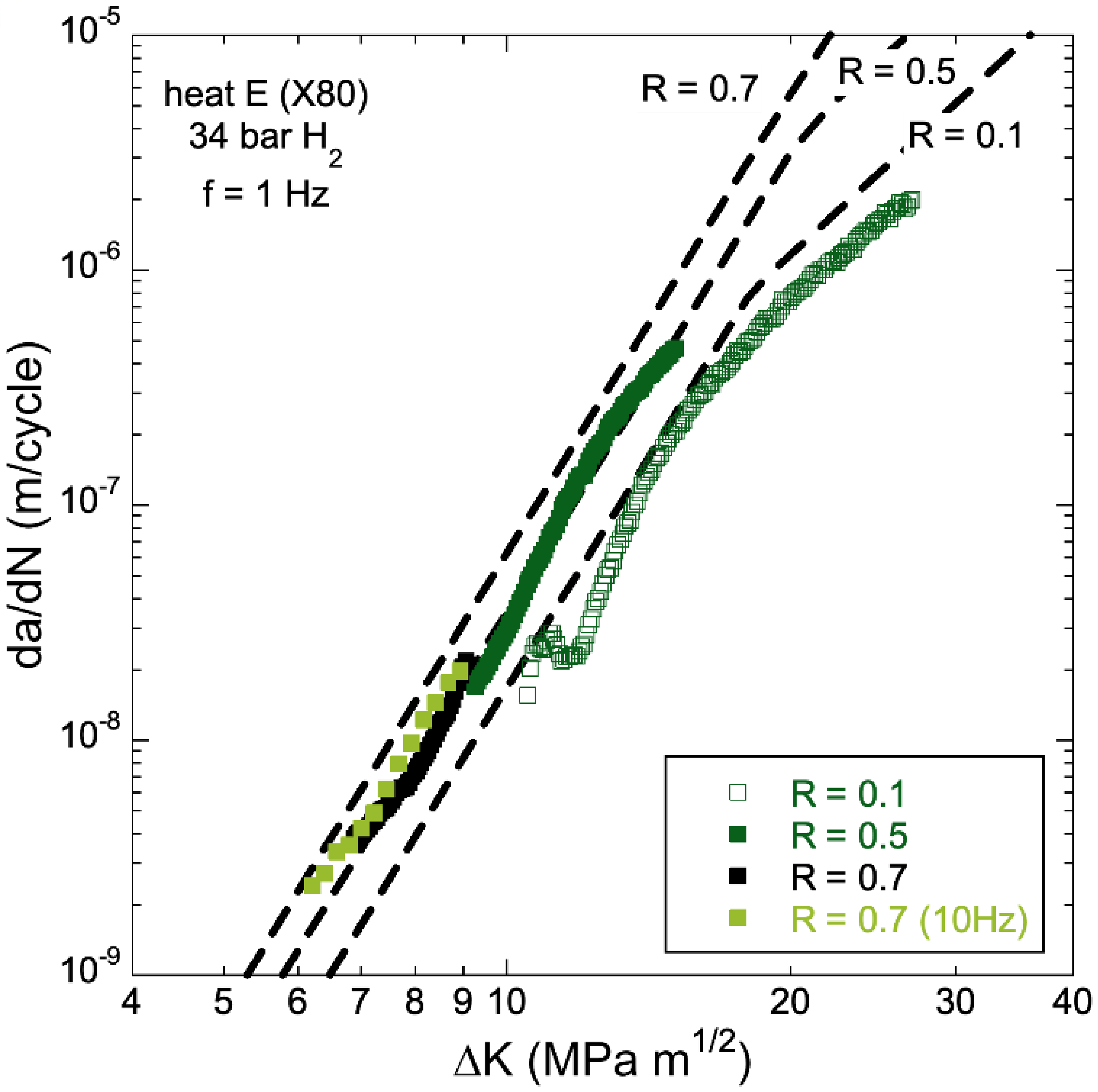
Master design curves bound pipeline steel data & are sensitive to observed dependence on <u>pressure</u>



Ref.: San Marchi et al, PVP2021-62045

Even low partial pressures can exhibit accelerated FCGR

Fatigue crack growth in H_2 depends on load ratio, R



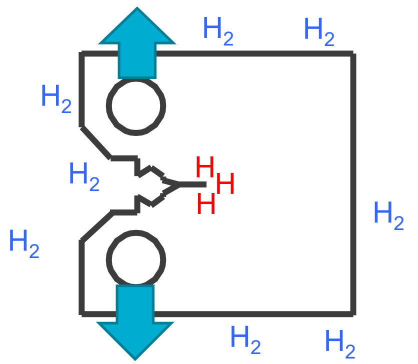
- Three load ratios were evaluated including the influence of frequency for R = 0.7
- Unlike tests in air and general recommendations in the codes, R has an effect on da/dN in hydrogen
- Higher frequency does not necessarily affect da/dN for low ΔK

Ref.: San Marchi et al, PVP2022-84757

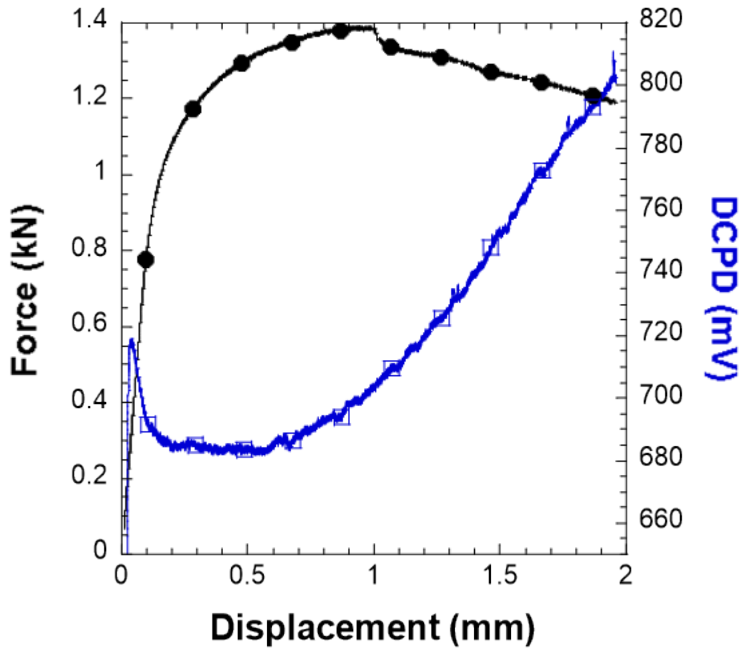
Trends in Fracture Toughness in H_2

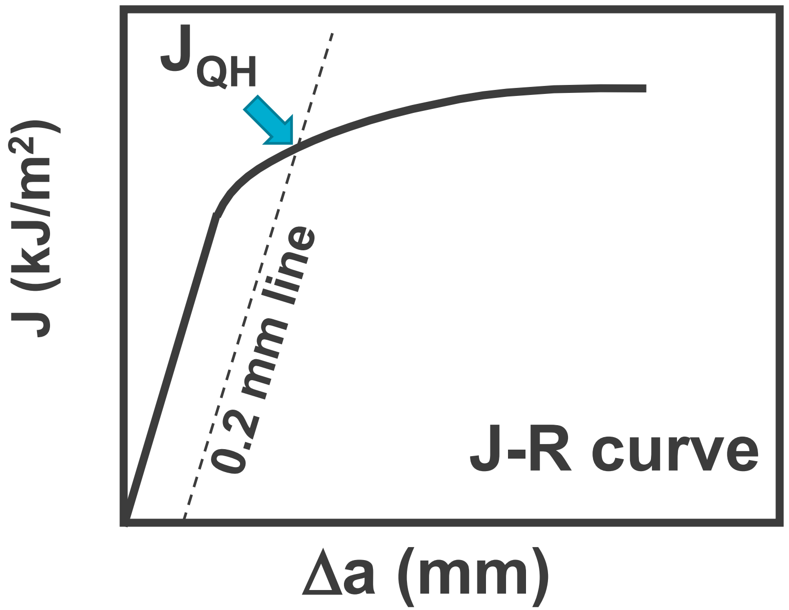
Hydrogen Assisted Fracture Testing

Fracture: subcritical crack extension as defined in ASTM E1820



- Monotonically load sample until crack extension
- Instrumented with DCPD



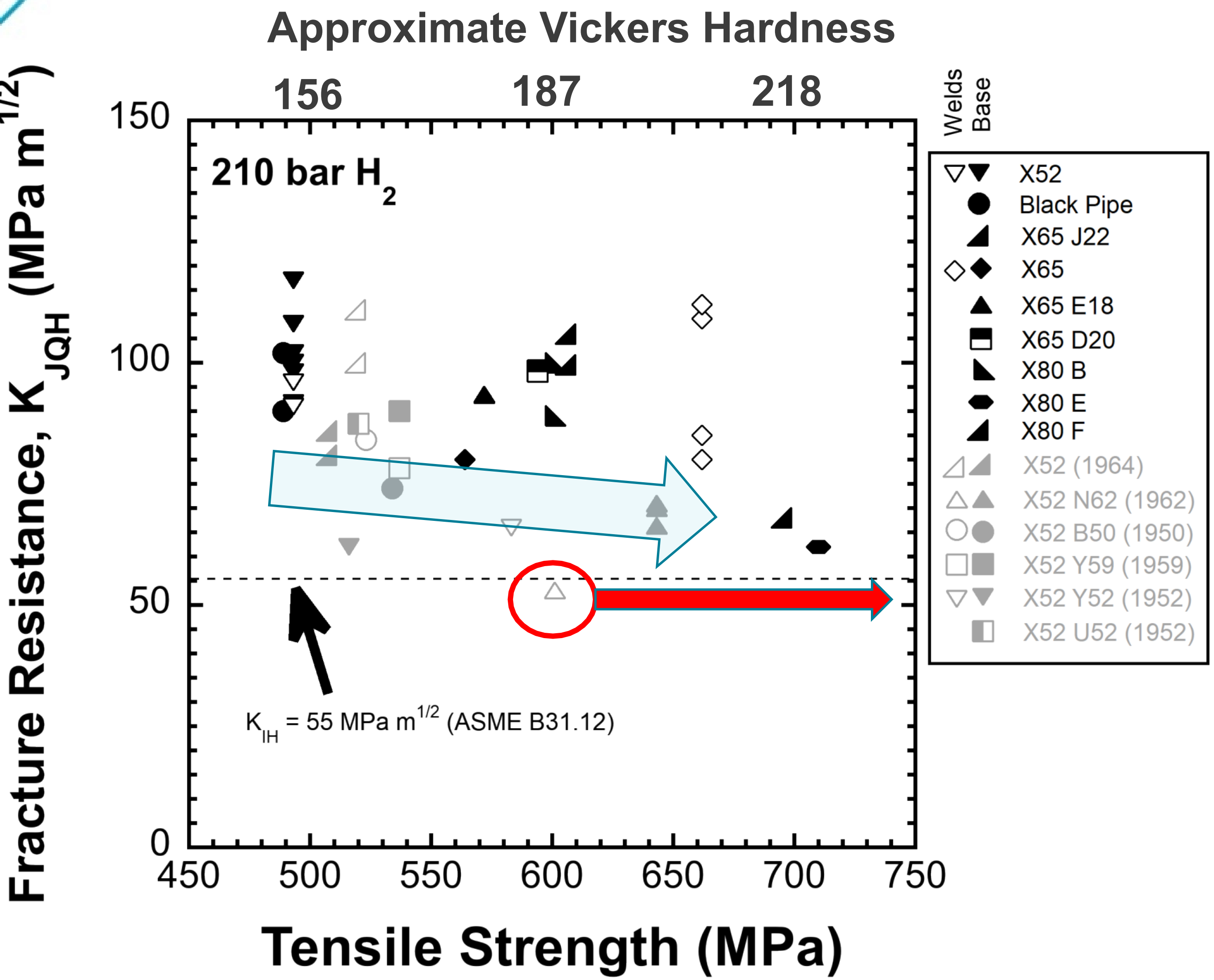


$$K_{JQH} = \sqrt{\frac{E J_{QH}}{(1-\nu^2)}}$$

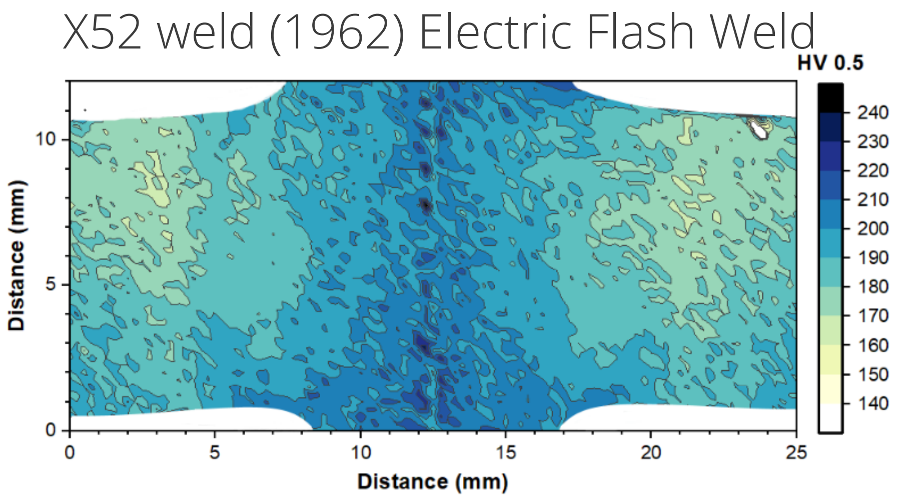
In Hydrogen, K_{JQ} is referred to as K_{JQH} as it is hydrogen dependent

Fracture resistance, K_{JQH}, is environmentally dependent (e.g. pressure, rate)

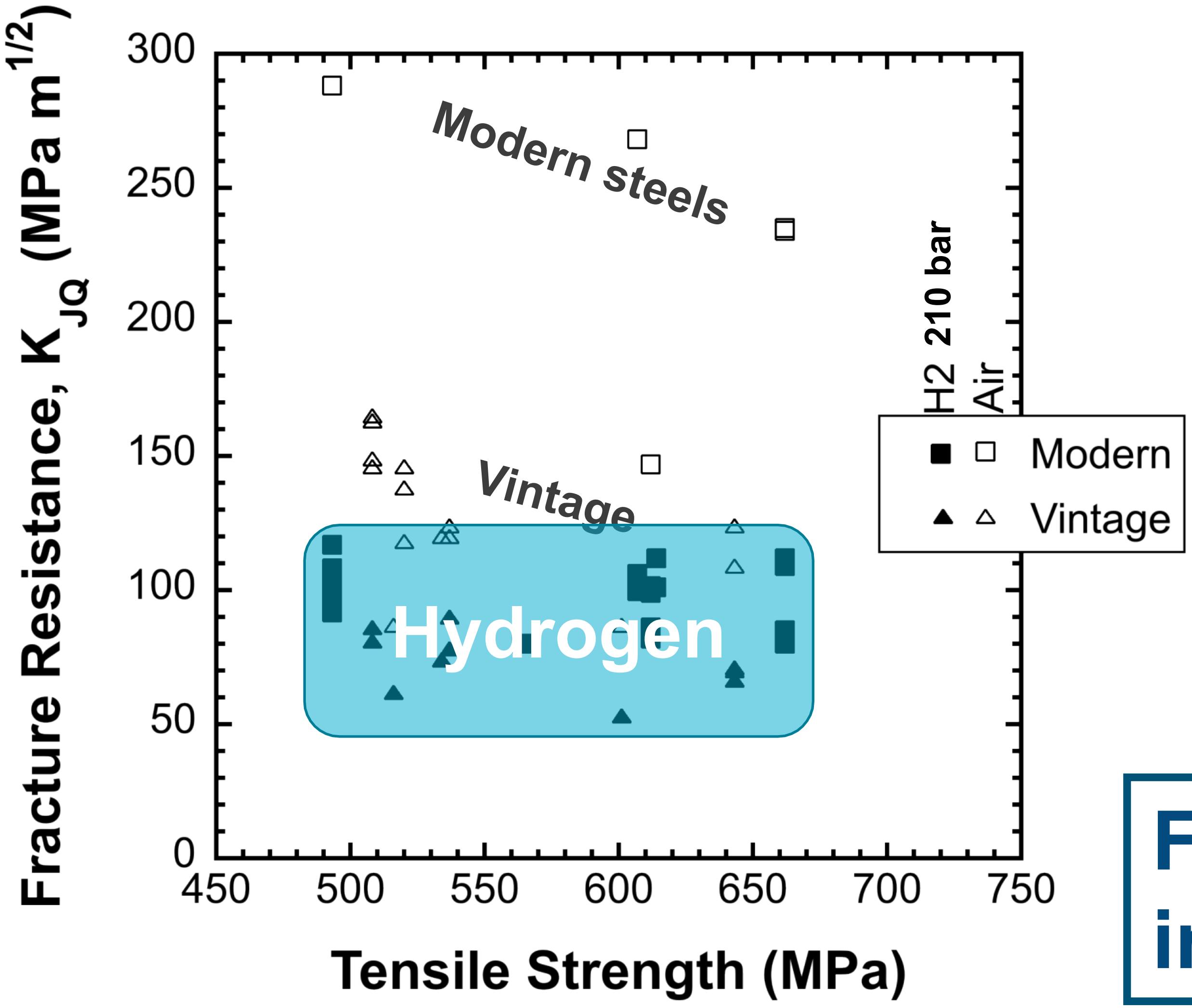
Fracture resistance trends for pipeline welds and base metals are similar in H_2



- K_{JQH} is generally greater than 55 MPa $m^{1/2}$
- Strength has only minor effect on lower bound K_{JQH} for steels with tensile strength < 650 MPa
- Local hard spots might account for lower toughness of welds



Older pipeline steels tend to have poorer fracture toughness in air



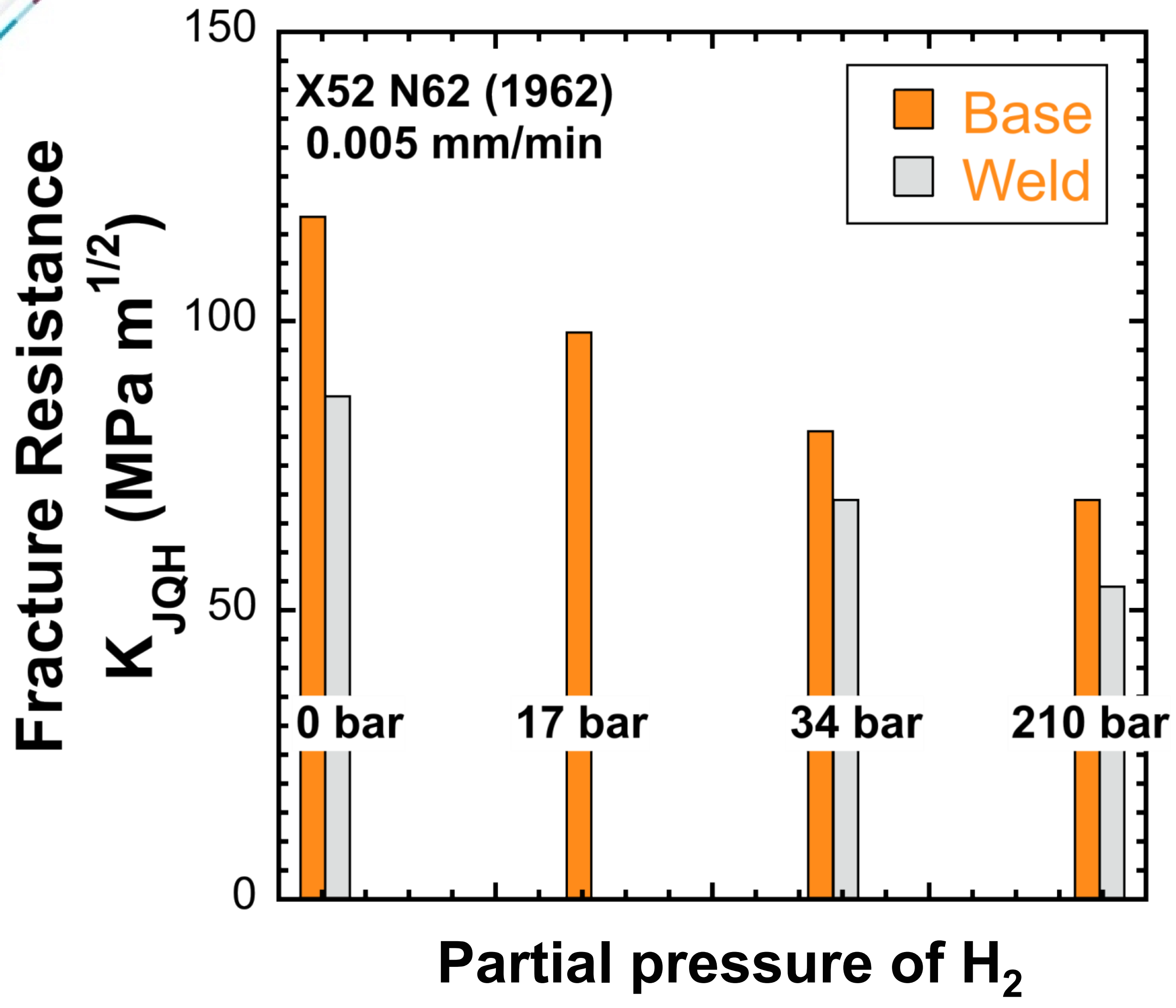
- **Modern steels have greater percent drop in fracture resistance than vintage steel**

→ Broad knock-down factors may be non-conservative

Fracture in air is not a great indicator of performance in H_2

Ref: Ronevich et al. 4th Int Conf on Metals and Hydrogen

Fracture resistance decreases with increasing hydrogen pressure



- Significant reduction of fracture resistance (K_{JQH}) is apparent at low pressure
- Further reduction of K_{JQH} at higher pressure is non-linear

Summary of Pipeline Behavior in Hydrogen Gas

Fatigue crack growth rate (FCGR) accelerates by 10X in H_2

- Similar behavior among grades, age, strength, microstructure, weld
- Pressure sensitive in low ΔK regime
- Design curves capture FCGR relationship with pressure and R

Fracture resistance decreases in gaseous H_2

- Pressure dependent and non-linear
- Welds exhibit similar behavior for same hardness
- No significant influence of strength on lower bound fracture behavior for tested X52-X80
- Fracture in air is not a great indicator of performance in H_2

Gaps Remaining:

- Role of hard spots, HAZ, dents, bends
- How do we define bounding fracture behavior
- Anomalies to trends identified

Thank you for your attention!

Joe Ronevich
jaronev@sandia.gov

Chris San Marchi
cwsanma@sandia.gov

Milan Agnani
magnani@sandia.gov

HEML Team
James McNair
Brendan Davis
Keri McArthur

ORNL
Yanli Wang
Zhili Feng

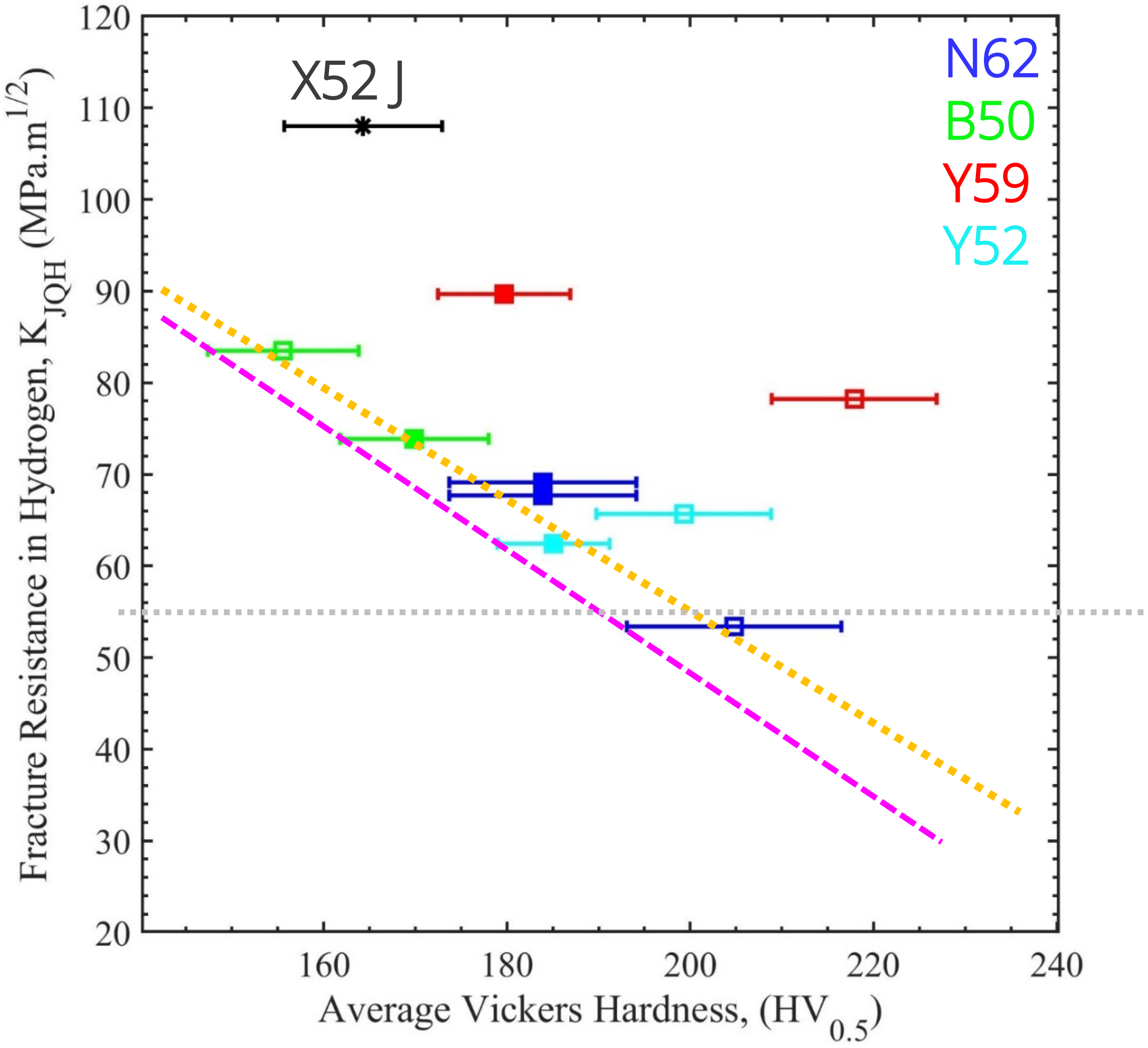
EPRI
Mike Gagliano
Jonathan Parker
Andrea Bollinger

ExxonMobil
Neeraj Thirumalai

Acknowledgements: Additionally the help of Rob Wheeler, Fernando Leon Cazares, Rakish Shrestha. This work is supported by the U.S. Department of Energy, through the Office of Energy Efficiency and Renewable Energy's (EERE) Hydrogen and Fuel Cell Technologies Office (HFTO). *Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.*

Backup slides

Hardness Results



Y52 and U52 data taken from flat faces

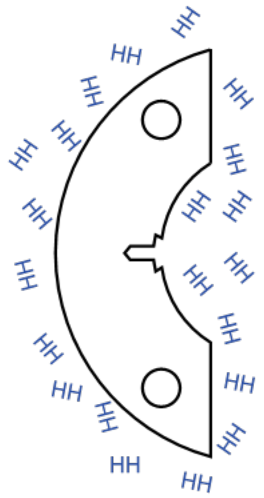
Lower bound HV at 55 MPa√m

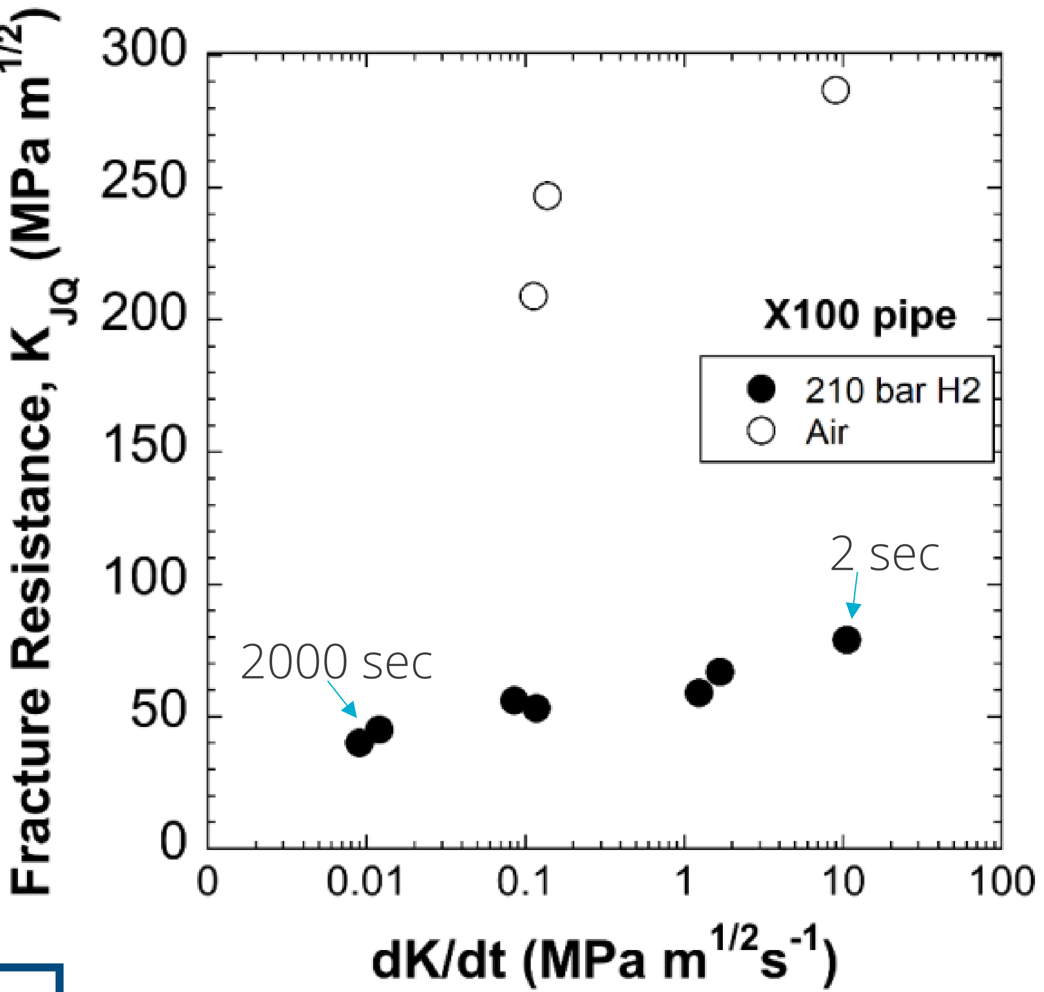
Minima: ~190 HV

Mean: ~205 HV

Gaseous hydrogen affects fracture at high deformation rates

- 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}
- At high rate, limited time for H diffusion; however, background (equilibrium) H is sufficient to degrade fracture resistance compared to air





Effect of H_2 on fracture at high rate should not be ignored

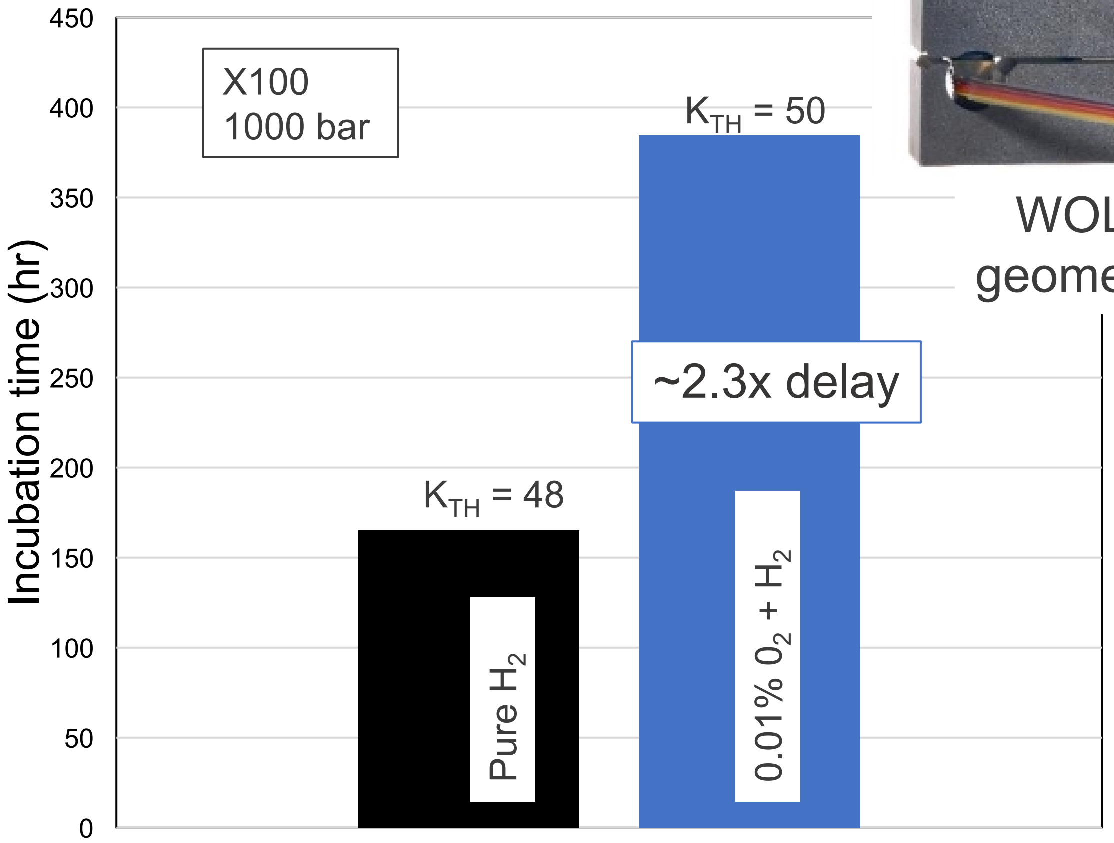
Ref.: Ronevich, San Marchi (unpublished)

Oxygen did not affect hydrogen fracture resistance for long exposures

- 8 different materials with yield strengths from 760 to 1480 MPa all exhibited a delay in cracking (i.e., incubation time increased) but ultimate fracture resistance in hydrogen was not affected
  - K_{th} ~ 48 to 50 MPa $m^{1/2}$
- Evaluated O_2 contents from 0.01% to 1%

<u>Impact</u>: Long-term benefits of O_2 cannot be relied on to mitigate H-embrittlement

Constant displacement fracture tests



ASTM E1681

WOL geometry

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