Implications of Gaseous Hydrogen on Welded Construction of Pipelines

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2022 API/AGA Joint Committee on Oil and Gas Pipeline Welding

26 January 2022

SAND2022-0429 PE

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Outline

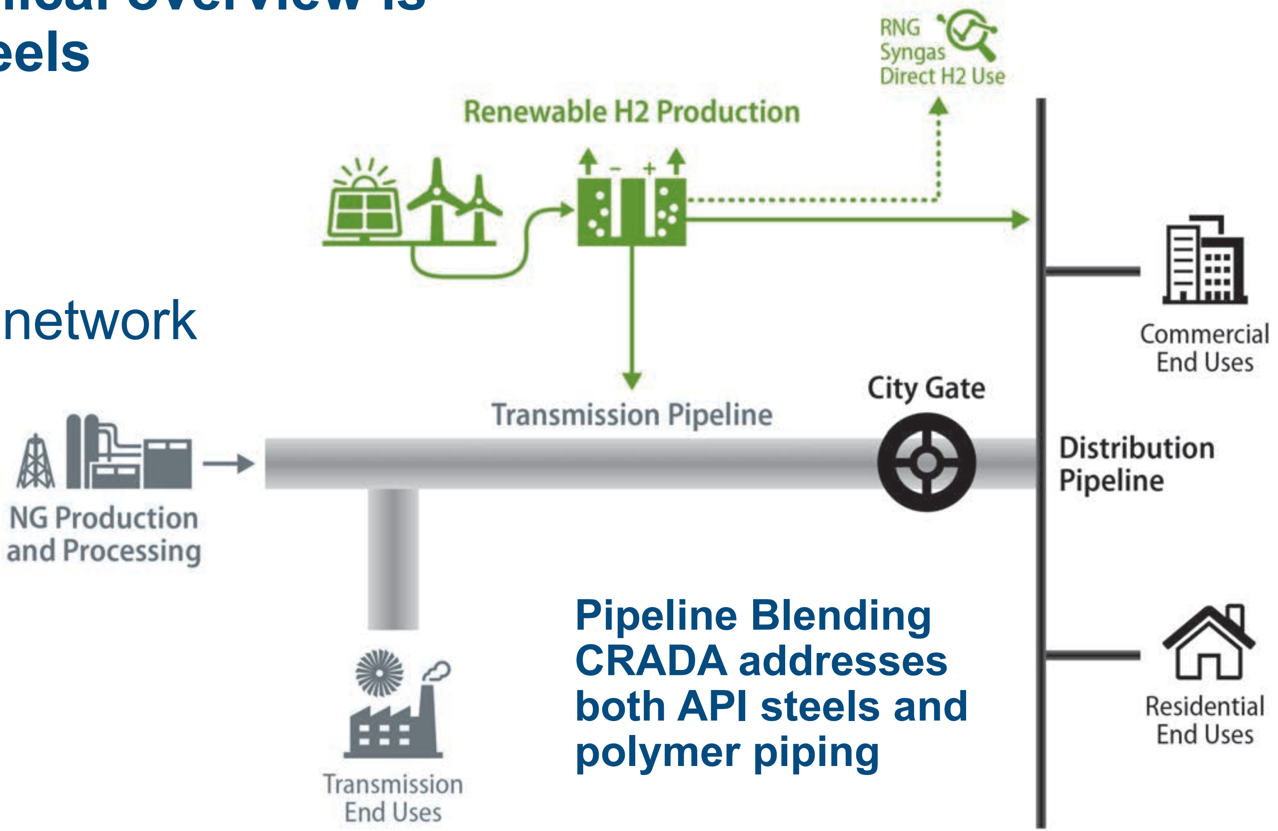
- Introduce DOE-funded Pipeline Blending CRADA (often referred to as HyBlend)
- Basic trends in pipeline steels in hydrogen
  - Fracture mechanics-based characterization of microstructure, strength, pressure variables
  - Variance of welds from basic trends
- Simple example of implications of hydrogen on structural integrity
- Quick glance at plans for materials testing in Pipeline Blending CRADA

Pipeline Blending CRADA: LCA, TEA and materials

Focus of this technical overview is compatibility of steels

Transmission
- Mostly steels
- Extensive existing network

Distribution
- Legacy metals
- Extensive polymer networks



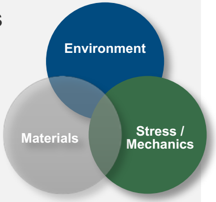
Pipeline Blending CRADA addresses both API steels and polymer piping

Materials activities in 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

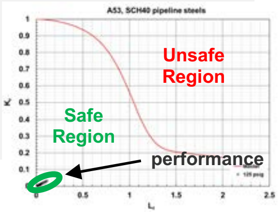
- Assessment of critical parameters determining materials response in hydrogen environments
- Survey of critical materials in ancillary equipment (eg, pumping stations)
- Long-duration aging of polymers in piping systems
- Evaluation of vintage materials in existing infrastructure



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 NRC framework
- Uncertainty analysis to inform experimental evaluation
- Sensitivity analysis to determine opportunities for system and operational improvements
- 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

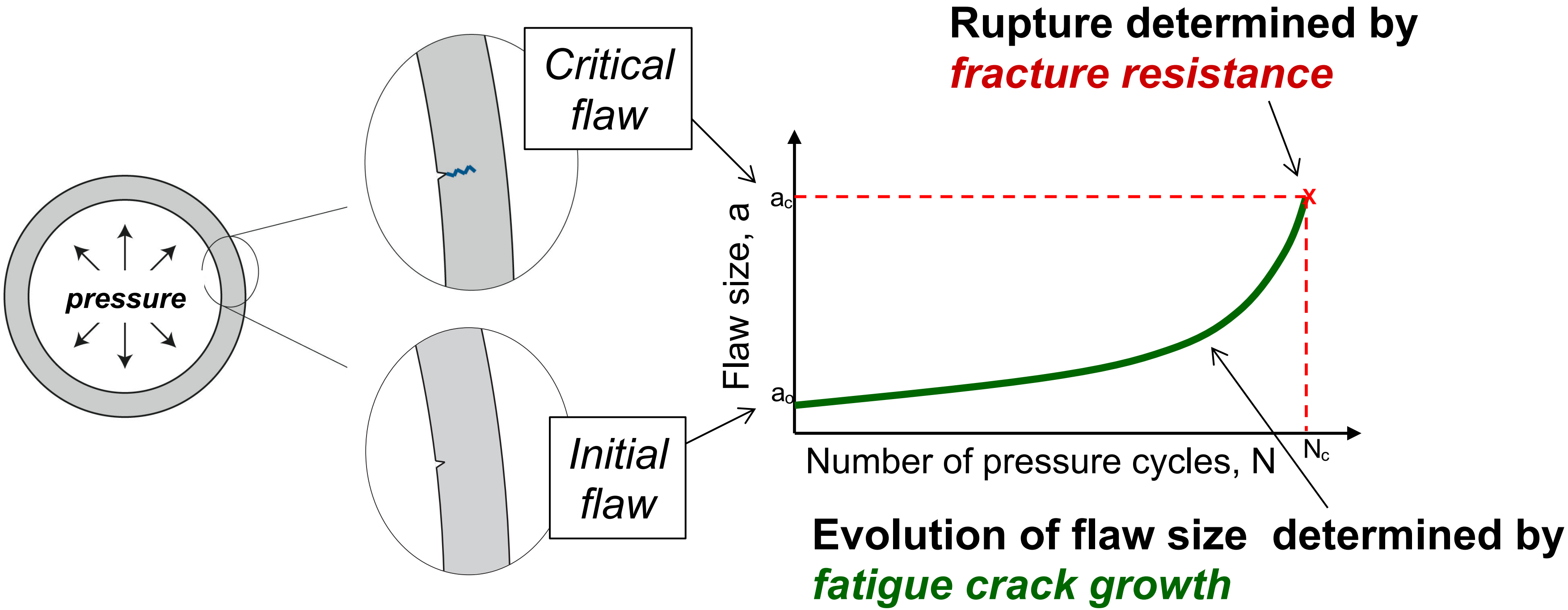
PRCI EPRI gti

State-of-the-art characterization

H-Mat

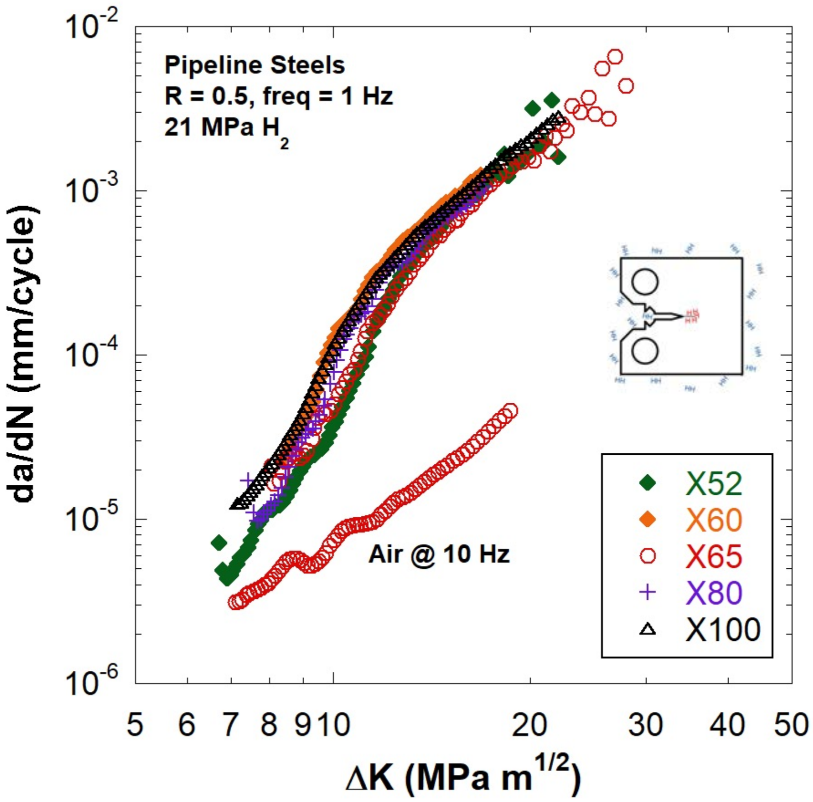
International coordination *facilitates* definition of requirements, *reduces* redundancy, *enhances* rigor, and *improves* breadth of structural integrity tools

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

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

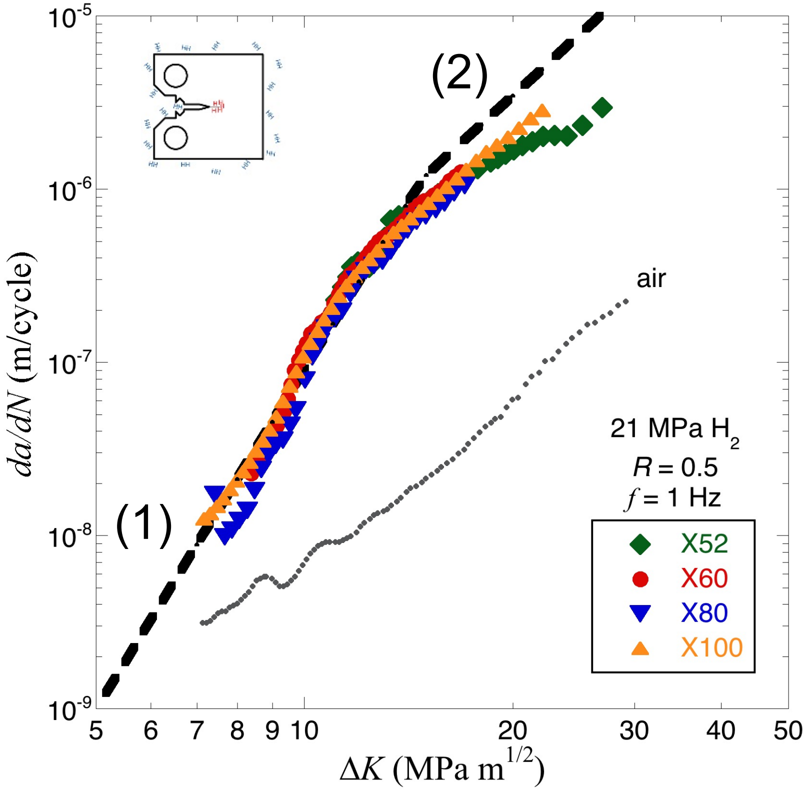


A wide variety of pipeline steels display nominally the same fatigue response in high-pressure GH2

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 hydrogen on pipeline steels are captured by ASME CC2938 design curve for pressure vessels



CC2938 design curve was based on high pressure data

$$(1)\quad \frac{da}{dN} = C_1\left[\frac{1 + C_2 R}{1 - R}\right]\Delta K^{m_1}\boxed{\left(\frac{f}{f_0}\right)^{1/2}}$$

Pressure compensation term not in CC2938

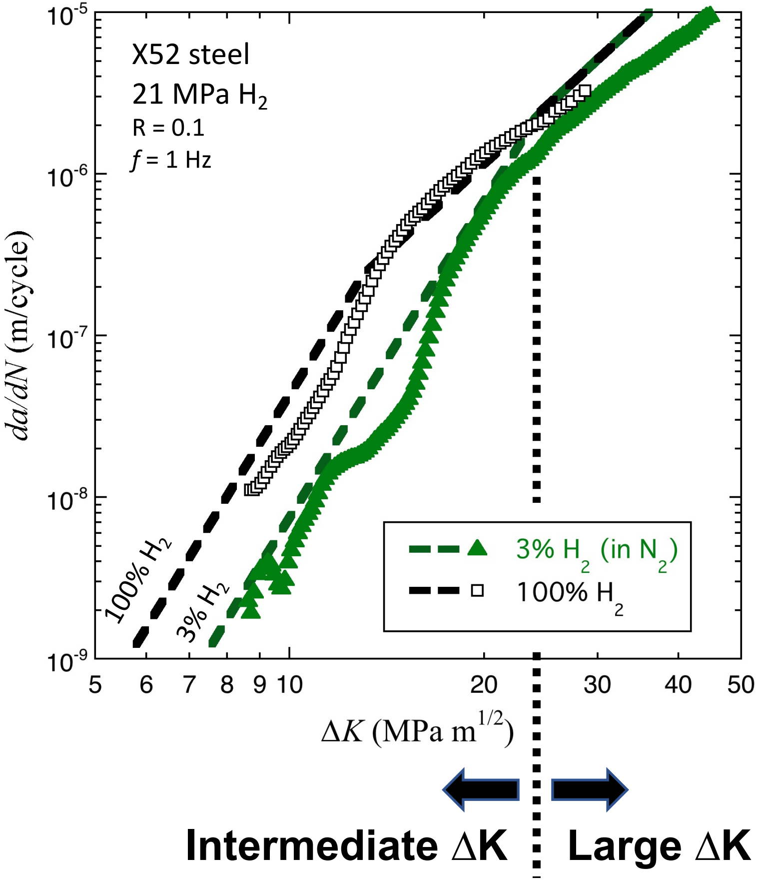
$$(2)\quad \frac{da}{dN} = C_3\left[\frac{1 + C_4 R}{1 - R}\right]\Delta K^{m_2}$$

f is the thermodynamic pressure or fugacity
f_o is the reference fugacity (211 MPa)

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?**

Fatigue crack growth of X52 is strongly affected by low partial-pressure hydrogen



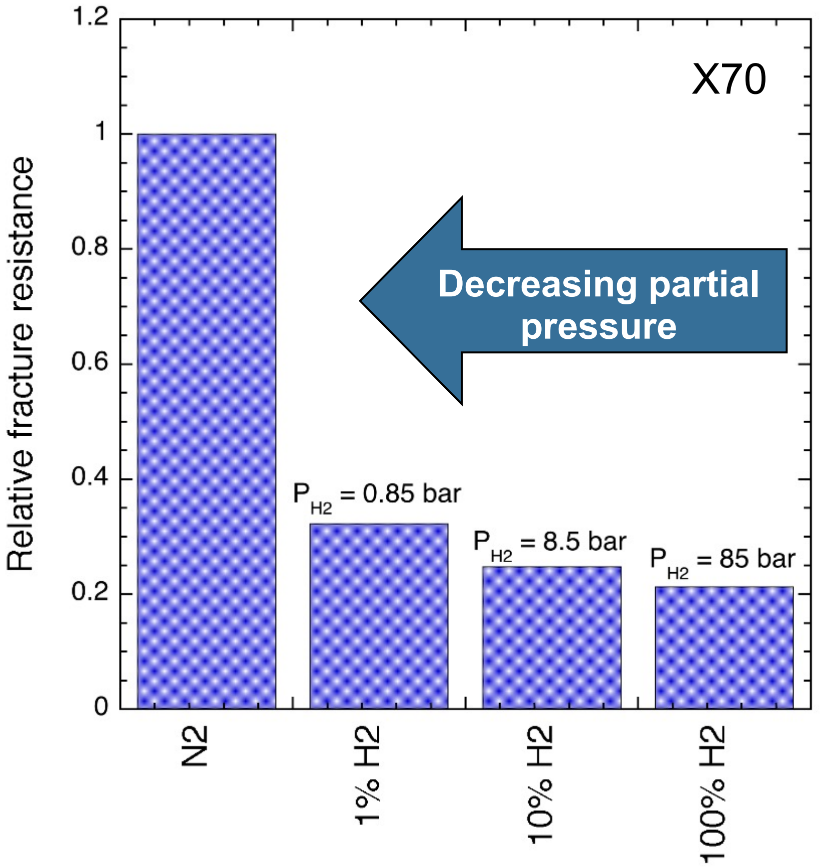
- **Large ΔK**
  FCG remains independent of pressure
  - **FCG in hydrogen at partial pressure of 0.6 and 21 MPa converge**
- **Intermediate ΔK**
  FCG is dependent on hydrogen partial pressure
  - **Dashed lines represent pressure-corrected predictions from ASME CC2938 for 100% and 3% H_2 at total pressure of 21 MPa**

Ref: San Marchi et al, PVP2021-62045

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

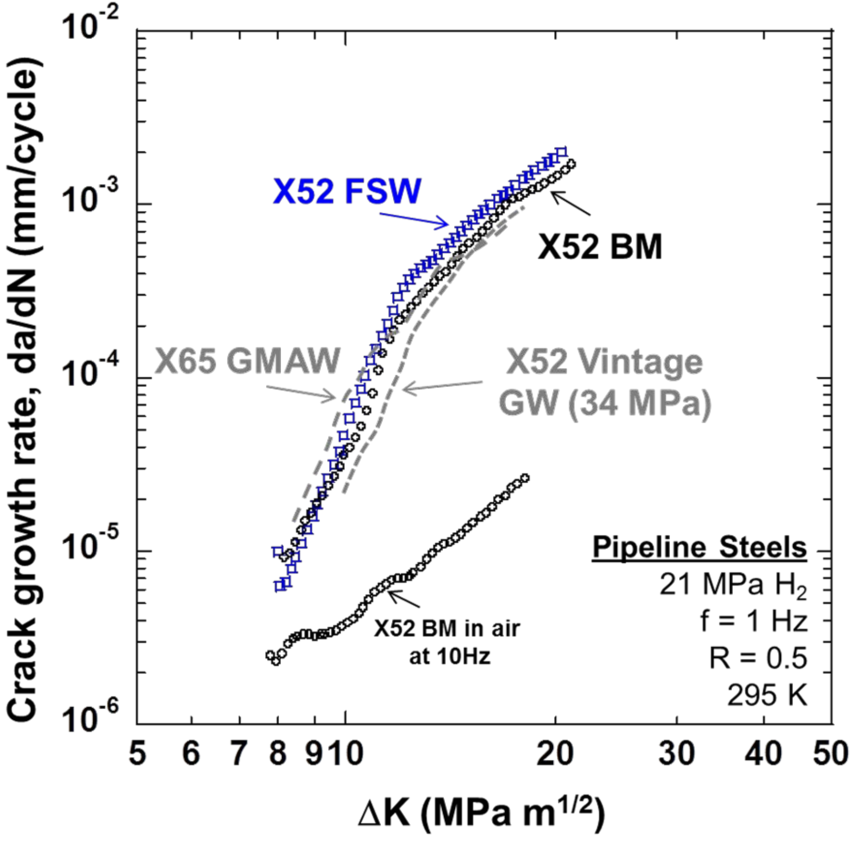
- **Measurements of fracture resistance in gaseous mixtures of H_2 and N_2 show substantial effects of H_2**
- **1% H_2 is only modestly different than 100% H_2**
- **Fracture resistance does not scale linearly with pressure/fugacity**

<1 bar of H_2 reduces fracture resistance

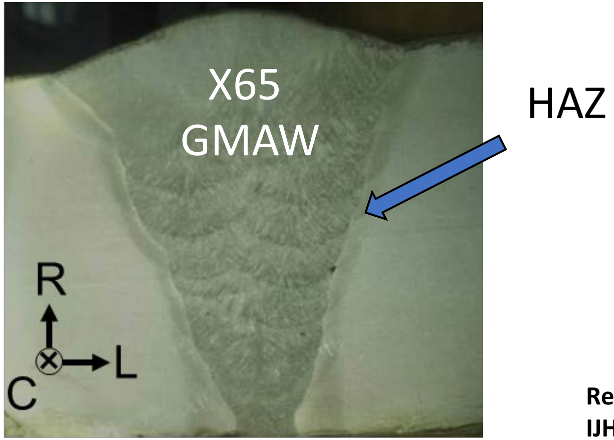


Ref.: Briottet et al, PVP2018-84658

Welds and base materials behave similarly

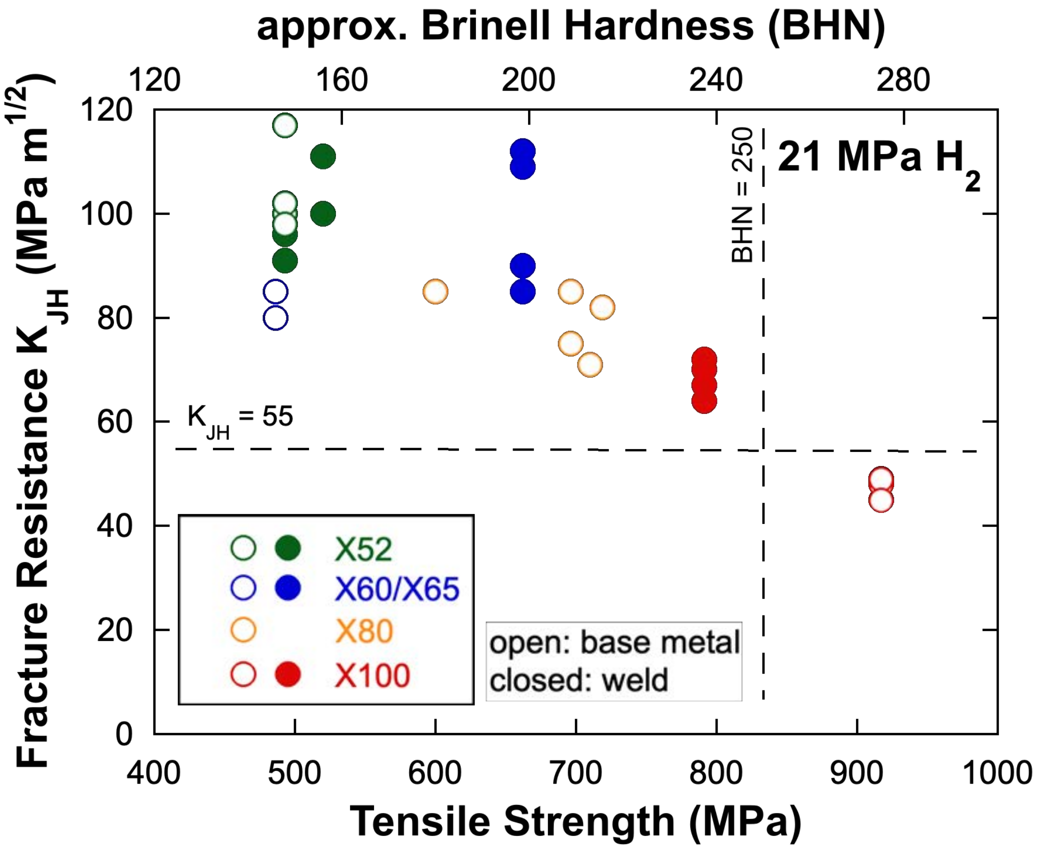


- To first order and if residual stress is considered, welds show similar fatigue and fracture behavior in gaseous H_2 as the base metals
- Similar trends have been observed for a variety of weld processes



Ref: Ronevich et al. IJHE 42 (2017)

Fracture resistance trends for welds and base metals are similar in gaseous hydrogen



- **Fracture resistance in H_2 decreases with increasing strength**
- **Welds behave nominally the same as base metals for same strength/hardness**
- **K_{JH} > 55 for BHN < 250 (for $P_{H2} \leq 21$ MPa)**

BHN estimated from tensile strength (=0.3TS)

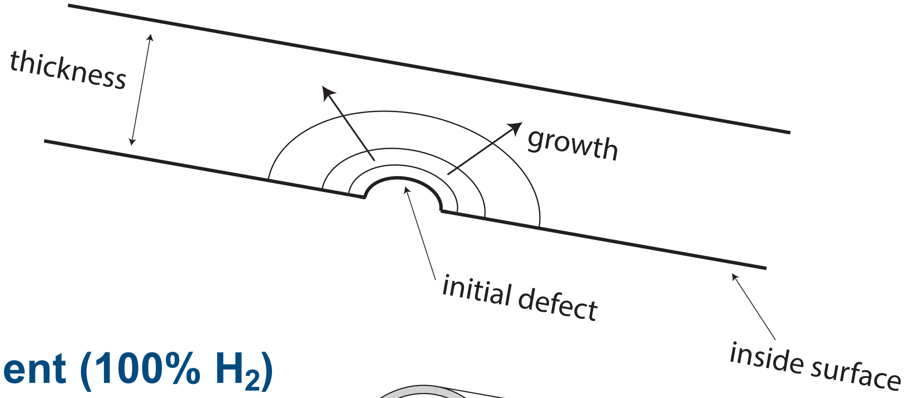
Ref.: Ronevich et al, IJHE 46 (2021)

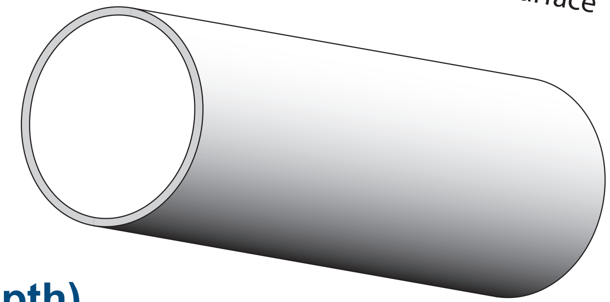
Summary of *materials* behavior in GH2

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

Analysis of transmission pipe structure (simple example)

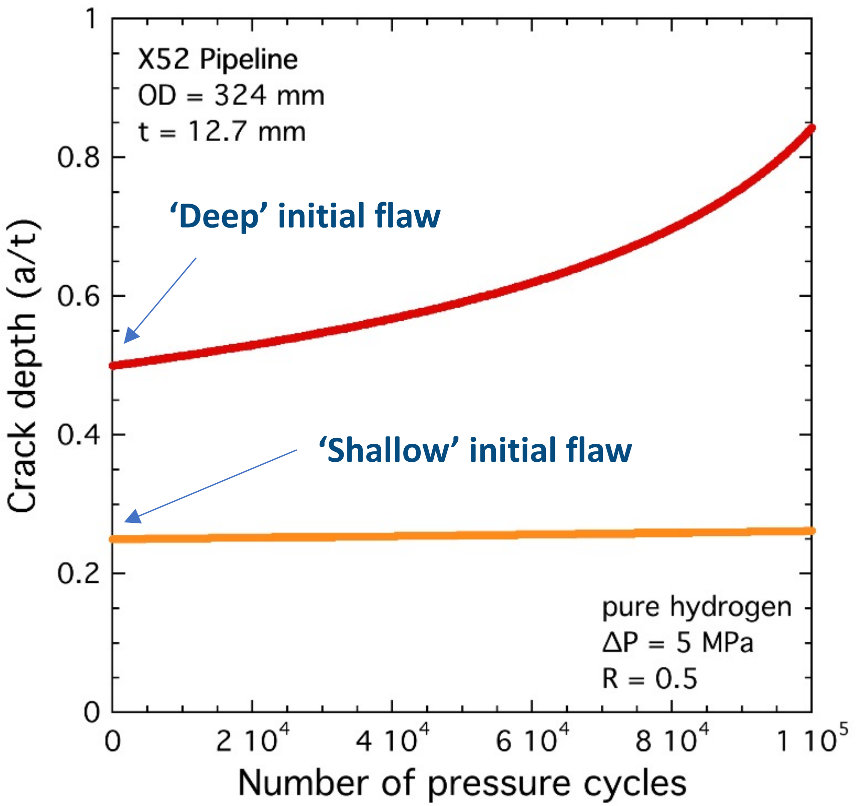
- ***Material***:
  - API grade X52 pipe
  - OD = 324 mm
  - t = 12.7 mm
- ***Environment***:
  - Pure hydrogen at pressure of 10 MPa
  - Consider aggressive service environment (100% H_2)
- ***Stress***:
  - Hoop stress ~ 120 MPa (~35% SMYS)
  - Cyclic pressure: ΔP = 5 MPa
  - Flaw depth: 25% and 50% of wall thickness propagate with constant aspect ratio of 3:1 (length:depth)





Analysis of transmission pipe structure (simple example)

- **Stress is rather modest in this example, where P = 10 MPa, ΔP = 5 MPa**
- **Shallow initial crack/flaw: a/t = 0.25**
  - $K_{applied}$ = 11.2 MPa $m^{1/2}$
  - Crack does not extend significantly after 100,000 cycles with ΔP = 5 MPa
- **Deep initial crack/flaw: a/t = 0.50**
  - $K_{applied}$ = 16.5 MPa $m^{1/2}$
  - Nearly 100,000 cycles required to extend crack to a/t = 0.80
- **Crack depth: a/t = 0.80**
  - $K_{applied}$ = 22 MPa $m^{1/2}$
  - $K_{material}$ ~ 100 MPa $m^{1/2}$



Priority for metals testing in Pipeline Blending CRADA

1) **Baseline fatigue crack growth and fracture resistance of base materials**
   - *Legacy: pre-1960s*
   - *Vintage: 1960s-1970s*
   - *Modern: 1980s to present*
2) **Evaluation of fatigue/fracture of Legacy/Vintage welds & HAZ**
   - *Low frequency ERW*
   - *EFW, DSAW seam welds*
   - *Girth welds*

Reference conditions:
pressure = 21 MPa
pure hydrogen
R = 0.5 (fatigue)

3) **Effect of pressure (pure hydrogen)**
   - *0.1 to 21 MPa*
   - *Establish pressure correlation, if possible*
   - *Evaluate rate effects as function of pressure*

Rate effects in fracture

R = 0.5 to 0.8 when convenient

Thank You!

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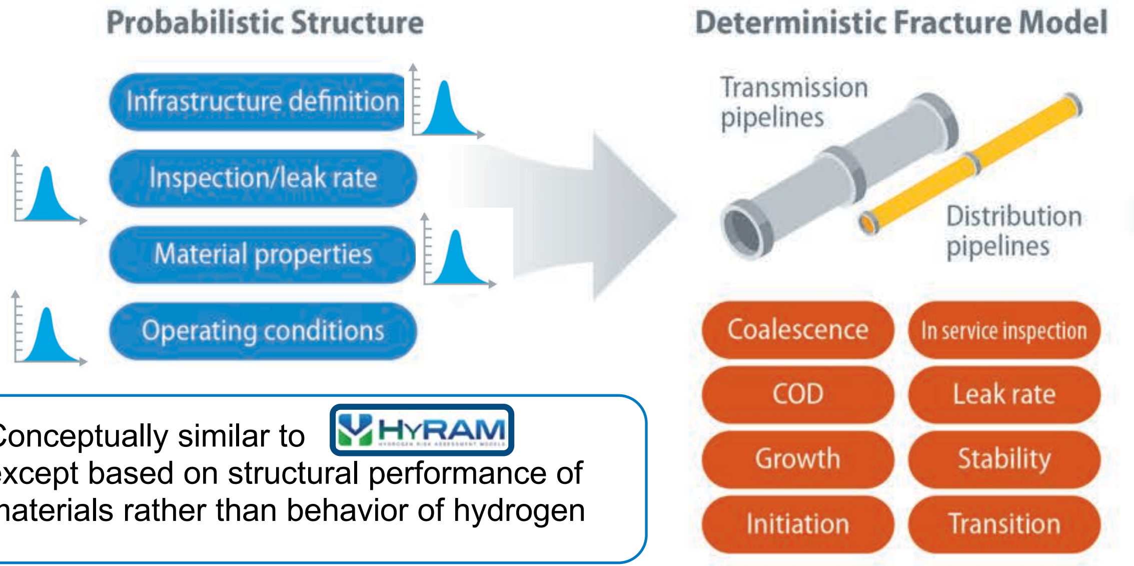
https://h-mat.org/

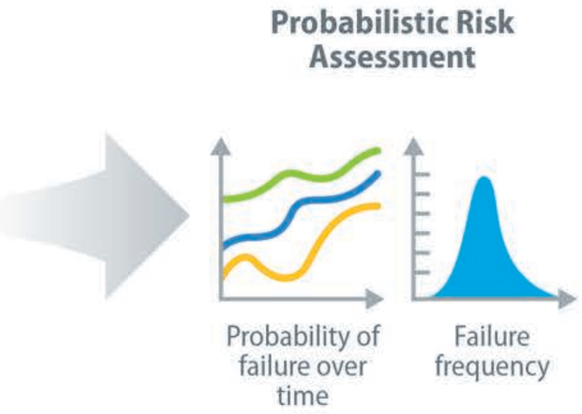
https://www.sandia.gov/matlsTechRef/

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

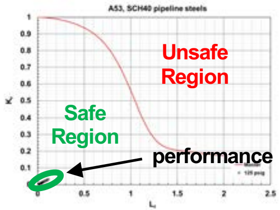
Key deliverable: Hydrogen piping and pipeline structural integrity assessment tool (HyPSI)

<u>Goal</u>: use NRC framework (xLPR) and state-of-the-art uncertainty analysis to develop probabilistic tool suite for quantitative risk assessment of NG assets containing hydrogen environments





Conceptually similar to HyRAM except based on structural performance of materials rather than behavior of hydrogen



Outputs intended to be aligned with relevant RCS

Sustained and emerging 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)**