

Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn

Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn

B31.8 Hydrogen Pipelines

HYDROGEN STUDY GROUP AT PVP

TAYLOR SHIE, FASME (SHELL)
SIMON SLATER (ROSEN)

Agenda

- » Background of Case for Change, ASME Process, and Path Forward
- » Background for PRCI's Emerging Fuels Institute and the Consensus Engineering Requirement Project
- » Discuss Next Steps for ASME B31.8 Hydrogen Task Group
- » Discussion

Background, ASME Process, and Path Forward

ASME Approve Path for Pipelines (June 2023)

- » **Development of B31.8 chapter for hydrogen pipelines ahead of 2026 edition**
- » Sour service can be used as a template for the update
- » Mirror the approach for CO₂
- » Other gases (e.g. N₂, O₂, etc.) may need similar chapters
- » Sections of B31.8 are already incorporated in 49 CFR 192 (ASME B31.12 not referenced in regulation)
- » Note: ASME additionally elected to move Power Piping elements to B31.1 and Process piping elements to B31.3 as well

Implementation Plan for Pipelines

- » PRCI EFI has funded a project to write the new exception chapter of ASME B31.8 on ASME's behalf.
 - Work will include other international research groups work in the space
 - PRCI EFI will engaged the B31.12 and ASME B31.8 committee during the project to ensure industry consensus is achieved
 - ASME and PRCI EFI will jointly discuss the pending changes with PHMSA
 - Similar to recently approved CO2 chapter
- » Work product will be provided to ASME B31.8 with sufficient time for review and approval ahead of the 2026 edition's publication

Background for PRCI's Emerging Fuels Institute and the Consensus Engineering Requirement Project

What is the Emerging Fuels Institute?

- » The Emerging Fuels Institute (EFI) was started by Pipeline Research Council International (PRCI) and has 23 corporate members
- » PRCI/EFI performed a state-of-the-art study related to emerging fuels, specifically hydrogen, in 2020 to identify gaps for closure with subsequent research.
- » Target areas are: 1) Transmission and distribution pipeline integrity, 2) Safety, 3) End-use, 4) Metering & gas quality, 5) Network management & compression, 6) Maintenance & inspection, 7) Hydrogen-natural gas separation, and 8) Underground gas storage.
 - EFI Summaries by topic: <https://www.prci.org/Research/JEFI/222296/EFI-00-01/239815/248383.aspx>
- » PRCI/EFI expects to spend ~\$9MM between 2022 and 2025 to close the gaps identified in the 2019 report
 - EFI is also leveraging work performed by national labs and joint industry projects
- » PRCI/EFI desires to imbed these learnings in ASME B31.8/B31.12 or equivalent industry standard.

Structure for Development of Hydrogen Consensus Engineering Requirements

» The new chapter was broken into seven Work Packages

- 1) General (Introduction, scope, intent)
- 2) Materials and Equipment
- 3) Welding
- 4) Design, installation, and testing
- 5) Operations and maintenance
- 6) Repurposing
- 7) Non-mandatory appendices

Stakeholder Engagement – Groups Involved

- » American Petroleum Institute (API)
- » American Society of Mechanical Engineer (ASME)
- » Australian Pipelines and Gas Association (APGA)
- » Canadian Standards Association (CSA)
- » European Pipeline Research Group (EPRG)
- » Pipeline and Hazardous Materials Safety Administration (PHMSA)

Significant technical team representing the pipeline industry

Tracking

ASME B31.8-2022	Add Gaseous H to the Scope of B31.8
PRESENT TEXT	PROPOSED CHANGES
Background The move toward emerging fuels, in particular the use of hydrogen, requires the need for hydrogen transportation pipeline systems. These systems may operate with pure hydrogen or blends of hydrogen and natural gas. This proposal is to include gaseous hydrogen and hydrogen blends into the scope of the ASME B31.8 Code. Guidance currently exists in ASME B31.12 for transmission pipelines. Following review and agreement within the ASME B31 committees, the guidance requires revision and moving to ASME B31.8. This aligns with the ongoing project to include CO2 in ASME B31.8. The intent is to include hydrogen in a new chapter X, with each clause identified with a 'H'. Due to synergies with Sour service, Chapter X will be developed using the content of ASME B31.8 and ASME B31.8 Chapter IX as the foundation. This document is an expectation document. Only clauses that are amended, removed, or new clauses are included. All other guidance remains the same as per ASME B31.8. Red is replacement of the current content in ASME B31.8. Green is content from ASME B31.8 Chapter IX (amended if required). Blue is a new content to ASME B31.8 (Based on state of the art and guidance from ASME B31.12 brought across) Hyperlinks included to rationale for specific changes	
820 WELDING (incorrectly included in B821.1 when it should have been B820) ***	H820 WELDING HYDROGEN GAS PIPELINES [add] This section addresses the welding of pipe in hydrogen gas and hydrogen gas blend service in both wrought and cast steel materials. [add] Specific material requirements pertaining to hydrogen gas and hydrogen gas blend service in sections 841 and 842 apply.
821.1 Welding Processes (incorrectly included in B821.2 when it should have been B821.1) ***	H821.1 Welding Processes [add] This paragraph does not apply to the welding of the seam in the manufacture of pipe.

Discuss Next Steps for ASME B31.8 Hydrogen Task Group

Covers Updates to ASME B31.8 and B31.8S

B31.8 Hydrogen Task Group - Overview

- » In June 2023, ASME B31.8 established a hydrogen task group to update B31.8 and B31.8S for hydrogen
 - This is complementary to the CO2 efforts
 - Taylor Shie (Shell) as Chair
 - Simon Slater (Rosen) as Vice Chair
- » There are currently 14 voting members, 9 contributing members, and 12 visitors
 - PHMSA is represented as voting and contributing members

B31.8 Hydrogen Task Group - Timeline

- » August 1st, 2024 – CER Project Release to the public for free on PRCI.org
- » Late August – PRCI/EFI Kickoff meeting for B31.8S Update
- » October 4th, 2024 – Start first ballot for ASME comments on B31.8 Chapter
- » October 2024 to April 2026 – Work, update, and ballot revisions to B31.8 and B31.8S
- » April 15th, 2026 – B31 Standards Committee approval required to make 2026 edition for B31.8 and B31.8S

B31.8 Hydrogen Task Group - Remaining Points of Discussion

- » Definition of material equivalence
- » Use of residual stress in fatigue calculations
- » Fracture toughness testing best practice
- » Crack growth under static load best practice
- » Repair options for hydrogen
- » Response criteria for dents
- » Use of 30% SMYS as limit for reduced qualification/inspection criteria and defining limit for low stress option

B31.8 Hydrogen Task Group - Utilization of PHMSA Research

- » Intent is to incorporate learnings from PHMSA research in real time
- » Determining the Required Modifications to Safely Repurpose Existing Pipelines to Transport Pure Hydrogen and Hydrogen-Blends
 - <https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=978>
- » Review of Integrity Threat Characterization Resulting from Hydrogen Gas Pipeline Service
 - <https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=985>
- » Investigate Damage Mechanisms for Hydrogen and Hydrogen/Natural Gas Blends to Determine Inspection Intervals for In-Line Inspection Tools
 - <https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=1009>
- » Determining Steel Weld Qualification and Performance for Hydrogen Pipelines
 - <https://primis.phmsa.dot.gov/matrix/PrjHome.rdm?prj=976>

Discussion

Example Rationale

» H821.3 Weld acceptance

» Cracks that can be identified are not permitted in hydrogen pipelines. Hydrogen diffuses to the plastic zone that forms in front of a crack and degrades the resistance to crack propagation. There is a reference in API 1104 that crater cracks and star cracks are permitted and these are not deemed acceptable for hydrogen pipelines.

» Industry guidance on the issues with under matching welds and HAZ softening needs to be taken into consideration. Undermatching girth welds and/or HAZ softening make girth welds sensitive to experiencing strain localization and tensile overload failure when displacement controlled external forces act on the pipeline (e.g. ground movement). The effect could be even more critical for hydrogen pipelines, considering the effect of Hydrogen on fracture toughness and ductility and therefore could impact the critical defect sizes and the failure strain. The generally accepted approach to mitigate strain localization in welds has been to overmatch girth welds and control weld HAZ width through weld heat input control. This means that weld metal hardness is typically higher than the unaffected base metal.

Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn



Exceptional service in the national interest

Hydrogen-Assisted Fracture of Hard Spots

Joe Ronevich, Milan Agnani, Chris San Marchi

Sandia National Laboratories, Livermore, CA, USA

Study Group on Materials Testing and Qualification for Hydrogen Service

August 2, 2024

SAND2024-09676PE

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.





Hard spots in pipeline steels are of higher concern in presence of hydrogen

- Occur typically in vintage pipes (pre-1970)
 - Localized, unintentional quenching of steel during manufacturing
- API 5L defines hard spot as hardness exceeding 327 HBW ($\sim 345 \text{ HV}_{10}$) and if larger than 50 mm, it is designated a defect.¹
- Can also be local in welds, particularly low frequency ERW

Table – Description of known hardness anomalies (Ref [2])

	Type 1	Type 2	Type 3
Description	A hardness anomaly that is typically circumferential in nature. These hardness anomalies tend to be a mixed microstructure and the increased hardness is typically apparent only on one surface.	A hardness anomaly that tends to be a mixed microstructure with martensite and are typically through-wall.	A hardness anomaly that typically has a mixed microstructure with martensite and the increased hardness is apparent only on one surface. Type 3 anomalies can sometimes be identified as a welded repair.
Max. validated hardness to date (HB)	320	400	370
Pipes types the anomaly types have been found on to date	A.O. Smith EFW, Bethlehem DSAW	A.O. Smith EFW, Bethlehem DSAW, Consolidated Western DSAW, Mannesmann DSAW, National Tube DSAW, Kaiser DSAW	A.O. Smith EFW, Bethlehem DSAW, Consolidated Western DSAW, Mannesmann DSAW, National Tube DSAW.
Etching			

Table 1: Description of known hardness anomalies

¹<https://www.rosen-group.com/en/expertise/experience-center/articles/the-hard-thing-about-hard-spots>

²K. Tran, S. Slater, "Managing the thread of hard spots in gas transmission pipelines," Pipeline Technology Journal 3/2023



Most codes / standards suggest limiting hardness to < 250 HV

- ASME B31.12¹ has general hardness testing acceptance criteria **235 HV** and **248 HV** for production pipeline welds
- EIGA IGC Doc 121/04/E² recommends max hardness of **248 HV** for welds/HAZ
- NACE MR0175³ is use for selection of materials for H₂S and specifies max **250 HV**

Is 250 HV appropriate for hydrogen pipelines?

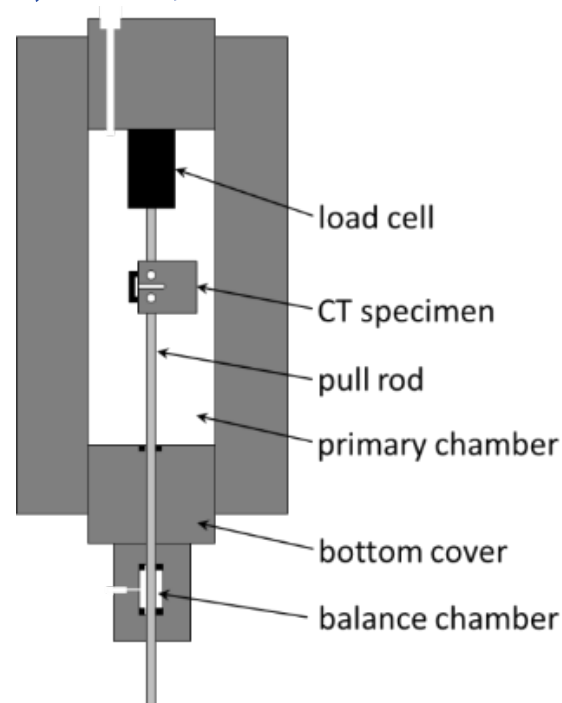
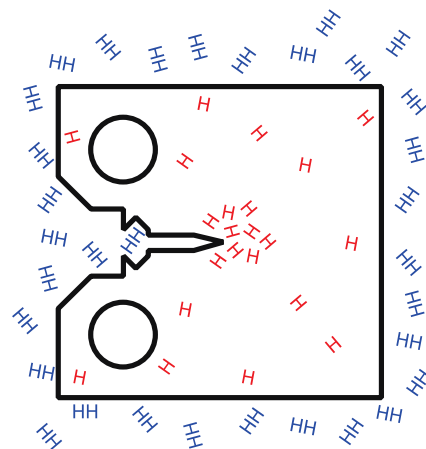
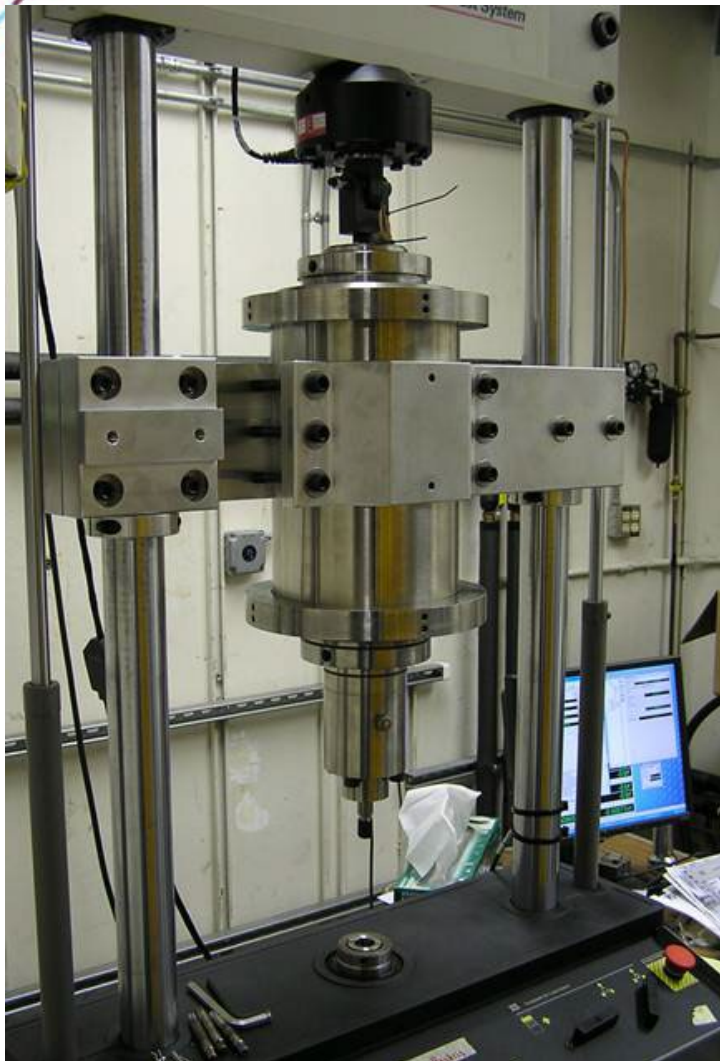
[1] ASME. B31.12-2019 Hydrogen Piping and Pipeline ASME Code from Pressure Piping New York, NY: ASME; 2019.

[2] Association EIG. Hydrogen Transportation Pipelines. IGC Doc 121/040E: EIGA; 2004.

[3] ANSI. ANSI/NACE MR0175/ISO 15156: Petroleum and natural gas industries - Materials for use in H₂S-containing environments in oil and gas production. ANSI / NACE; 2015.



Fracture testing performed in high-pressure hydrogen gas



Instrumentation

- Internal Load cell and displacement on specimen
- Direct Current Potential Difference (DCPD)

Fracture: ASTM E1820 (Elastic-Plastic)

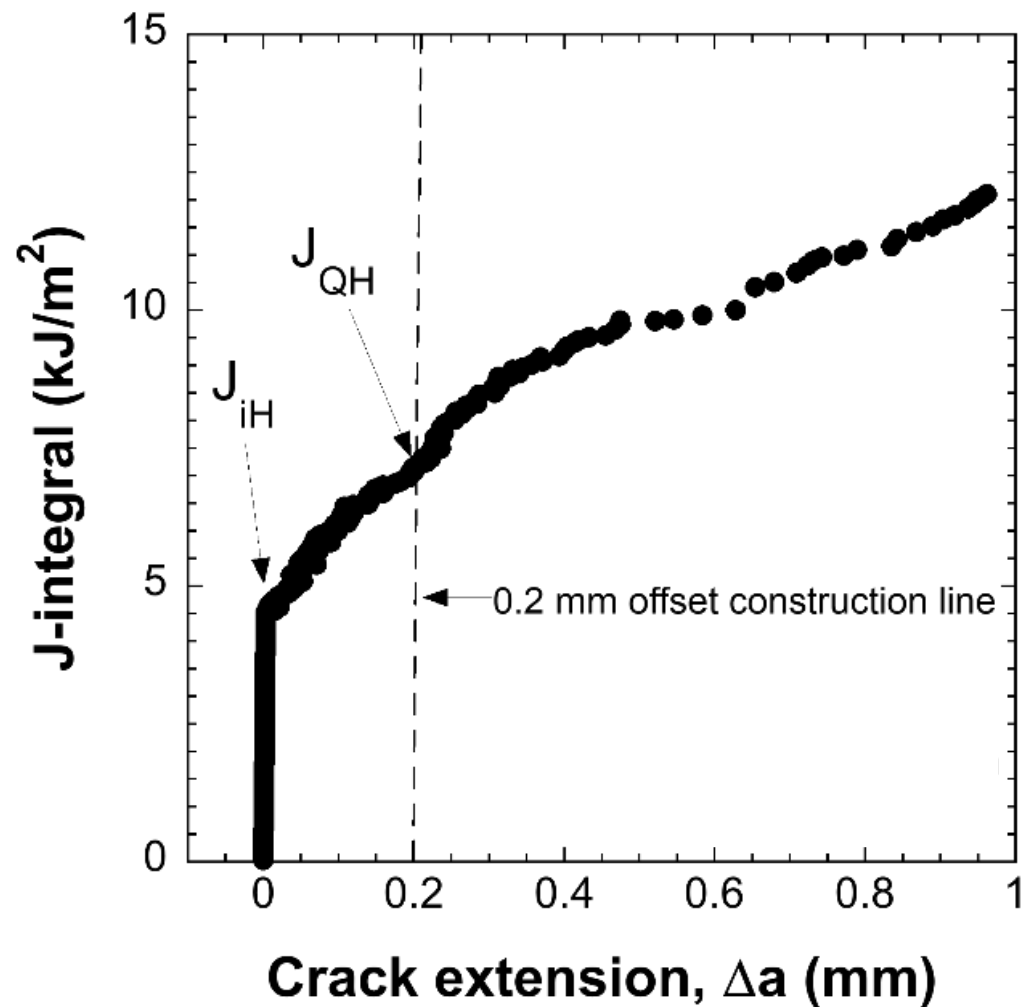
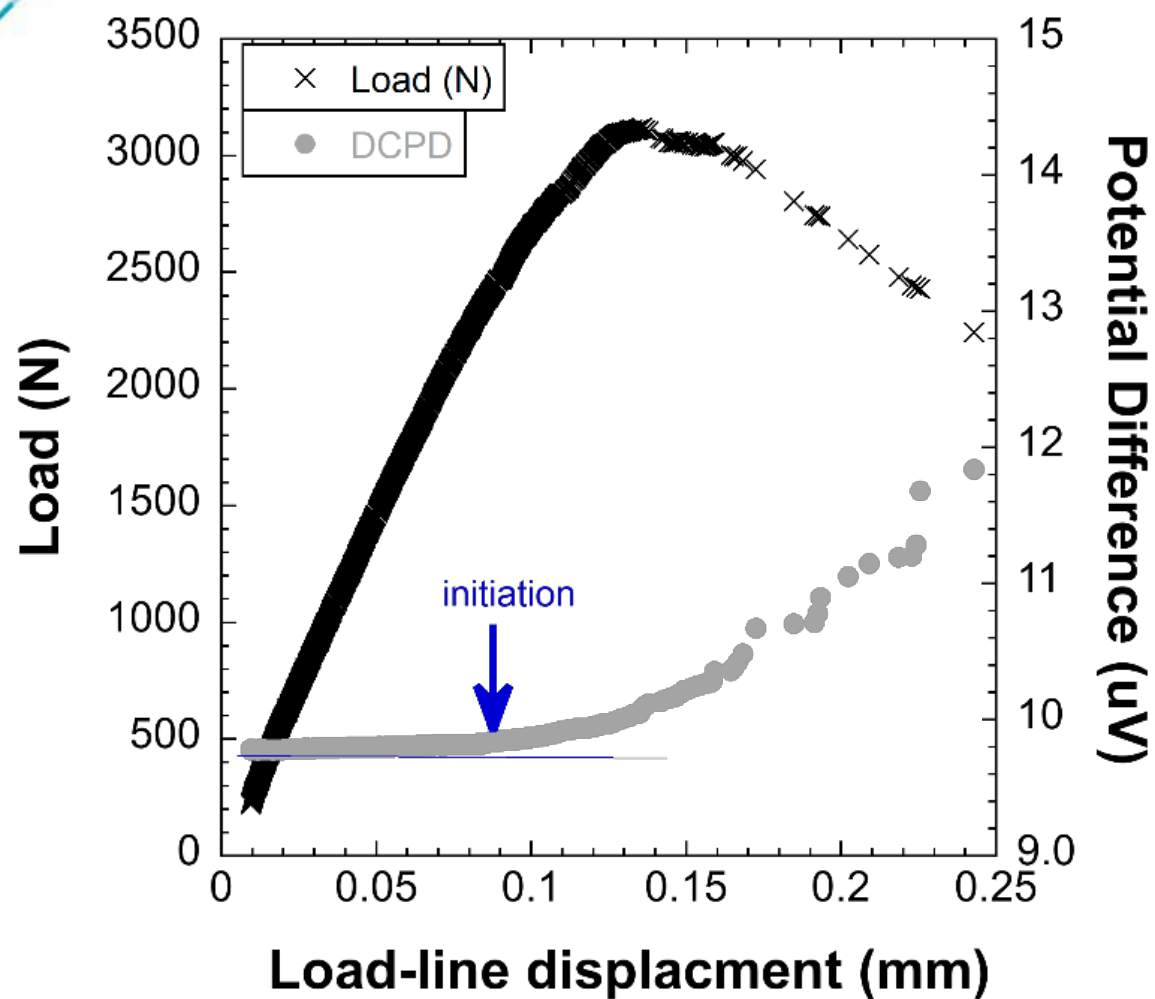
- Loading rate ($\sim 0.5 \text{ MPa m}^{1/2} \text{ min}^{-1}$)
 - CSA CHMC-1
- Direct Current Potential Difference (DCPD) for crack length monitor

Environment

- Air
- Pure H_2 (210 bar)



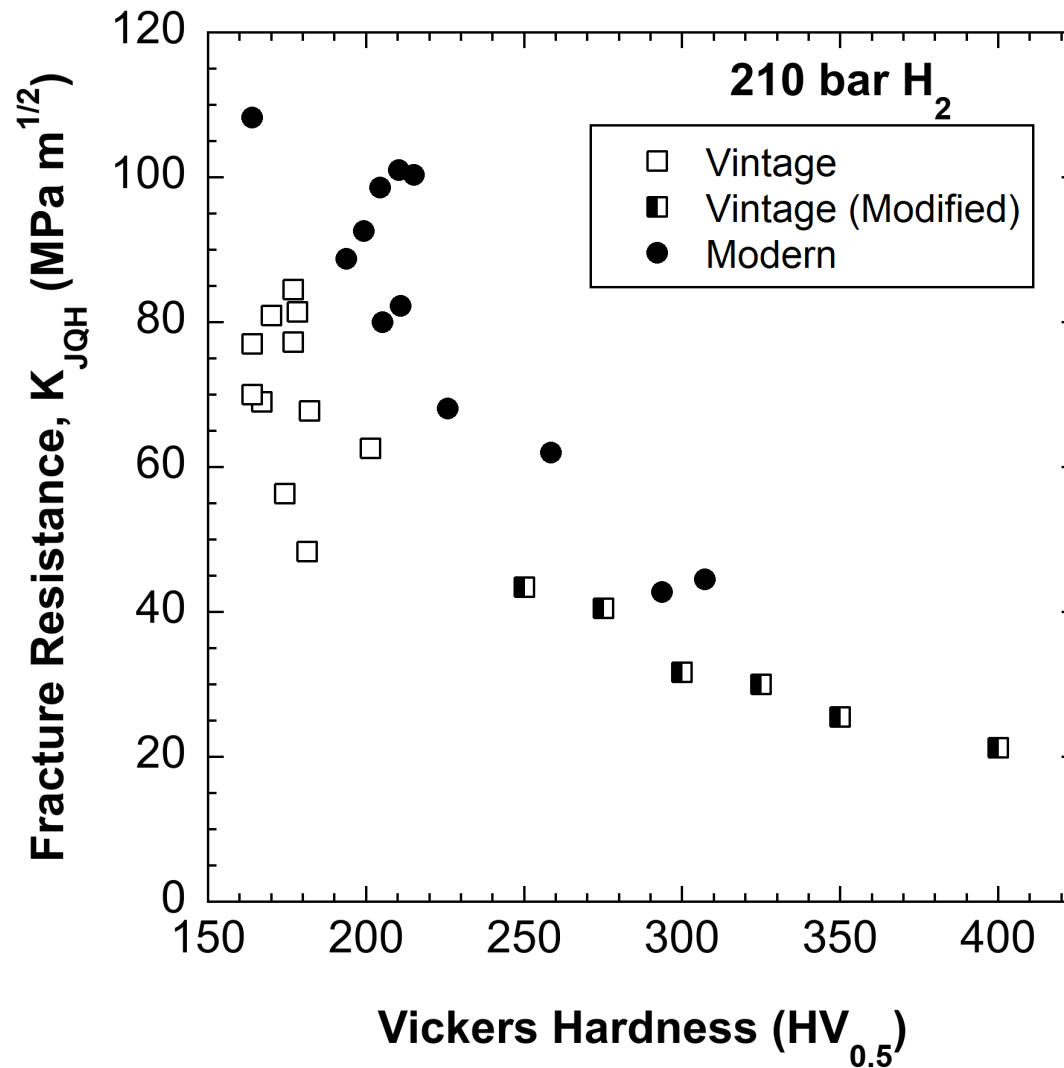
Rising displacement fracture testing was used to determine fracture initiation (J_{iH}) and fracture resistance (J_{QH}) in gaseous H_2



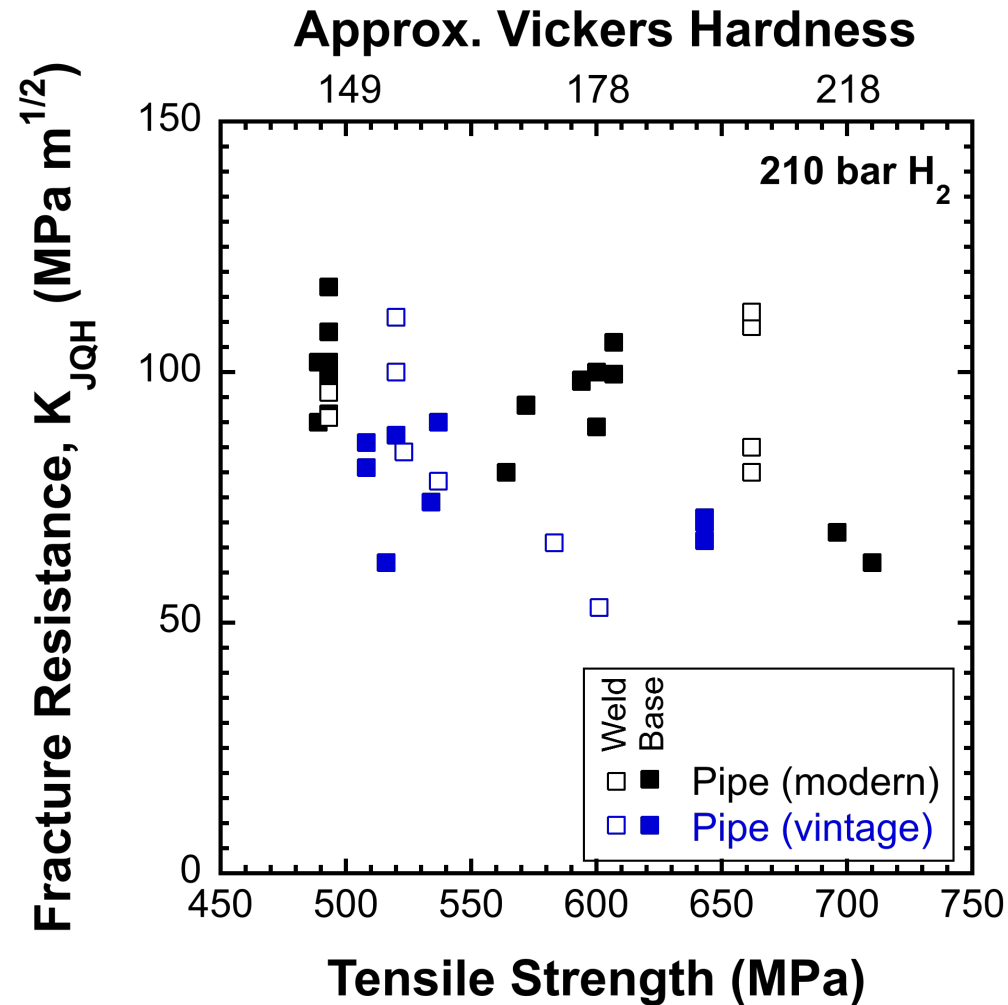
$$K_{JQH} = \sqrt{\frac{E J_{QH}}{(1-\nu^2)}} \text{ Convert J to K}$$



General trend shows fracture resistance (K_{JQH}) decreases with hardness for base metals



At hardness $< 200 \text{ HV}_{0.5}$, too much scatter to show a clear lower bound relationship of K_{JQH} and hardness



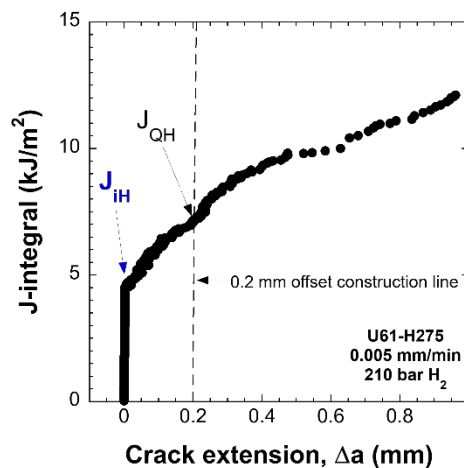
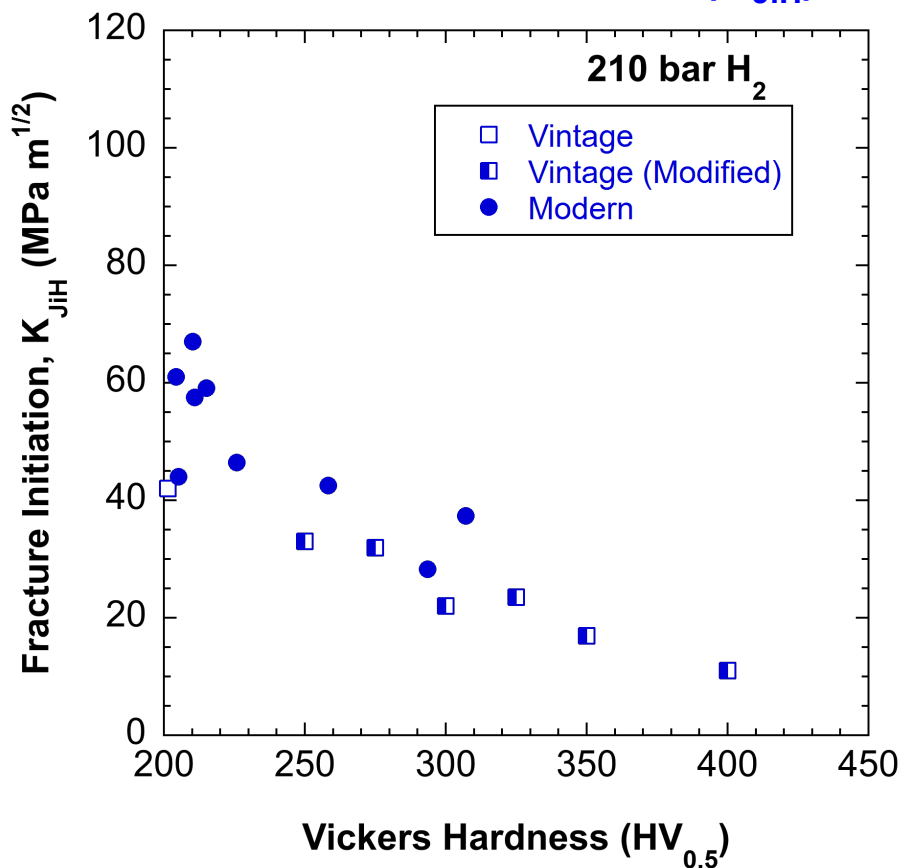
- Welds show similar fracture behavior to base metals
- Vintage materials have lower fracture resistance (in general)



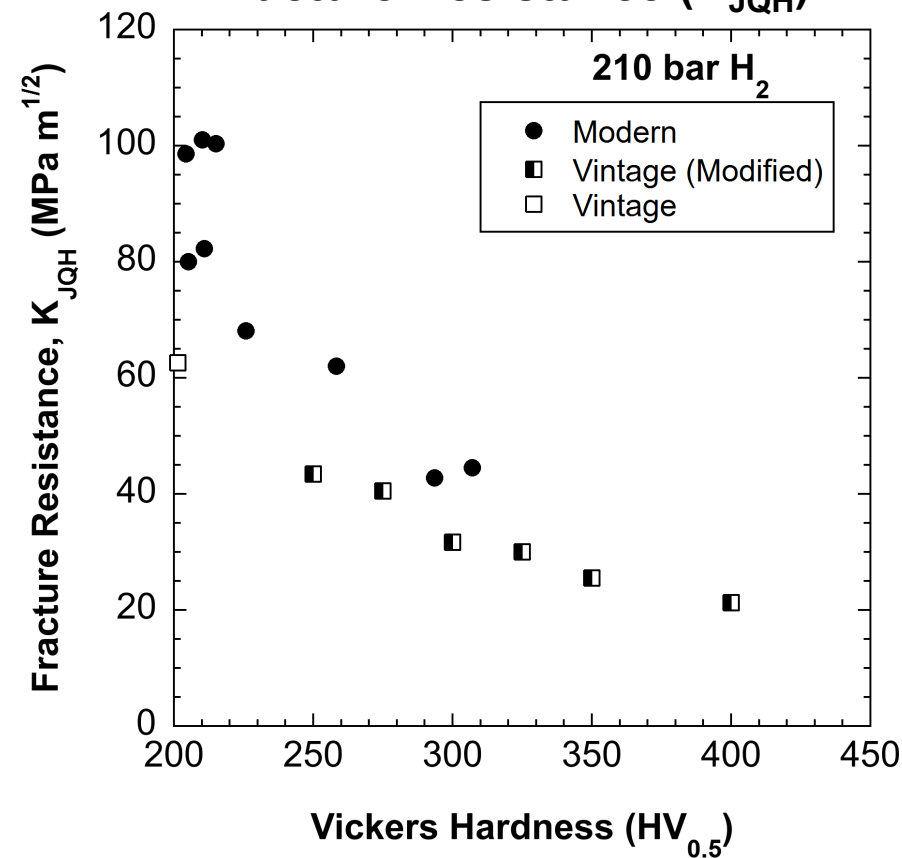
Fracture initiation (K_{JiH}) and fracture resistance (K_{JQH}) decreases steadily at higher hardness

Data from ref: Ronevich, IPC2024-133937

Fracture Initiation (K_{JiH})

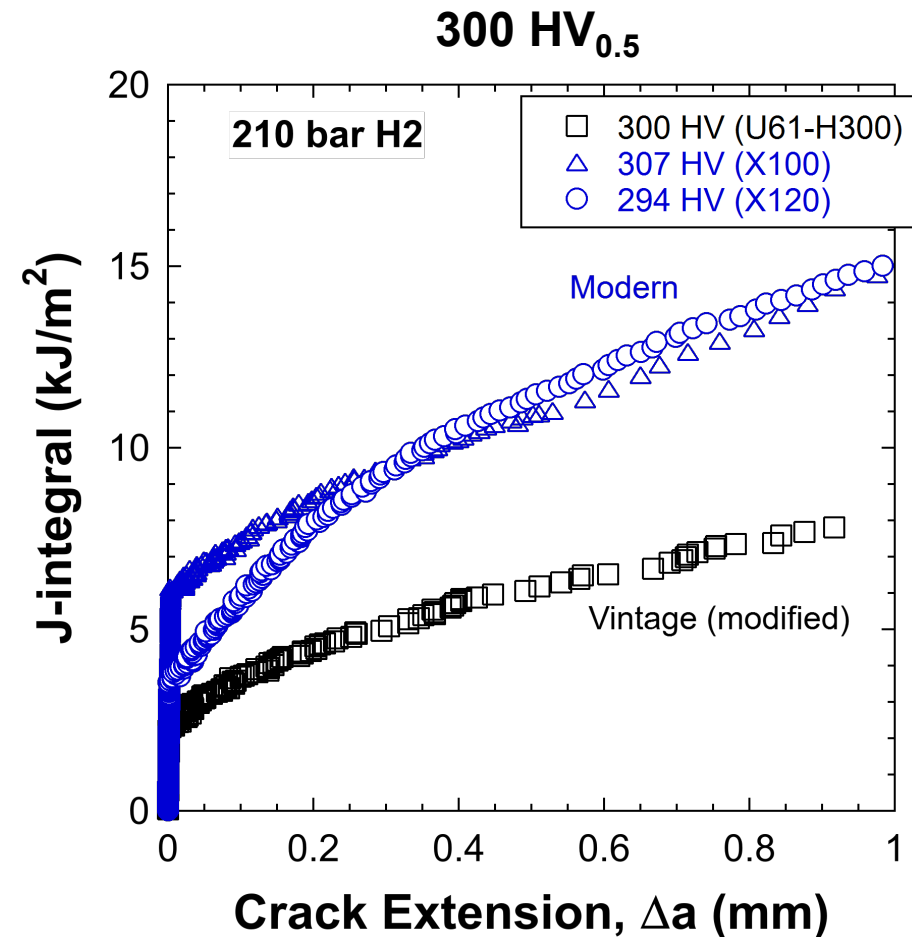
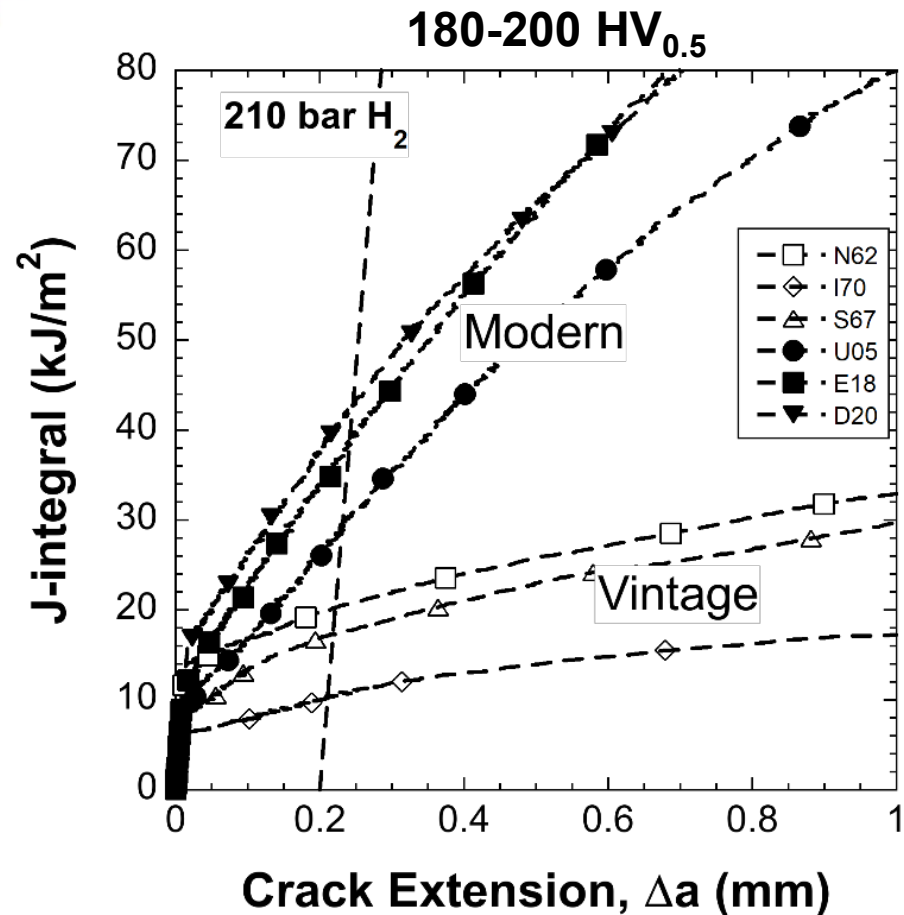


Fracture Resistance (K_{JQH})



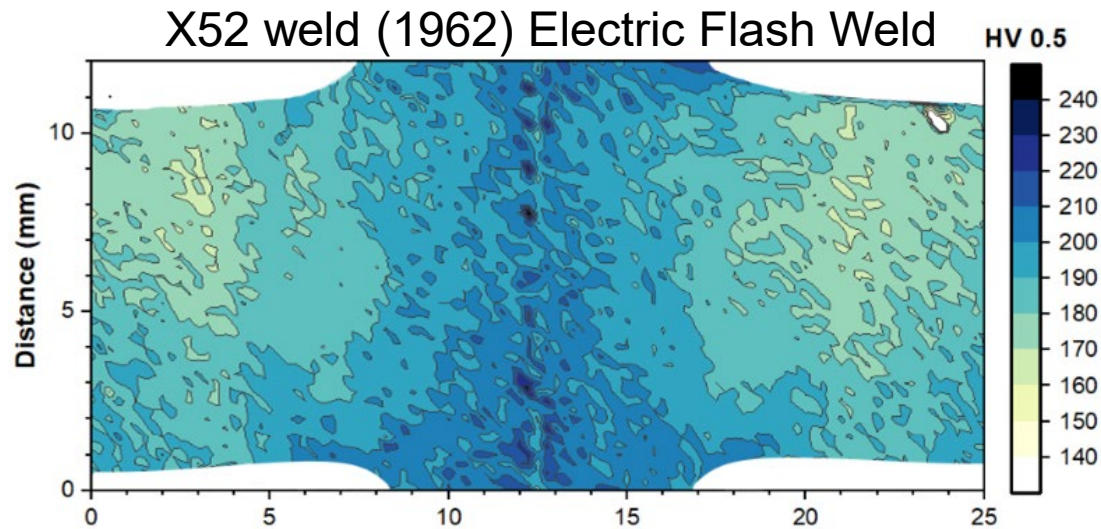
Less scatter in fracture initiation (K_{JiH}) values which trend well with hardness

For same hardness range, modern steels exhibit improved tearing modulus and higher fracture resistance compared to vintage steels



- Fracture initiation (K_{JiH}) values are consistent for a given hardness
- Fracture resistance (K_{JQH}) and tearing modulus is greater for modern steels

What is the appropriate hardness value for gradient microstructures?



Hardness varies depending on area examined:

- Base metal: 150-180 HV_{0.5}
- HAZ: 160-190 HV_{0.5}
- Weld: 180-240 HV_{0.5}

Local hard spots might account for lower toughness of welds.

How big does a hard spot have to be to influence fracture resistance (K_{JQH})?

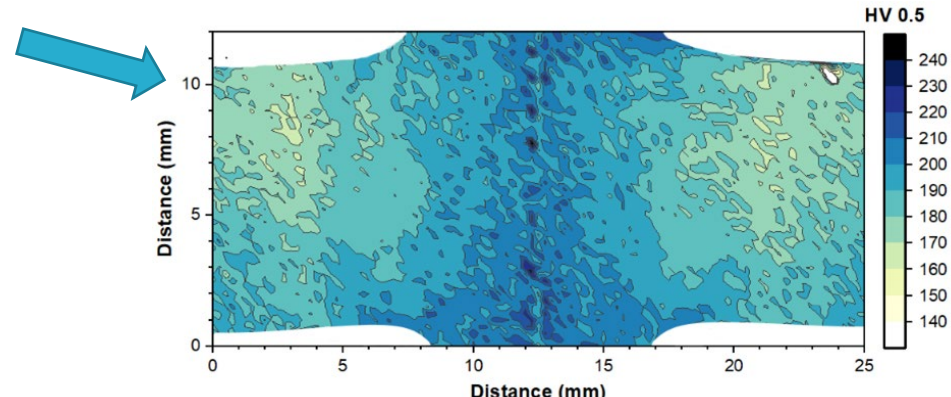


Summary

- Fracture initiation (K_{JiH}) and resistance (K_{JQH}) in hydrogen decreases as hardness increases
- For equivalent hardness, modern steels exhibit higher fracture resistance (K_{JQH}) than vintage (modified) microstructures
- Fracture initiation is controlled by hardness
 - Crack propagation (tearing modulus) is dependent on era of steel fabrication

Open questions:

- How large does a hard spot need to be to affect fracture resistance?
- What is the appropriate hardness limit for use in hydrogen?
- How does one measure hardness, particularly what is the hardness of a microstructure with gradients?



Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn



Exceptional service in the national interest

BRIEF TUTORIAL ON HELPR AND DISCUSSION ON PROBABILISTIC TOOLS FOR FRACTURE ASSESSMENT

Presenter: Benjamin Schroeder

Study Group on Materials Testing and Qualification for Hydrogen Service

Discussion Topic for Standards for Material Testing and Hydrogen Infrastructure Session

Friday, August 2nd 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.

WHAT IS HELPR?



Hydrogen Extremely Low Probability of Rupture (HELPR) is a modular probabilistic fracture mechanics platform developed to assess structural integrity of natural gas infrastructure for transmission and distribution of hydrogen natural gas blends. HELPR contains fatigue and fracture engineering models allowing fast computations, while its probabilistic framework enables exploration and characterization of the sensitivity of predicted outcomes to uncertainties of the pipeline structure and operation.

Publicly available

GUI Interface

Windows and Mac installers available

- <https://helpr.sandia.gov>

Open-source distribution

- <https://github.com/sandialabs/helpr>
- Sphinx documentation of code
 - <https://sandialabs.github.io/helpr/>



HELPR GUI Interface

The screenshot displays the HELPR GUI interface for 'Probabilistic Fatigue and Fracture Analysis for Pressurized Cylindrical Shells'. The interface includes a menu bar (File, Demo, Help), a toolbar with icons for settings, save, undo, and redo, and a main panel with several sections:

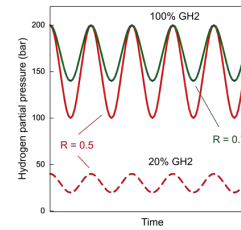
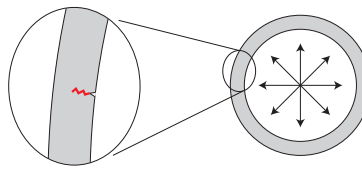
- Analysis Settings:** Analysis name (Probabilistic demo), Study type (Probabilistic), Random seed (1234567).
- Probabilistic:** Aleatory samples (50), Epistemic samples (0).
- Geometry:** Outer diameter (in, Uniform, Nominal value: 22, Uncertainty: Aleatory, Lower bound: 21.9), Wall thickness (in, Uniform, Nominal value: 0.281, Uncertainty: Aleatory, Lower bound: 0.271), t/R (0.026).
- Material Properties:** Yield strength (psi, Deterministic, 52000), Fracture resistance (MPa-m^{1/2}, Deterministic, 55).

On the right side, there is a table of results:

Analysis Type	Time	Status
Deterministic	00:00:04	✓
Probabilistic demo	00:00:11	✓
Sampling demo	00:00:11	✓
Bounding demo	00:00:09	✓

At the bottom, there is a blue 'Analyze' button.

TECHNICAL UNDERPINNING



Stress intensity factor (K) used for stress at crack tip

- Analytical Anderson textbook solutions (2nd edition)
- Considering internal elliptical and infinite pressure driven cracks.
- API 579-1 internal and external cracks in upcoming V2.0.0

Fracture/fatigue mechanisms:

Crack growth due to **pressure cycling** (internal load)

- Crack growth rates determined using ASME B31.12 Code Case 220 bounding curves with hydrogen partial pressure term

Effect of H₂ on fracture and fatigue properties

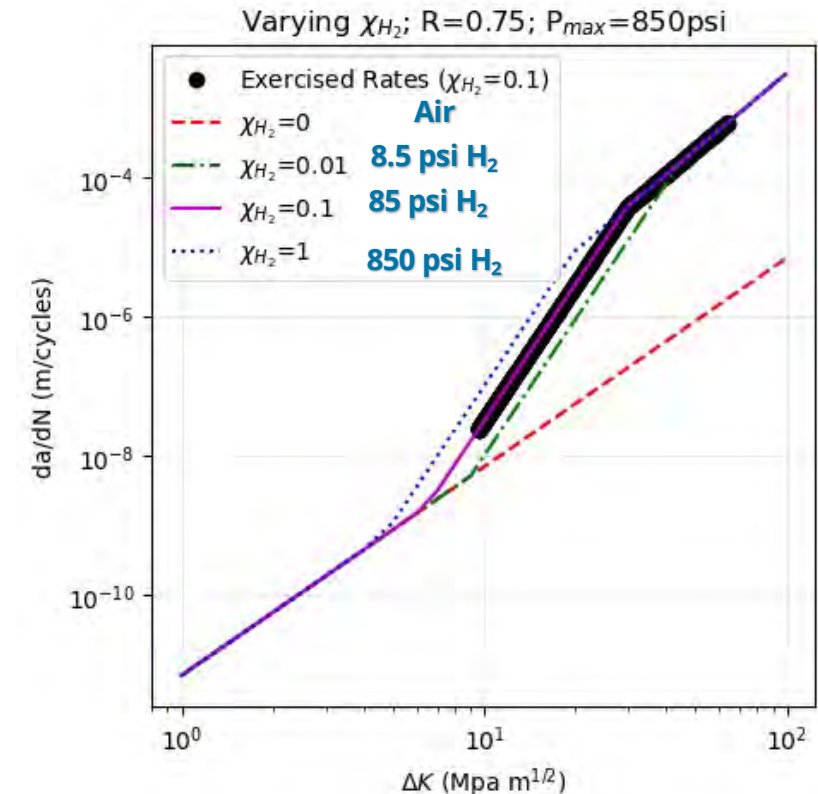
- H₂ partial pressure impacts crack growth rate & reduces fracture resistance (**user input**)
- H₂ correction term included in crack growth curves

Evolving crack in pipe walls until crack size become unstable

- Unstable / critical crack size **a(crit)** is the crack depth at which the applied K (K_{max}, due to hoop stress) is equal to fracture resistance (K_{IH}) of the material
- Constant crack depth to crack length ratio assumed (a/2c)

Failure Assessment Diagram (**FAD**) used for assessment of material failure

Crack Growth Rate Curves



HELPR TUTORIAL: USER INPUTS



Users specify analysis inputs as deterministic or an uncertainty distribution

User inputs:

- Outer diameter } Geometry
- Wall thickness }
- Yield strength } Material Properties
- Fracture resistance }
- Max pressure } Operating Conditions
- Min pressure }
- Temperature }
- H2 volume fraction }
- Crack depth } Crack Specification
- Crack length }

Hydrogen Extremely Low Probability of Rupture (HELPR)

File Demo Help

Probabilistic Fatigue and Fracture Analysis for Pressurized Cylindrical Shells

Analysis Settings

Analysis name: Probabilistic demo

Study type: Probabilistic

Random seed: 12345

Probabilistic

Aleatory: 50

Samples: 0

Geometry

			Nominal value	Uncertainty	Lower bound
Outer diameter	in	Uniform	22	Aleatory	21.9
Wall thickness	in	Uniform	0.281	Aleatory	0.271

t/R: 0.026

Material Properties

Yield strength	psi	Deterministic	52000
Fracture resistance	MPa-m ^{1/2}	Deterministic	55

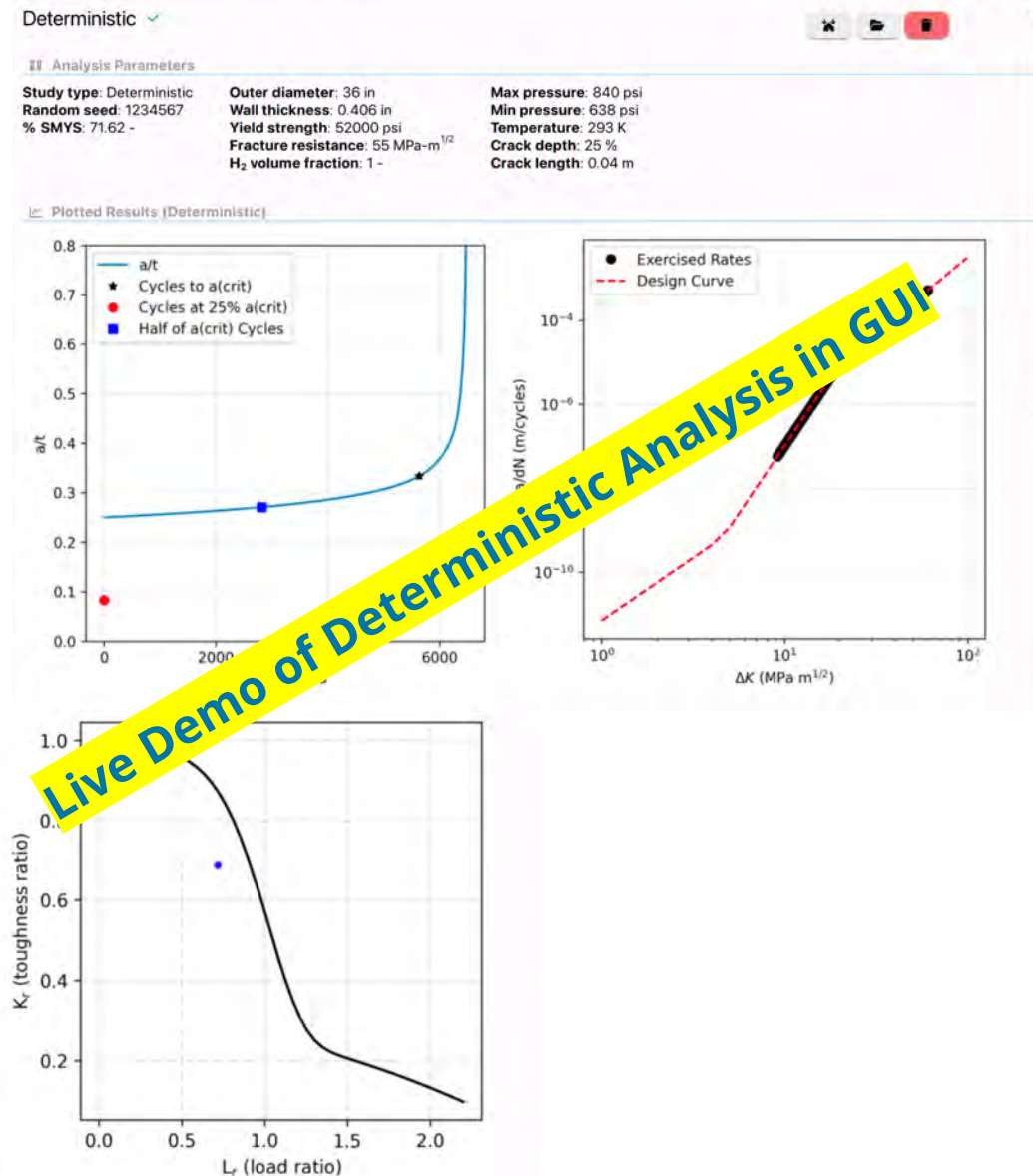
Analyze

HELPR Hydrogen Extremely Low Probability of Rupture

Deterministic	00:00:04	✓
Probabilistic demo	00:00:11	✓
Sampling demo	00:00:11	✓
Bounding demo	00:00:09	✓

Live Demo of User Inputs in GUI

HELPR TUTORIAL: DETERMINISTIC ANALYSIS



HELPR TUTORIAL: PROBABILISTIC RESULTS



Probabilistic demo ✓

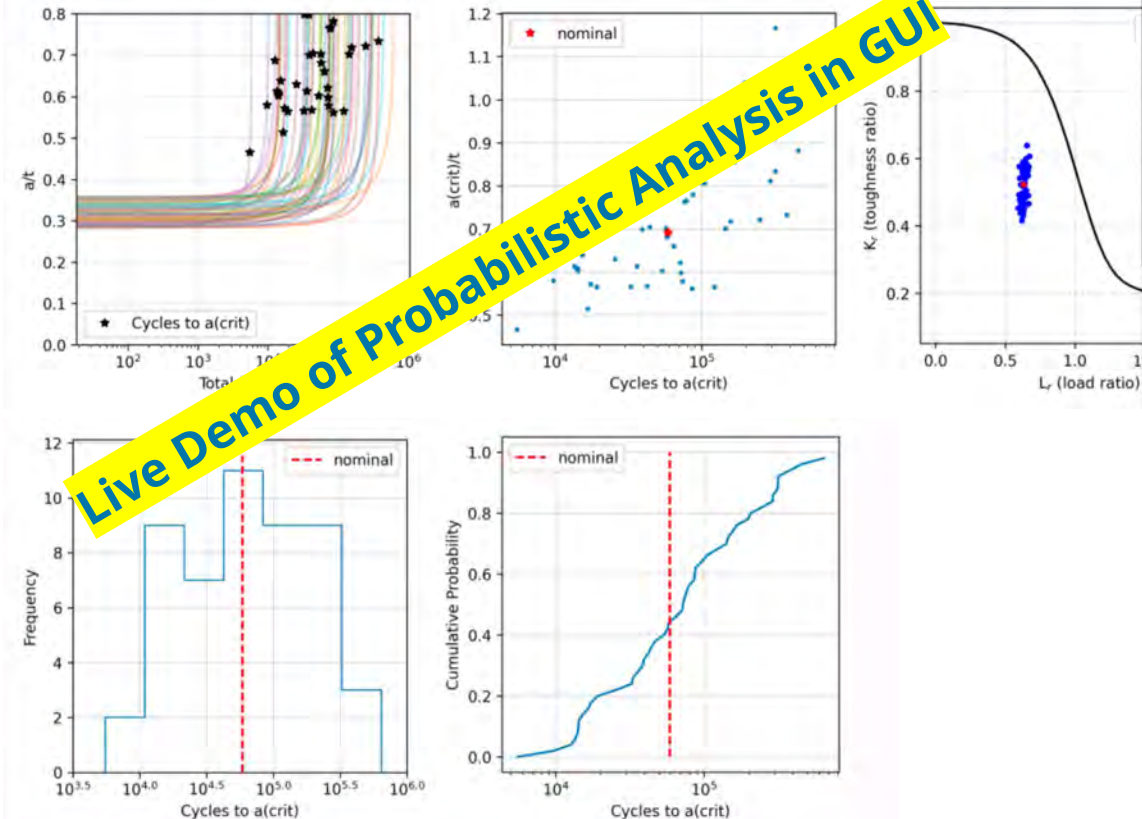
Analysis Parameters

Study type: Probabilistic
Random seed: 1234567
Aleatory samples: 50
% SMYS: 63.24 -

Outer diameter: 22 in (Uniform 21.9 to 22.1, aleatory)
Wall thickness: 0.281 in (Uniform 0.271 to 0.291, aleatory)
Yield strength: 52000 psi
Fracture resistance: 55 MPa-m^{1/2}
H₂ volume fraction: 1 -

Max pressure: 840 psi (Normal 840 +/- 20, aleatory)
Min pressure: 638 psi (Normal 638 +/- 20, aleatory)
Temperature: 293 K (Uniform 285 to 300, aleatory)
Crack depth: 32 % (Uniform 28 to 36, aleatory)
Crack length: 0.02 m (Uniform 0.01 to 0.03, aleatory)

Plotted Results (Probabilistic)



Live Demo of Probabilistic Analysis in GUI

HELPR TUTORIAL: PROBABILISTIC RESULTS W/ EPISTEMIC UNCERTAINTY



Probabilistic demo ✓

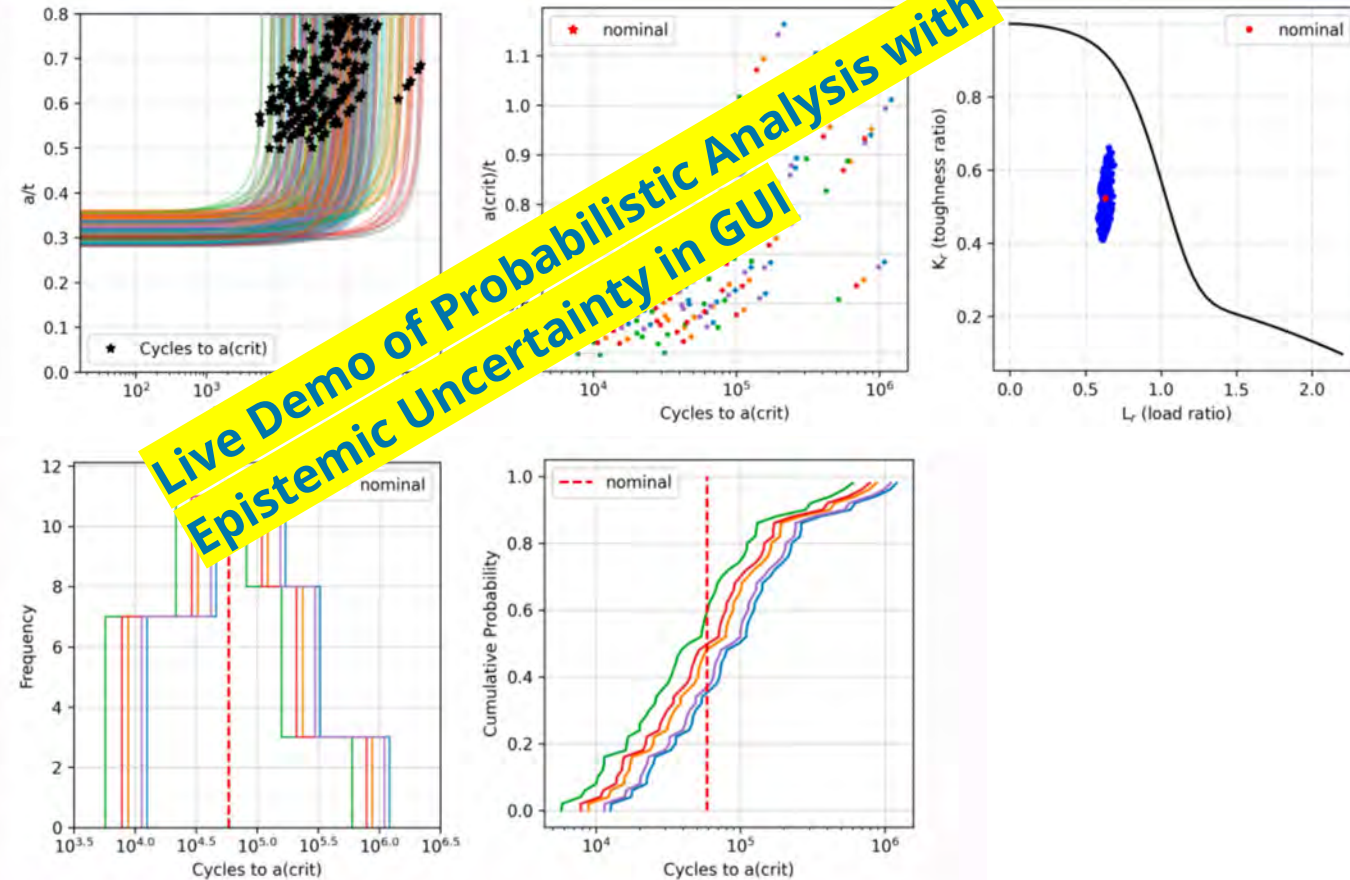
Analysis Parameters

Study type: Probabilistic
Random seed: 1234567
Aleatory samples: 50
Epistemic samples: 5
% SMYS: 63.24 -

Outer diameter: 22 in (Uniform 21.9 to 22.1, aleatory)
Wall thickness: 0.281 in (Uniform 0.271 to 0.291, epistemic)
Yield strength: 52000 psi
Fracture resistance: 55 MPa-m^{1/2}
H₂ volume fraction: 1 -

Max pressure: 840 psi (Normal 840 +/- 20, aleatory)
Min pressure: 638 psi (Normal 638 +/- 20, aleatory)
Temperature: 293 K (Uniform 285 to 300, aleatory)
Crack depth: 32 % (Uniform 28 to 36, aleatory)
Crack length: 0.02 m (Uniform 0.01 to 0.03, aleatory)

Plotted Results (Probabilistic)



HELPR TUTORIAL: SENSITIVITY STUDY



Sampling demo ✓



×

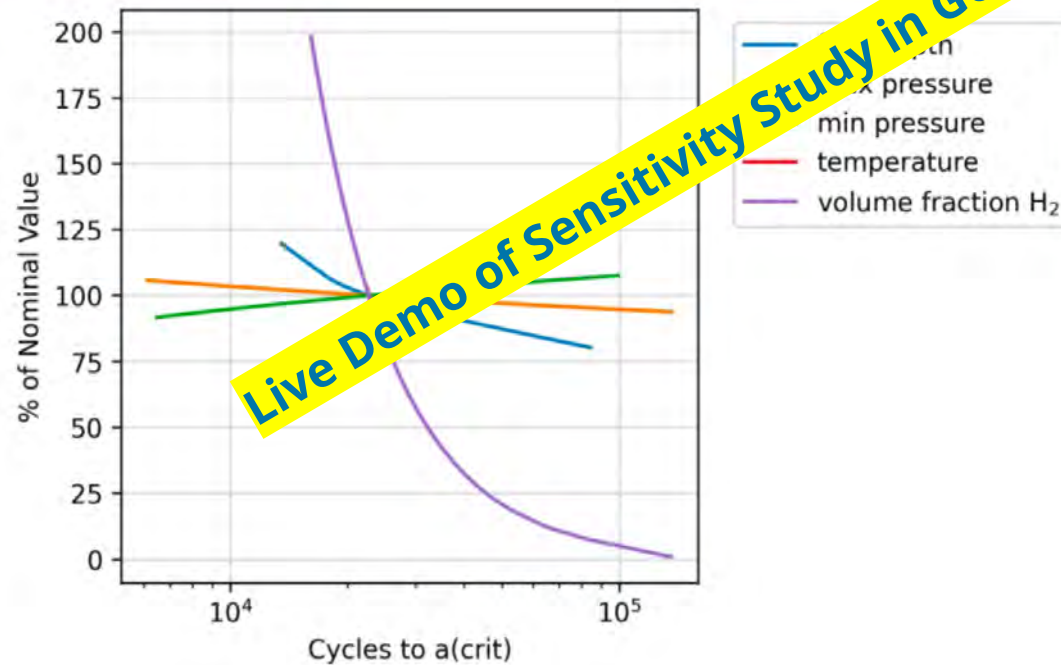
Analysis Parameters

Study type: Sensitivity (Samples)
Random seed: 1234567
Aleatory samples: 50
% SMYS: 71.62 -

Outer diameter: 36 in
Wall thickness: 0.406 in
Yield strength: 52000 psi
Fracture resistance: 55 MPa-m^{1/2}
H₂ volume fraction: 0.1 - (Uniform 0 to 0.2, aleatory)

Max pressure: 840 psi (Normal 840 +/- 20, aleatory)
Min pressure: 638 psi (Normal 638 +/- 20, aleatory)
Temperature: 293 K (Uniform 285 to 300, aleatory)
Crack depth: 25 % (Uniform 20 to 30, aleatory)
Crack length: 0.03 m

Plotted Results (Sensitivity)



HELPR V2.0.0 COMING FALL 2024



API 579-1 K solutions for internal and external cracks

Level 2 FAD from API 579-1

User selection of crack width growth assumption

- *Constant a/c , fixed c , independent c growth*

In-GUI visualization of sample distributions

Interactive results plots

Truncated Normal and Lognormal distributions

Material repository

Bug fixes and user experience improvements

FUTURE CAPABILITY DEVELOPMENT



User specified pressure load profiles

- How to sample probabilistically?

Inspection / Mitigation estimates

- Detection probability a function of size

What types of risk plots / data presentation would be useful?

Support for alternative crack initiation location types dents, bends, ...

What could be changed to make HELPR better fit into your typical workflows?

HELPR is available at help.pr.sandia.gov

QUESTIONS?

Benjamin Schroeder
bbschro@sandia.gov

Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn

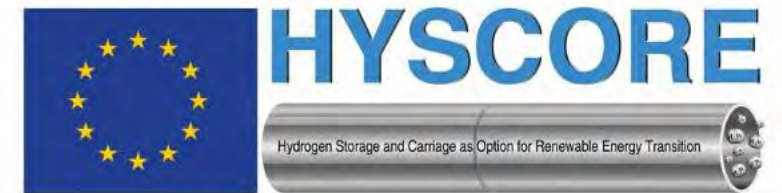
Summary of full scale tests on pipelines

Bostjan Bezensek

2nd August 2024

Sandia Hydrogen Study group

Several full scale H2 tests ongoing at present:



SAFEH2PIPE

Guidelines for material selection and qualification
for safe transportation of
H₂-NG mixtures
in EU pipelines

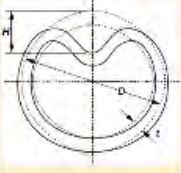
Name Surname
Job Title



Introduction

Aim of the project is to develop guidelines for material selection and qualification process for Safe transportation of H₂ and H₂NG for both new and existing pipelines.

Focus on fitness for service assessments in the presence of damage :

Geometry	Size		3.3b Vintage LSAW	3.2b Modern LSAW	3.1b Modern SMLS	3.3a Vintage LSAW
 Plain Dent	Height 2% of OD (Current B31.12)	H ₂		✓ (weld)		
	Height 6% of OD (criterion for NG)	H ₂	✓	✓		
 Dent-Gouge	Dent: Same as plain dent (6%OD)	Air			✓	
	Gouge: 1 mm deep 300mm long	H ₂			✓	
Corrosion	60%WT; 300mm long	H ₂				✓

The project is funded by EU Research Fund for Coal and Steel (RFCS), GA 101112650.

Project partners

This project involves a multinational collaboration among research centres and industrial operators from different EU Member States. All the partners have a proven expertise in their field of activity, having a long tradition and expertise in both pipeline manufacturing and operation. The partnership is balanced to achieve the activity transfer from R&D to laboratory and then to full industrial scale addition.

The project consortium includes:

- 2 Steel makers (TENARIS, OCAS)
- 2 Linepipe manufacturers (CPW, TENARIS)
- 2 Research centres (CSM, OCAS)
- 1 Integrated energy company (SHELL)
- 1 pipeline technology company (ROSEN)
- 1 pipelines Transmission System Operator (GRTGaz)

In addition, the consortium will take advantage of the presence of the international recognized organisation EPRG (European Research Group) as external advisor.

RINA CSM



CPW



Tenaris Dalmine



OCAS



Rosen



Shell



GRTGAZ

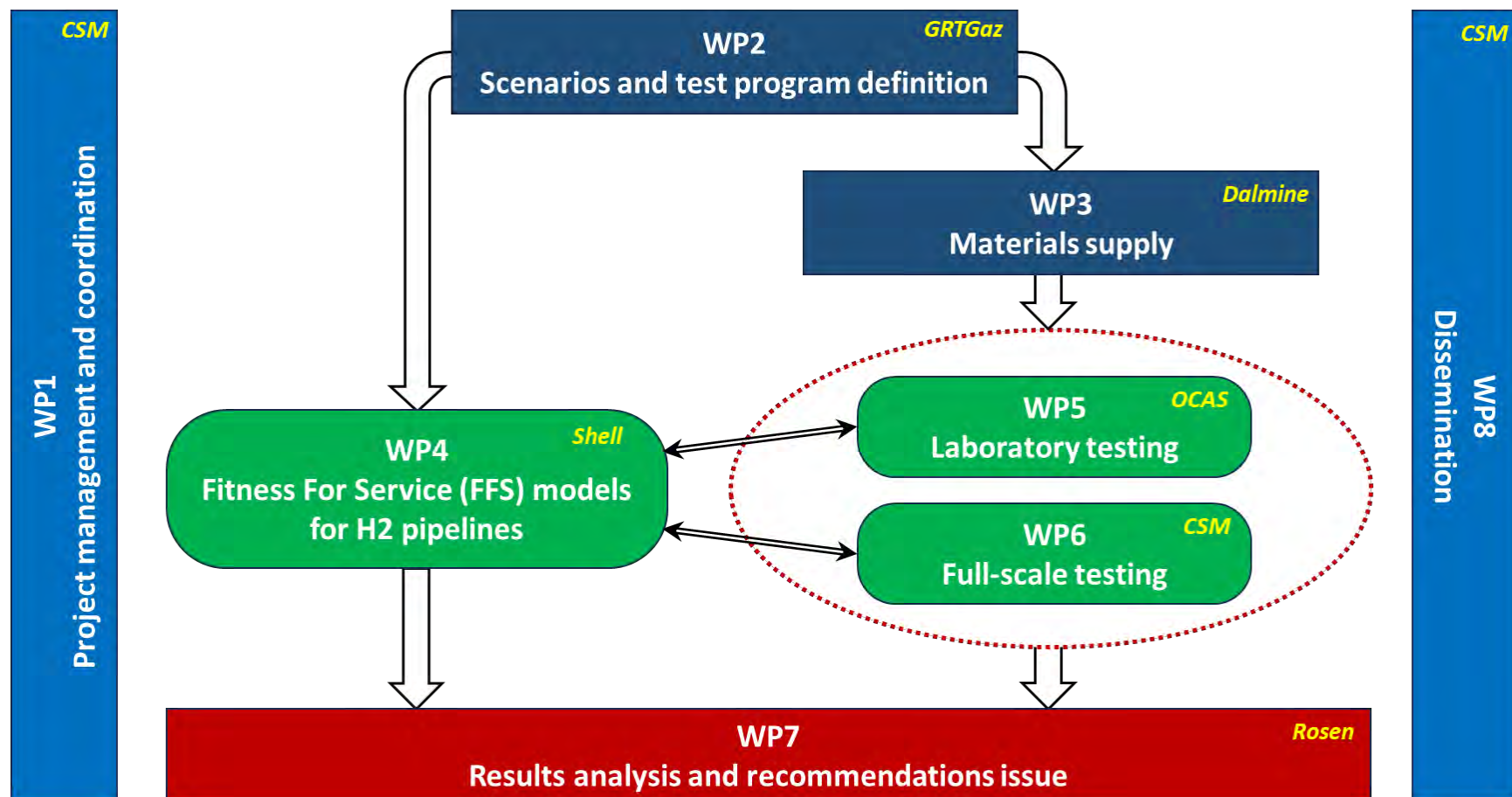


EPRG



Project structure

The project activities are divided into several WPs, arranged in order to allow the integration of all the foreseen activities without duplication and overlapping of works, and organized to achieve the final aim of providing guidelines for material selection and qualification process.



WP3	Test	Material
3.2b	Modern Mech Damage	Corinth 30" x 14.27 mm X65 LSAW
3.1b	Modern Mech Damage	Tenaris 24" x 12.7mm X70 SMLS
3.1b	Air reference Modern Mech Damage	Tenaris 24" x 12.7mm X70 SMLS
3.3b	Vintage Mech Damage	SNAM pipe 26" x 11.13mm X60 LSAW
3.3a	Vintage Corrosion	Shell pipe 36" x 22mm X60 LSAW

Envisaged strategy for full scale tests

Damage creation						
Ref	Test	Material	Defect	Environment	Notes	Step #
1.10	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	1
1.11	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	2
1.12	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	3
1.13	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	4
1.14	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	5
1.15	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	6
1.16	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	7
1.17	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	8
1.18	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	9
1.19	Hydrogen Damage	Carbon Steel	Cracks	High pressure, high temperature, high humidity	Hydrogen embrittlement	10

Rome

Ship to test site (Sardinia)

End caps + H₂

Oxide layer mitigation

Fatigue cycles

Inspect

Burst

Failure Investigation



ILI Inspection
Lingen

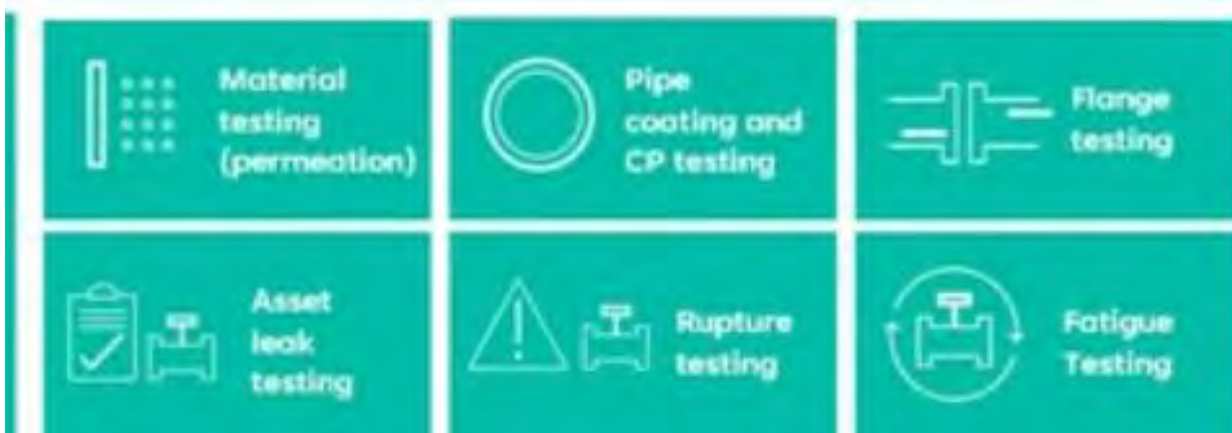
Sister sample
Tenaris Dent
Specimen only





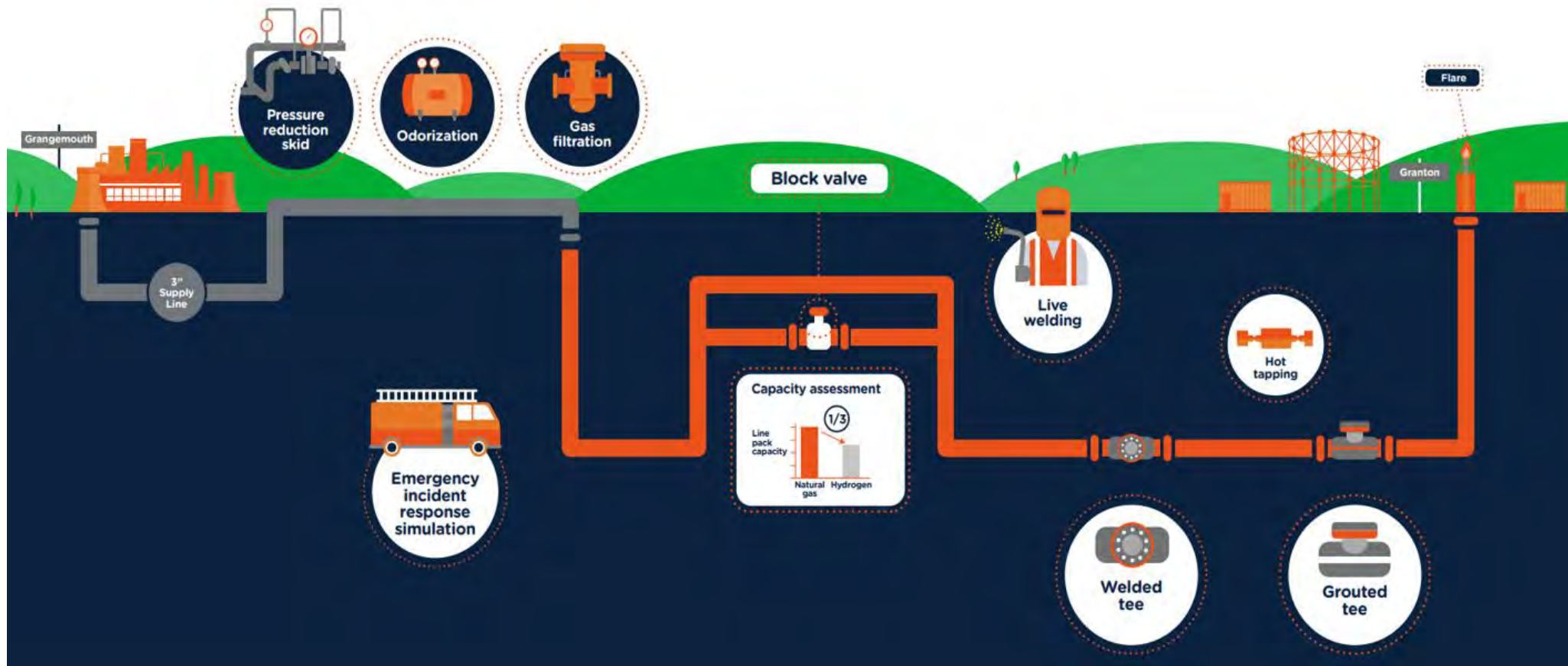
National gas – Future Grid

- Flowloop for process testing & live welding trials
- Material testing : fatigue and rupture
- System tests



SGN LTS futures

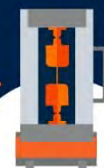
LTS Futures – Converted Hydrogen Transmission Pipeline



LTS Futures Research and Development

Material Testing

Small-scale mechanical testing of ex-service pipeline material and welds.



Materials testing

Burst and Fatigue of Defects

Burst and fatigue testing on vessels containing representative defects.



Burst and fatigue tests

Hot Works

Live maintenance and repair activities such as welding and hot tapping on a hydrogen pipeline.



Hot works testing

Venting and Flaring

Generating data on hydrogen venting and flaring for QRAs.



Vent and flare testing

Small Bore Connections

Fatigue testing of small-bore connections exposed to hydrogen gas.



Small bore fatigue testing

Pressure Reduction Installations

Testing an ex-service pressure reduction installation.



PRS testing

Burst and Fatigue Testing of Pipeline Defects



Hot Works Trials

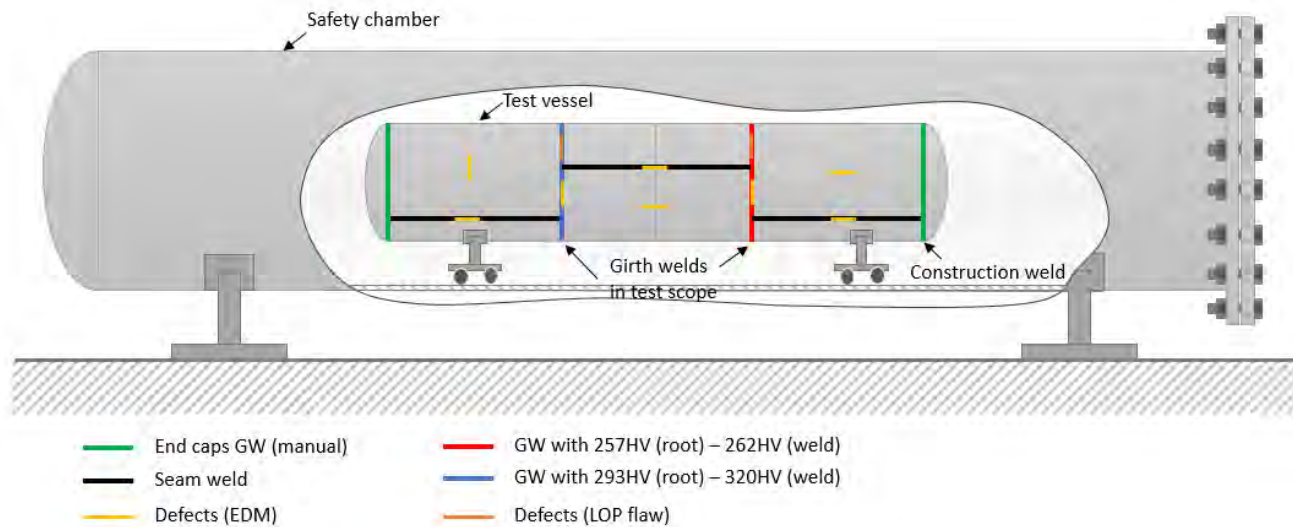


EPRG

- Fatigue crack growth until point of failure (leak / burst)
- Started in 2021 to challenge several B31.12 requirements and provide full scale fatigue crack growth reference data set
- Linepipe seam weld (LSAW) and girth welds in scope (250 HVN and 300 HVN)
- See PVP 2024-124195 for details

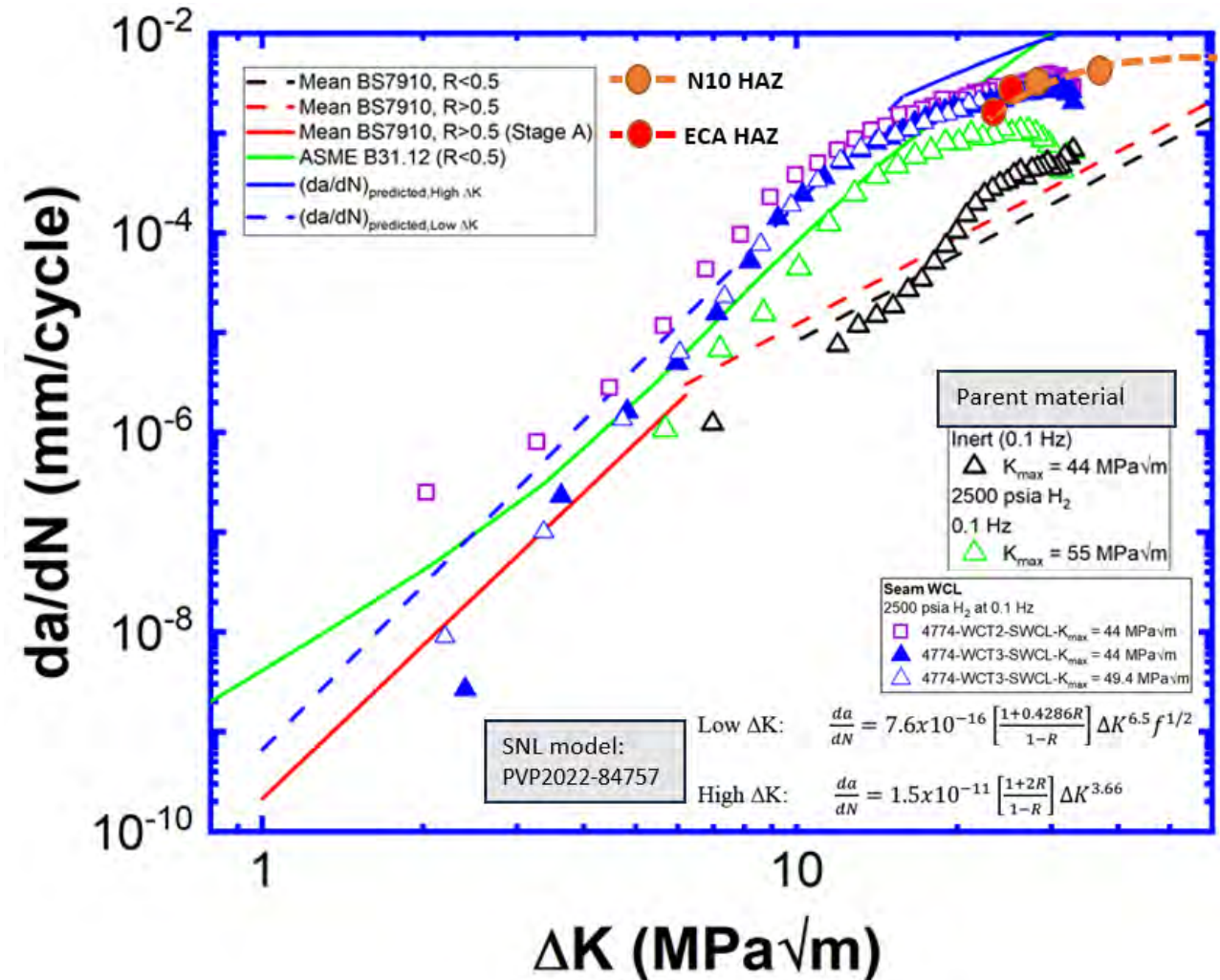
Approach

- Pj 231 – full scale fatigue test of 28” OD modern and vintage linepipes with notches
- Pj 232 – small scale material testing : fatigue and fracture



Findings on the modern pipe seam weld

- Very rapid initiation of a fatigue crack from an N10 EDM notch (~1500 cycles)
- Growth rate consistent with small scale predictions so far (further small scale tests still ongoing)



Findings on a repair weld

- Window cut-out repair
- Poor weld root
- Rapid initiation (again) and growth to failure in a total of 7000 cycles @ $R \sim 0.6$, 67% SMYS max



HCF (S-N)
Repair N10 weld root



Findings from the modern pipe test

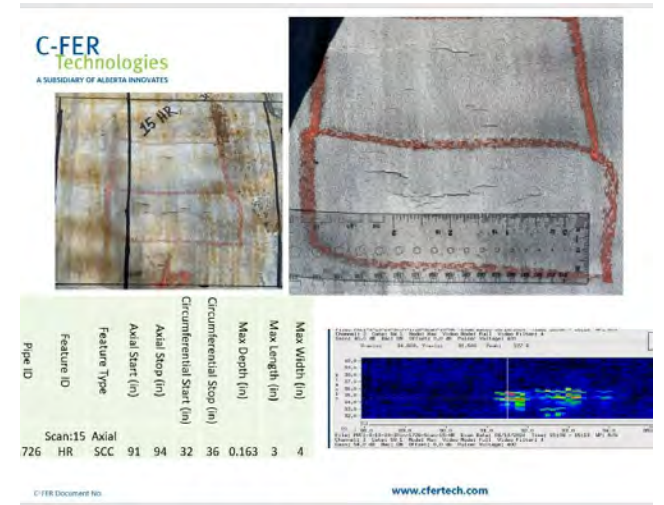
1. Rapid initiation in the order of 1,500 cycles (N10 notch) and 2,500 cycles (ECA notch) for long seam weld notches and about 2x longer for girth weld sharp notch
 1. Surface oxides found in the base of the notch → role unclear
2. Rapid fatigue crack growth but so far consistent with small scale data (
3. Constant pressure holds → crack stability inconclusive (transient effect + $J > J_{th}$)
4. Test ended 2x with a leak : @ machined HAZ notch and @ weld repair
5. Detecting and monitoring fatigue crack growth is challenging in Hydrogen (implication for future ILL inspection requirements...)

PRCI – Emerging Fuels Institute

- Full scale testing on 7 types of damages with C-FER
 1. SCC (stress corrosion cracking)
 2. Hard Spots
 3. Wrinkle Bends
 4. Planar Defects (Cracks, welding defects)
 5. Dents
 6. Corrosion as a stress raiser source
 7. Laminations

PRCI – Emerging Fuels Institute

- Pipes with realistic damages sourced
- Combination of real damages and machined damages in test samples
- Test protocol –
 - fatigue preconditioning to overcome the oxide layer
 - Select damages : fatigue cycling to mean predicted failure cycles
 - All damages: monotonic burst
- Twin samples for THE reference in-air test



HYSCORE – HYdrogen Storage and Carriage as Opportunity for Renewable Energy Transition

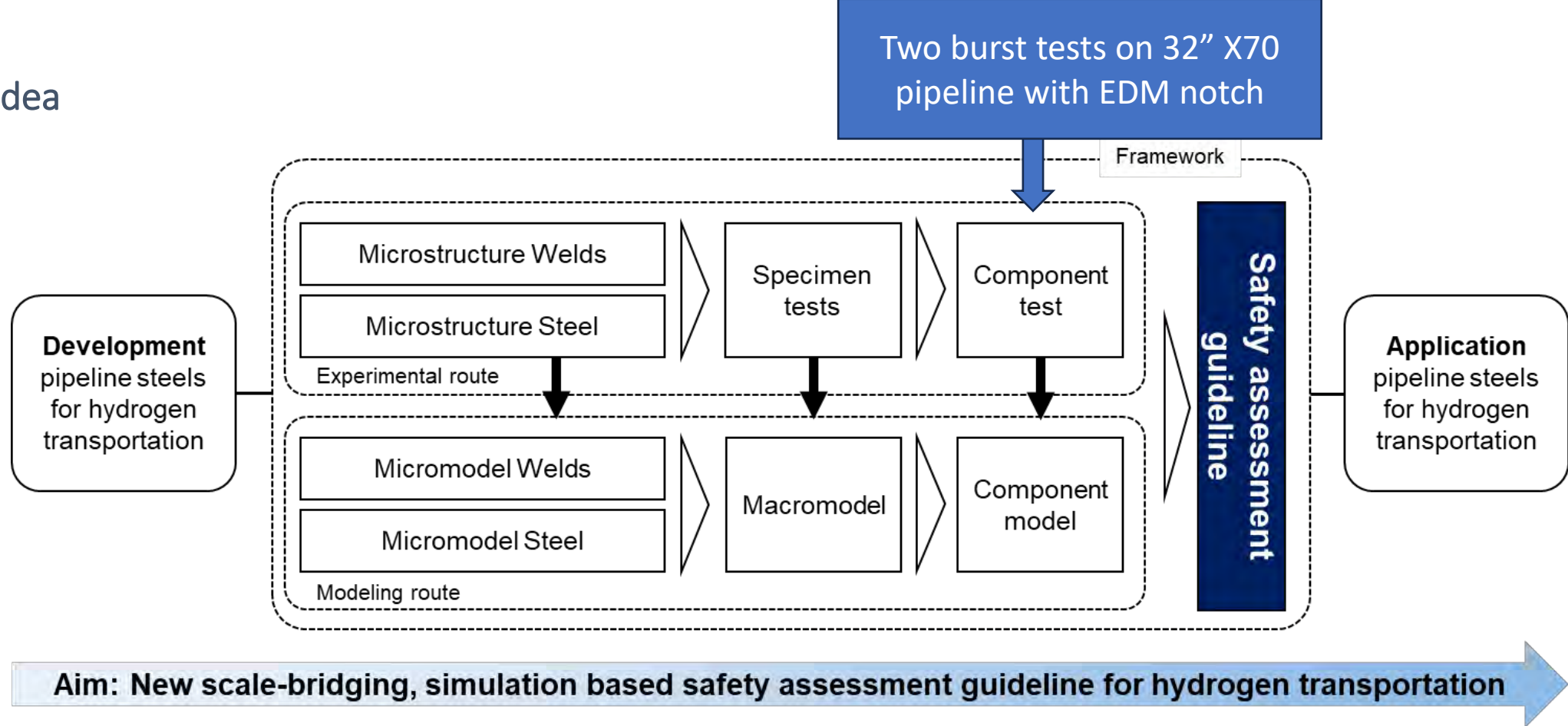


**Co-funded by
the European Union**

Partners in HYSCORE



General Idea



To sum up, the project will bring **added value** in the following terms:

- Identification of unknown mechanisms of **hydrogen-induced damage** at the **microstructure level**.
- Develops a new methodology for **safety assessment** of steel pipelines under hydrogen loading by improving existing ICME approaches.
- Strengthening the **competitive position of steel products** in the European countries.
- Promoting further expansion in the use of **renewable energies** across Europe.

General Idea

By setting the objectives of the applied research project, the following **7 innovations** can be defined, all of which will be developed within the proposed project.

1. Derivation of the **analytical equations** for hydrogen-induced damage based on **structural simulations**.
2. With experimental investigations, the relevant **damage mechanisms and material parameters** for each observed scale (μm to m) will be determined.
3. **FSI** model approach is **coupled** with effective **damage** models
4. The development of a **cross-scale modeling** approach for the description of **hydrogen-induced damage** in steel pipes and welds
5. **Characterization** of **hydrogen-induced damage** mechanisms on μ -structure scale
6. Development of **assessment rules** for weld fracture (in the presence of defects) and long-running fracture in pipes, that account for the detrimental effects of hydrogen on material fracture resistance.
7. Consideration of **microstructure** will allow appropriate material design in the future by **inverting** the material design with regard to microstructure in **hydrogen-induced damage**.

Thank you

Study Group on Materials Testing and Qualification for Hydrogen Service

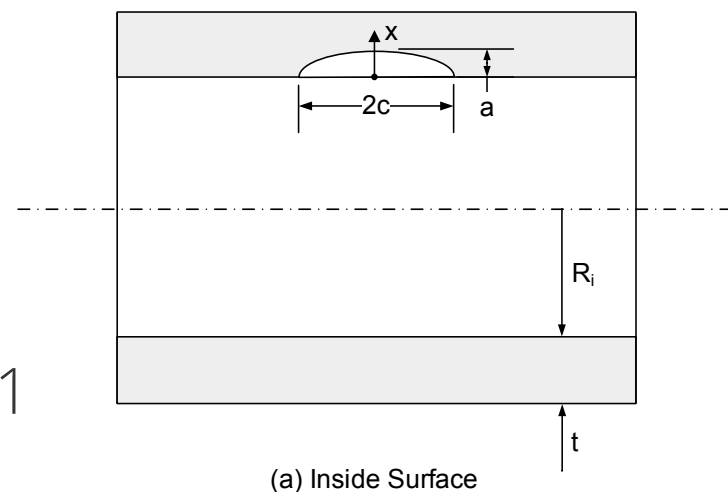
Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

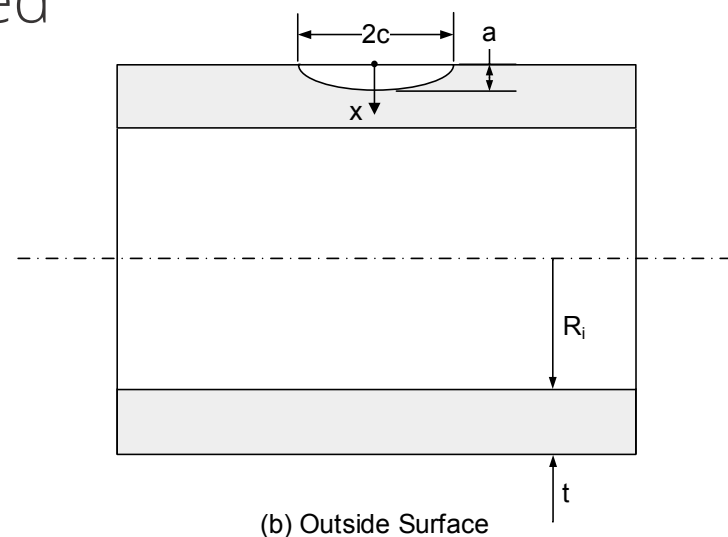
8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn



Subscale pipe testing



(a) Inside Surface



(b) Outside Surface

Testing parameters

OD = 2.375 in (60.3 mm)
t = 0.154 in (3.91 mm)

OD/t = 15.4
R/t = 7.7

a = 0.079 in (2.0 mm)
2c = 0.787 in (20.0 mm)

2c/a = 10

P_{max} = 4,000 psi (27.58 MPa)
P_{min} = 1,000 psi (6.894 MPa)

API 579-1
(2016)
designated
defects

Figure 9B.15 – Cylinder – Surface Crack, Longitudinal Direction – Semi-elliptical Shape



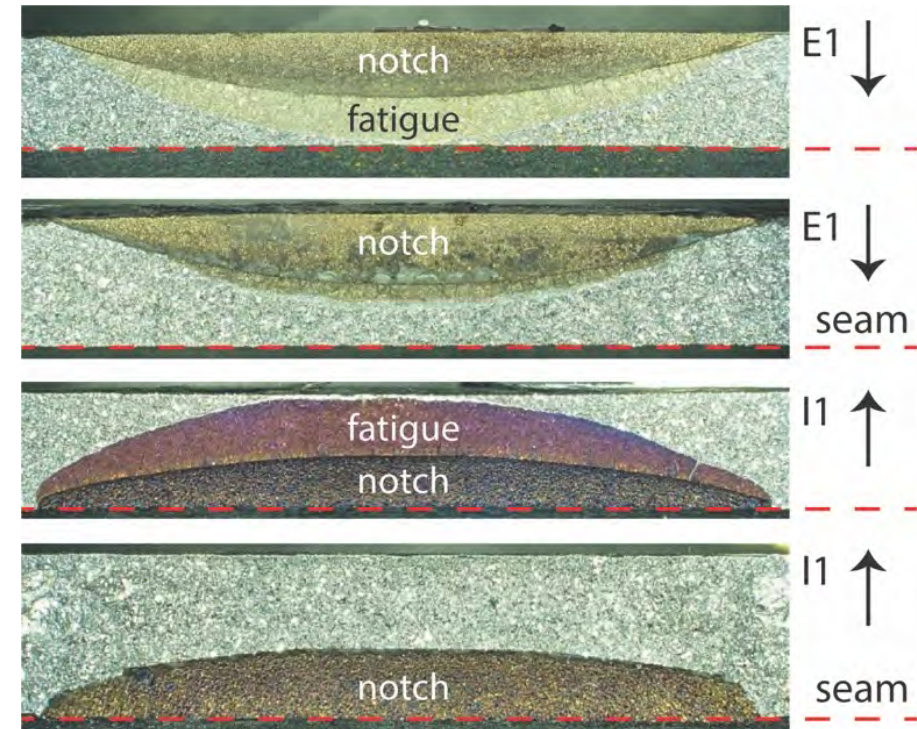
Testing of ASTM A53 pipe: engineering surfaces do not prevent hydrogen-assisted cracking in steels

- Hydrogen-assisted cracking is not limited by mill scale ('natural' surface condition) on natural gas pipe
- This result "busts the myth" that oxide surfaces prevent hydrogen embrittlement on infrastructure time scales



Pressure cycling pipe with engineered defects

Specimen		Gas	Measured cycles to Failure
Internal defects	I1	Hydrogen	636
	I4	Nitrogen	18,880
External defects	E1	Hydrogen	1,097
	E2	Hydrogen	1,191
	E3	Nitrogen	13,356



Dashed line = inside surface

Arrow = direction of crack

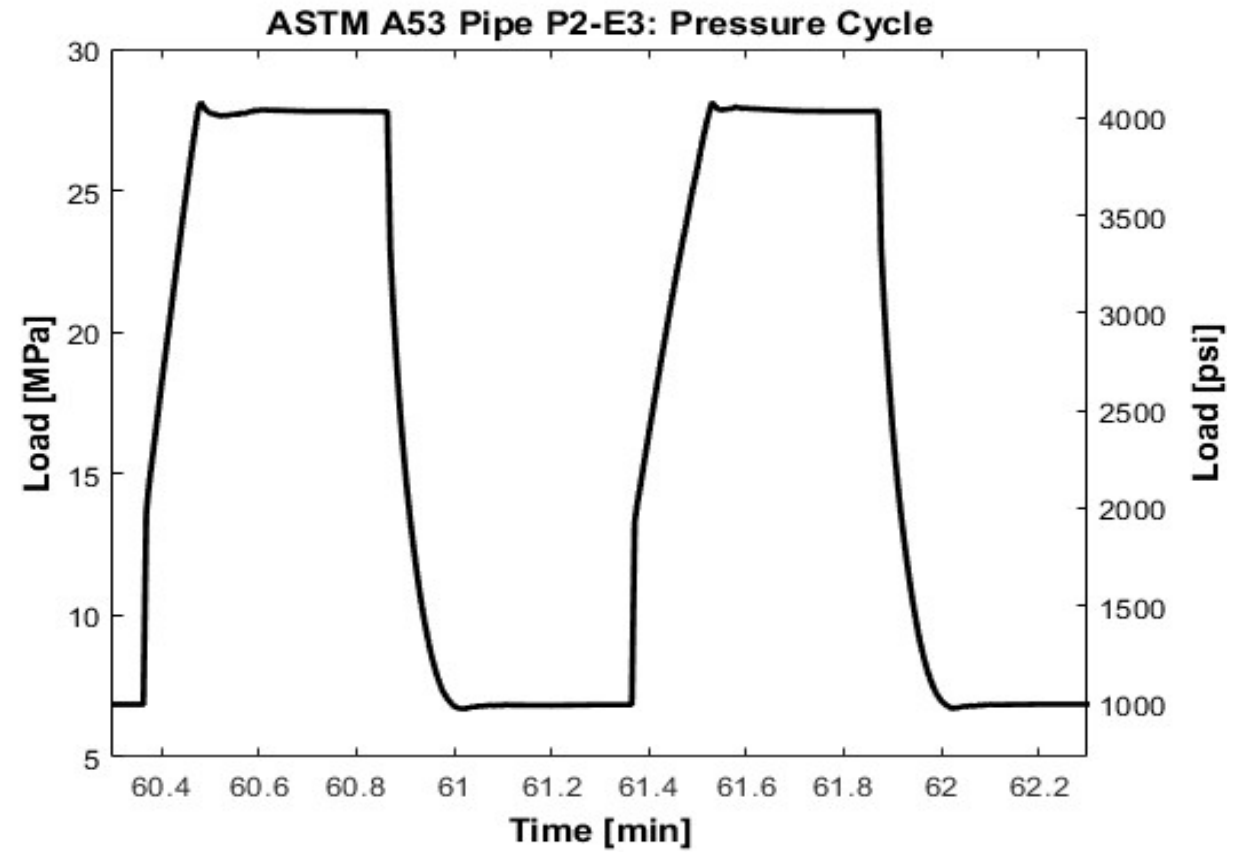
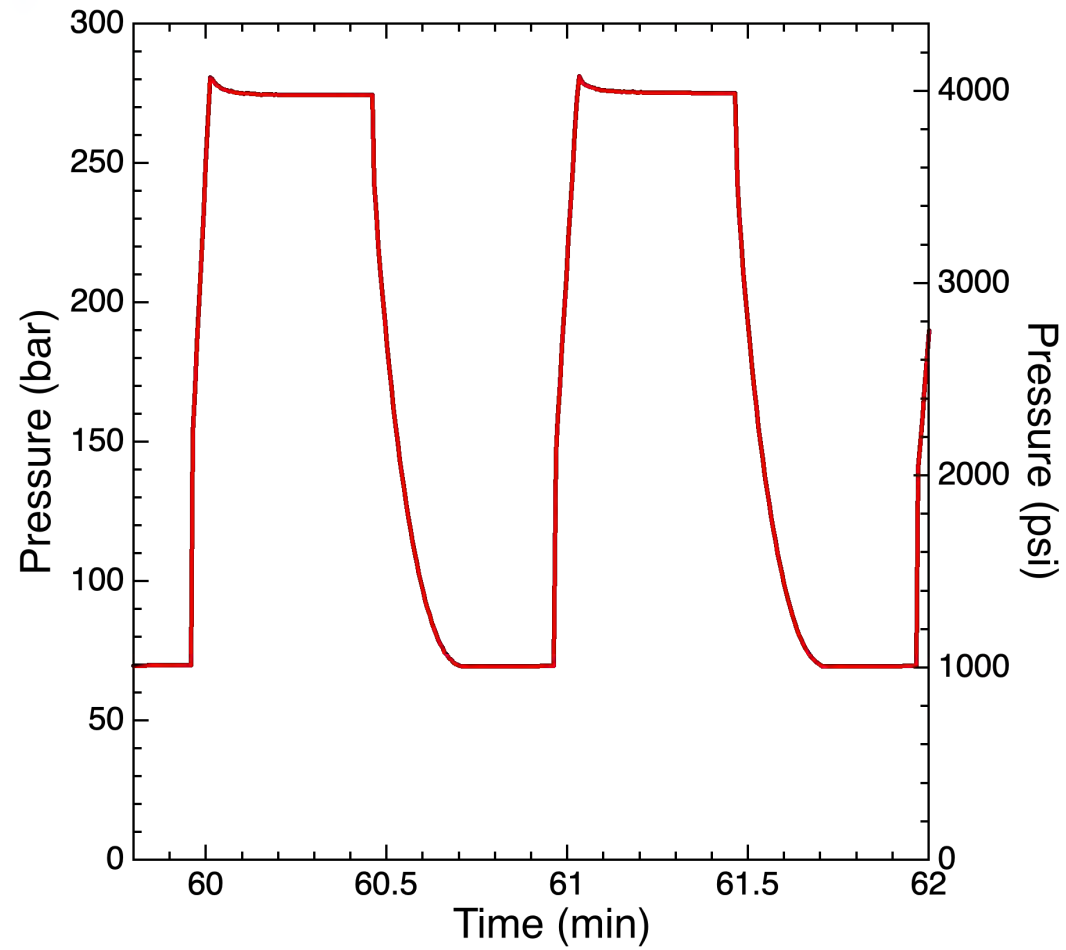


Predictions

Defect	Gas	Measurement	API prediction a/2c constant	API prediction 2c constant
Internal	Hydrogen	636	346	519
	3% H2	–	466	778
	air	18,880	11,931	16,908
External	Hydrogen	1,097 1,191	368	542
	3% H2	(7.738)	559	882
	air	13,356	12,417	17,452



Pressure cycles



Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn



Fatigue life testing in gaseous hydrogen: crack initiation

Fernando León-Cázares*

Milan Agnani

Joseph Ronevich

Chris San Marchi

Sandia National Laboratories,
Livermore, USA

Pressure Vessels & Piping® Conference
Bellevue, WA, USA

Study Group on Materials Testing and Qualification for Hydrogen Service
Bellevue, WA August 2nd, 2024

SAND2024-09654C

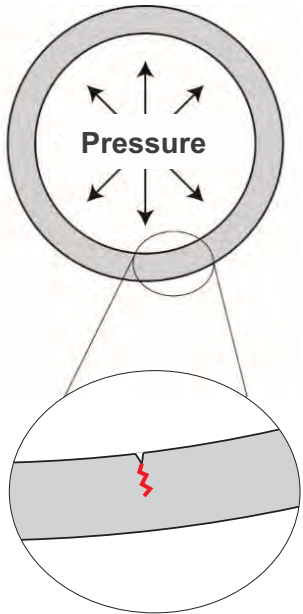
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia LLC, a wholly owned subsidiary of Honeywell International Inc. for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.





Motivation

Fatigue life = Crack initiation + Crack propagation + Fracture



Crack initiation often accounts for a significant part of the fatigue life, **but it is harder to assess and predict**

- Scatter in data
- Difficult to characterize
- Microstructure-dependent

➤ **How does H affect crack initiation?**

- Is there interest in S-N and crack initiation data?



Study case:

- Vintage pipeline steel
- Low H pressures
- Crack initiation



Obstacles to a wider
adoption of crack
initiation tests



Effects of hydrogen partial pressure on crack initiation and growth rate in vintage X52 steel

Fernando D. León-Cázares^{*}, Milan Agnani, Joseph Ronevich, Chris San Marchi

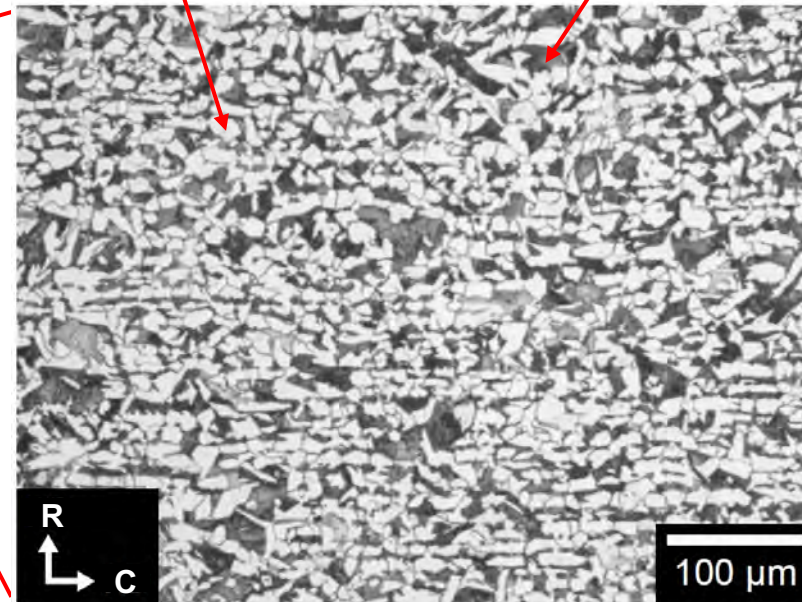
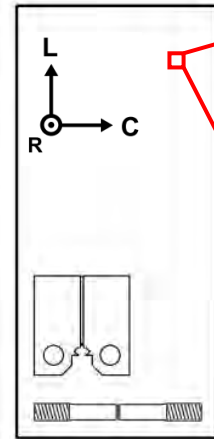
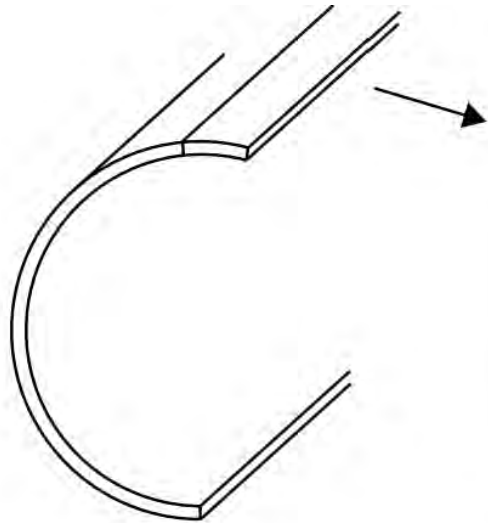
Sandia National Laboratories, 7011 East Avenue, Livermore, CA, 94550, USA



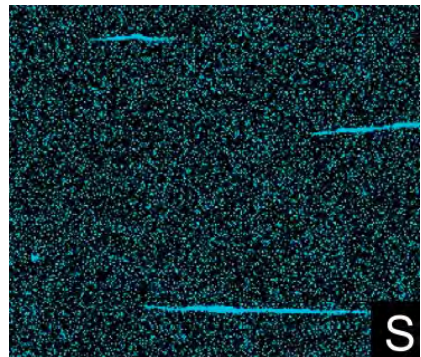
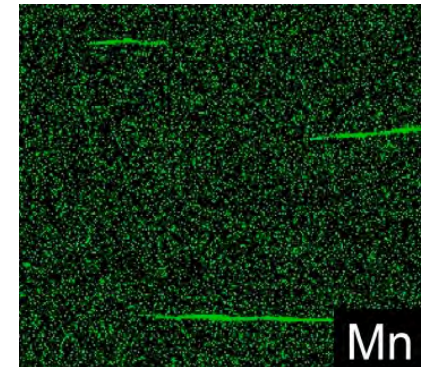
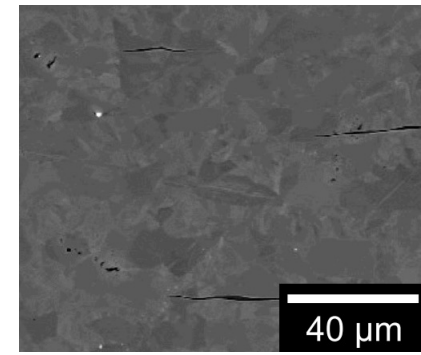
Material – Vintage (1962) X52 steel

Composition

Fe	C	Mn	Si	S	P
bal.	0.29	1.17	0.02	0.016	0.016



α – ferrite (white) Pearlite (grey)



NG pipeline

- Diameter: 0.91 m
- Thickness: 10.3 mm

Microstructure

- Bands of ferrite + pearlite
- MnS inclusions

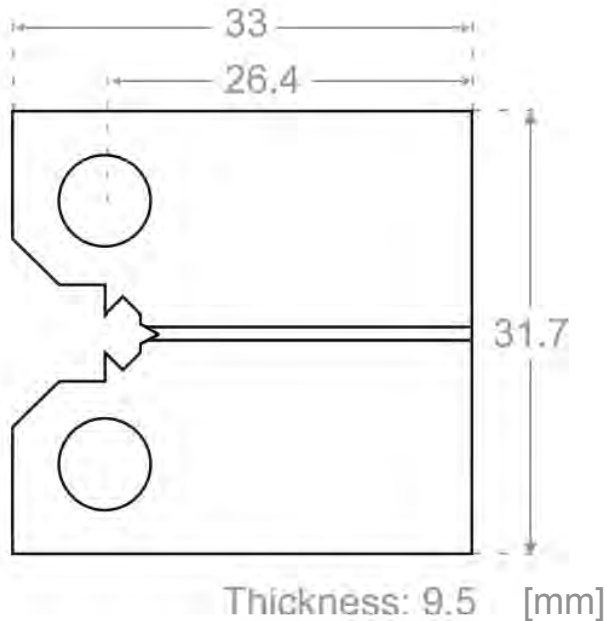


Test parameters

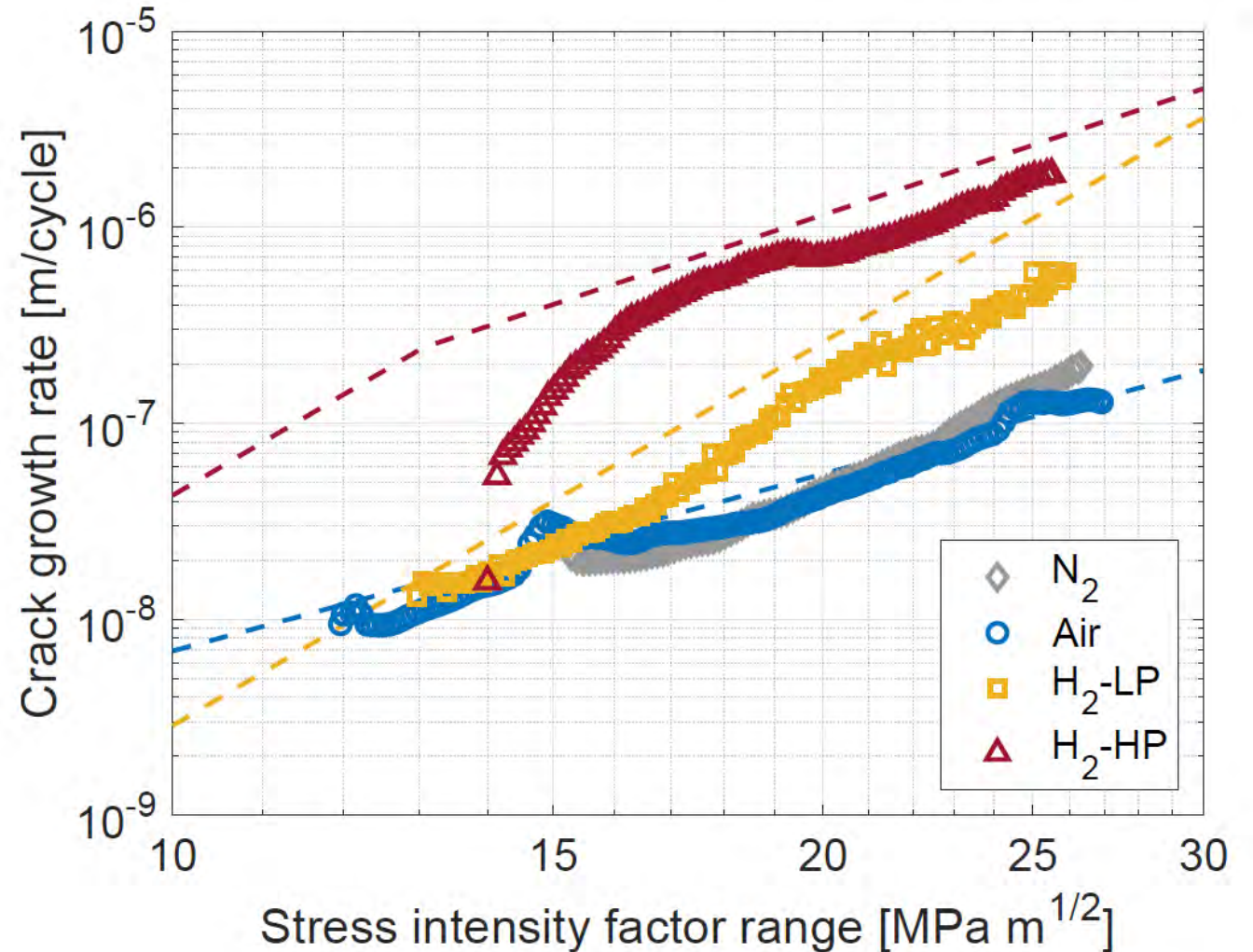
- Two test geometries:
 - Circumferential notch tension (CNT) → Crack initiation and failure
 - Compact tension (CT) → Crack growth rate
- Four atmospheres:
 - N_2 34 bar → Baseline
 - Air → Effects of O_2 and moisture
 - H_2 -LP N_2 -3% H_2 at 34 bar → Low H partial pressure (1 bar)
 - H_2 -HP H_2 at 207 bar → High H partial pressure (207 bar)
- Frequency of 1 Hz
- Loading ratio of $R = 0.1$



Compact tension (CT) → Crack growth rate

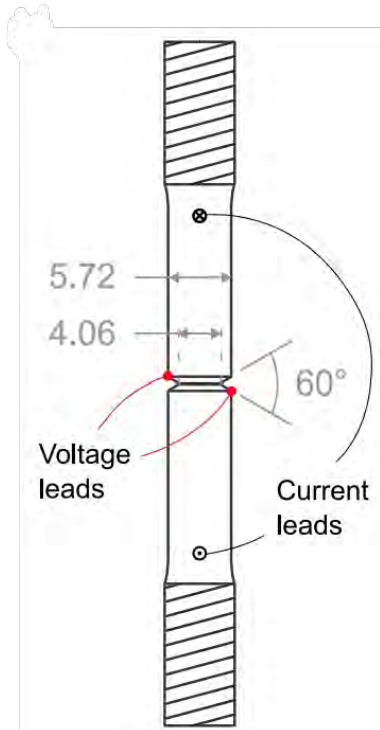


Standard ASTM E647

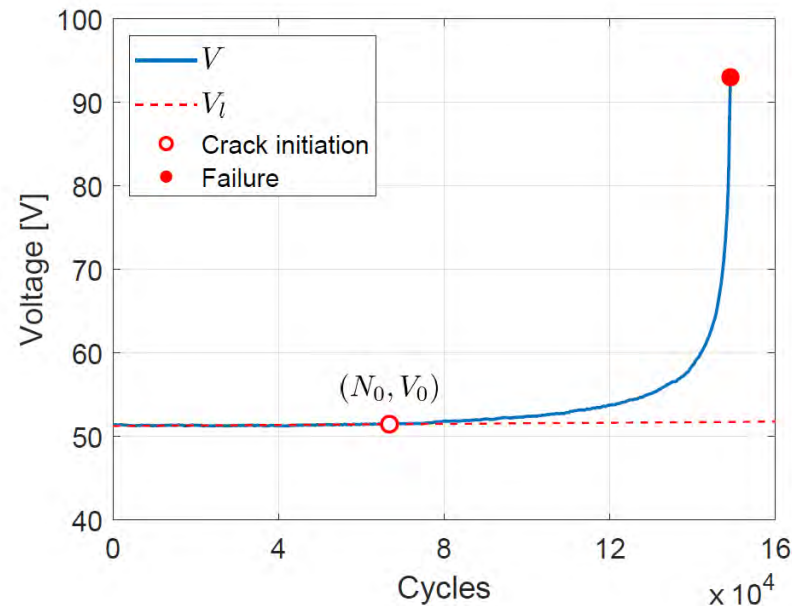




Circumferential notch tension (CNT) → Crack initiation & failure



Direct Current Potential Difference (DCPD)



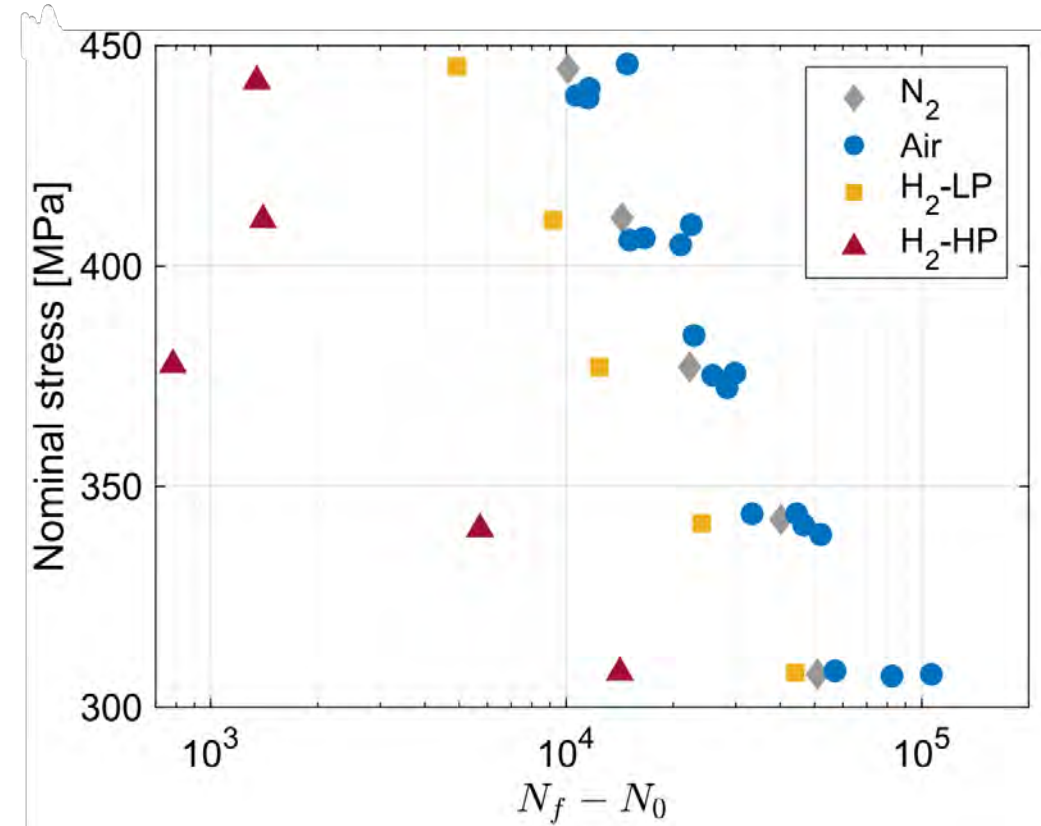
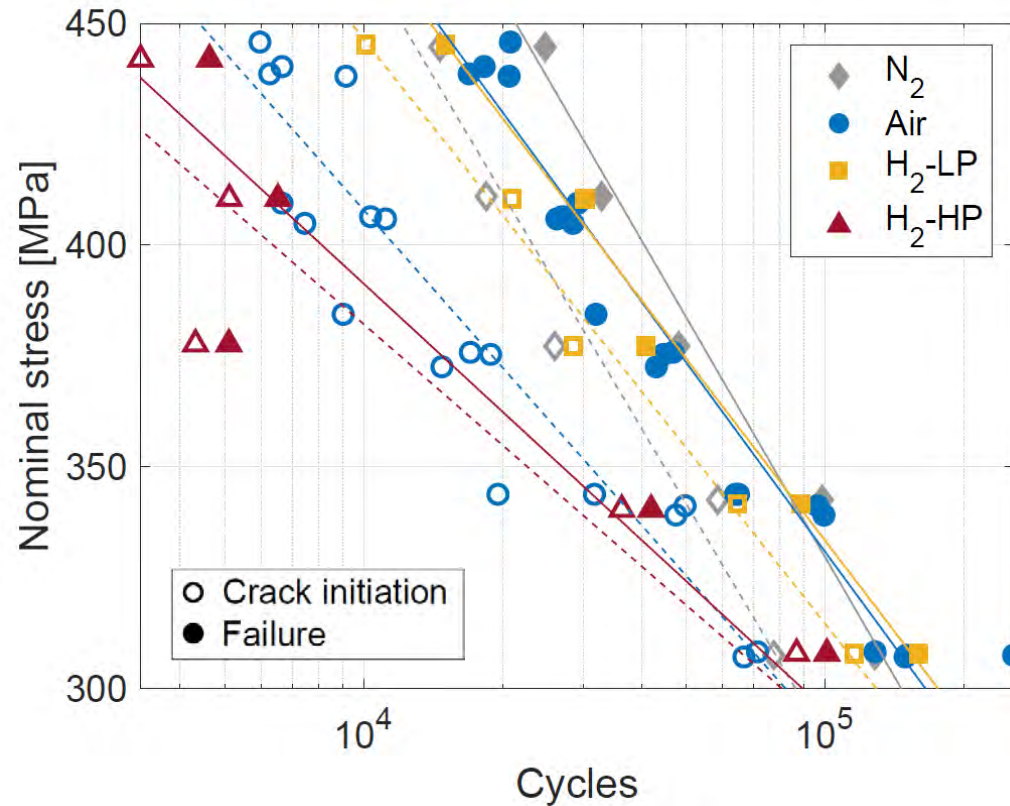
Automated approach to estimate the point of crack initiation by maximizing a gain function G

$$G = \sum_i G_i$$

$$G_i = \begin{cases} 1 - \frac{|V_i - V_{l,i}|}{V_{co}} & , |V_i - V_{l,i}| < V_{co} \\ 0 & , |V_i - V_{l,i}| \geq V_{co} \end{cases}$$



Circumferential notch tension (CNT) → Crack initiation & failure

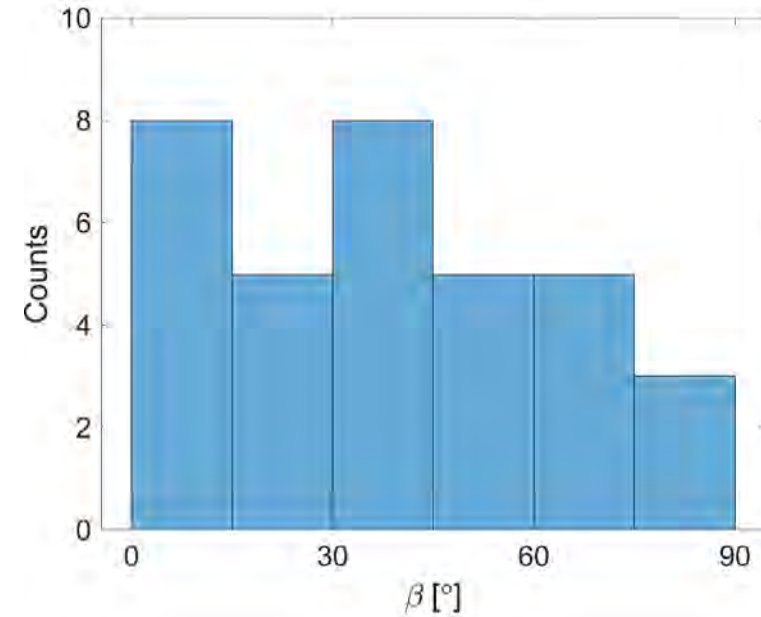
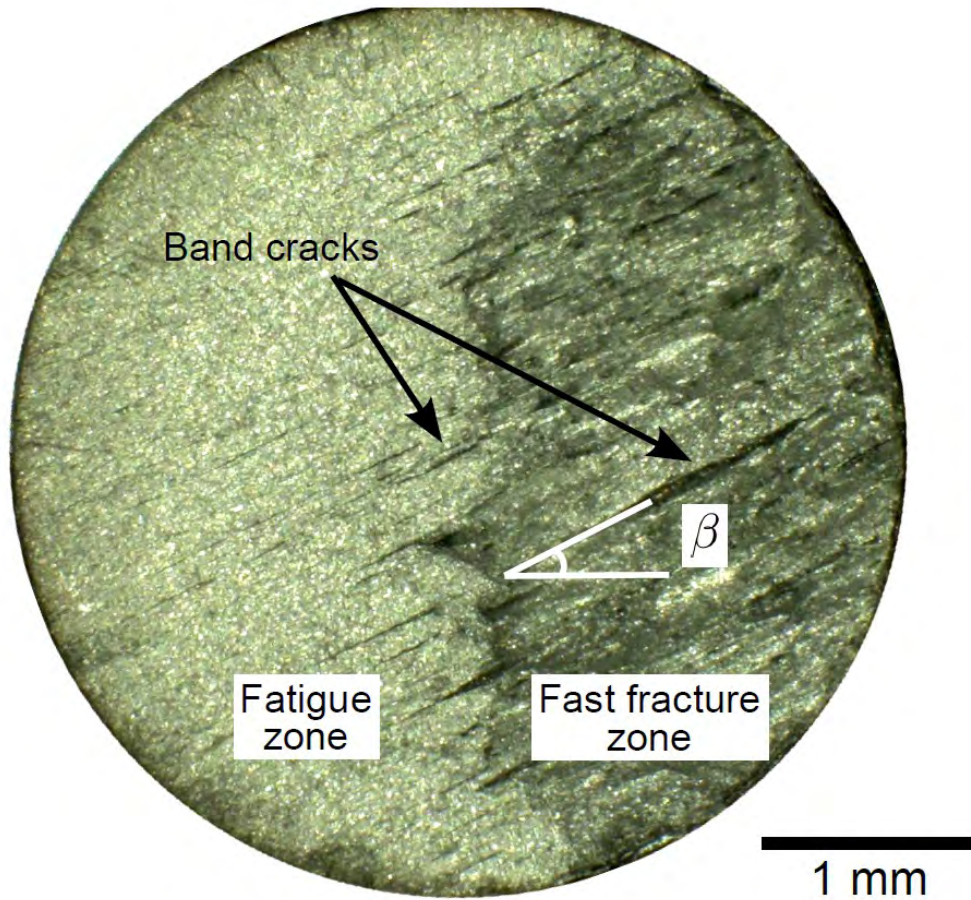


- Trends:**
- **Air** accelerates crack initiation
 - **H_2 -LP** accelerates crack growth rate
 - **H_2 -HP** accelerates both

**Different trends
than those for
crack growth rate!**



Crack initiation and evolution



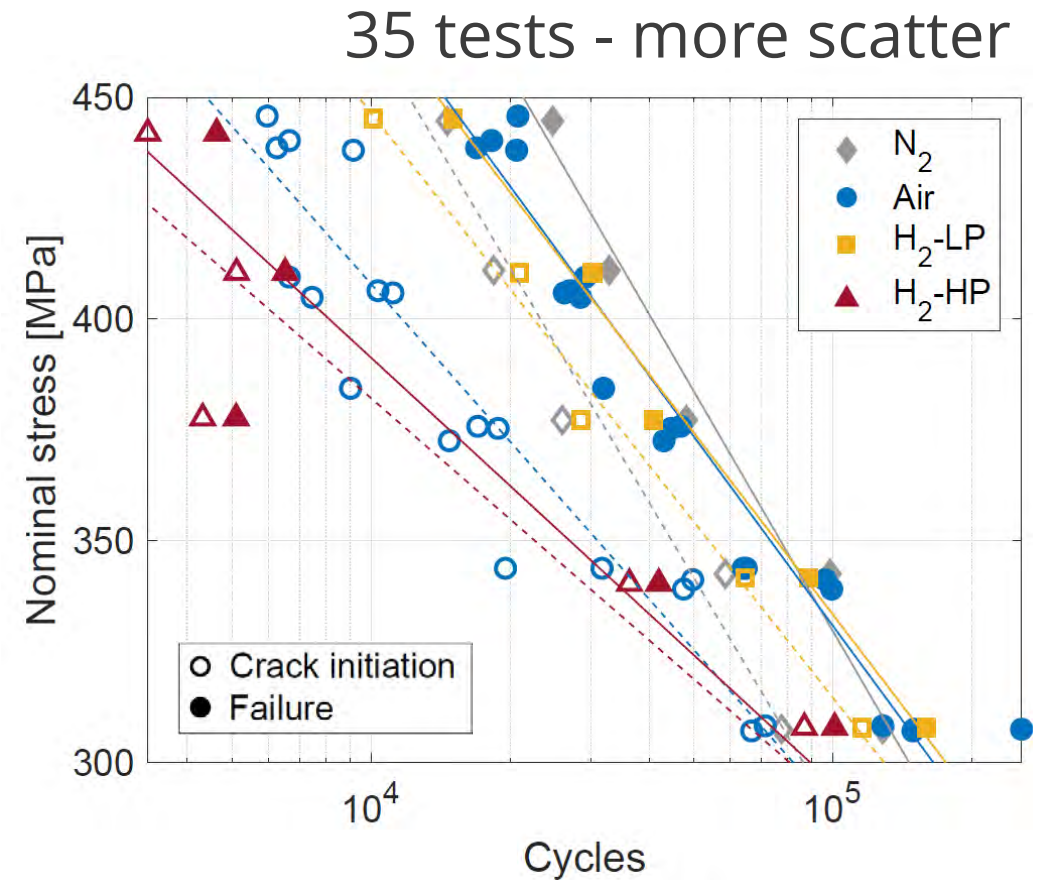
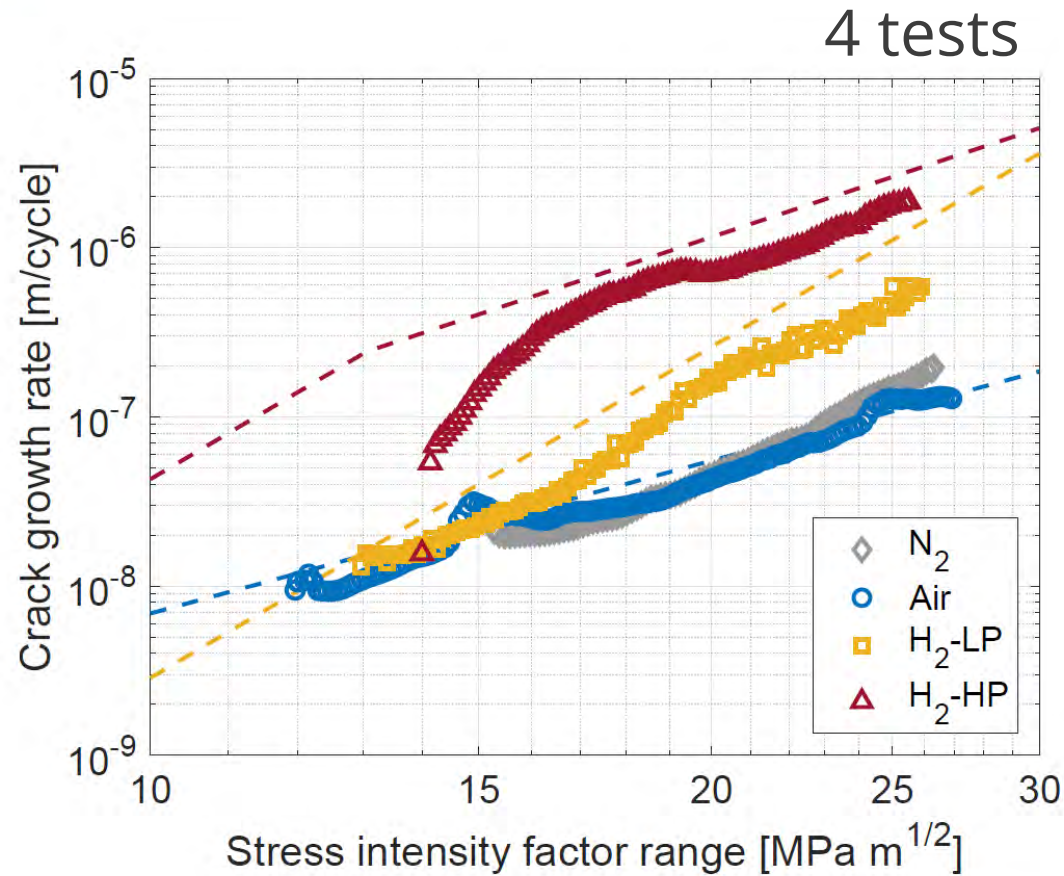
- Crack initiation appears to be independent of microstructural band orientation.
- Crack initiation may originate near MnS inclusions.



Findings

- H effects on crack initiation differ from those on crack propagation.
- Low H partial pressure (1 bar) has a negligible effect on crack initiation, but it accelerates crack growth rate.
- Damage in low H partial pressures may be small enough for the repurposing of vintage pipelines for use with H blends.

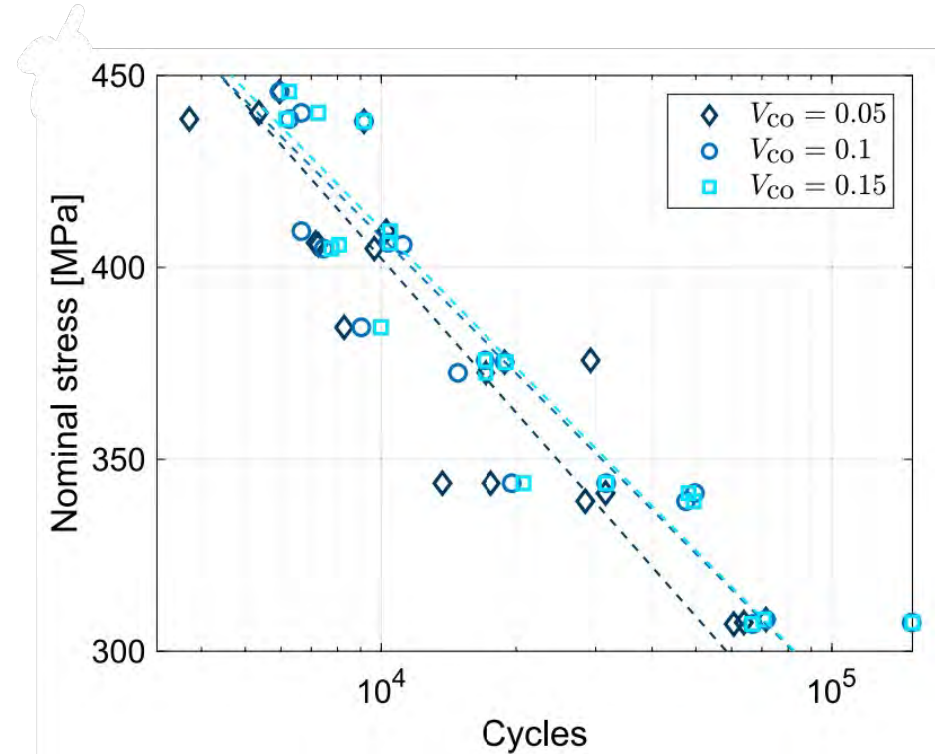
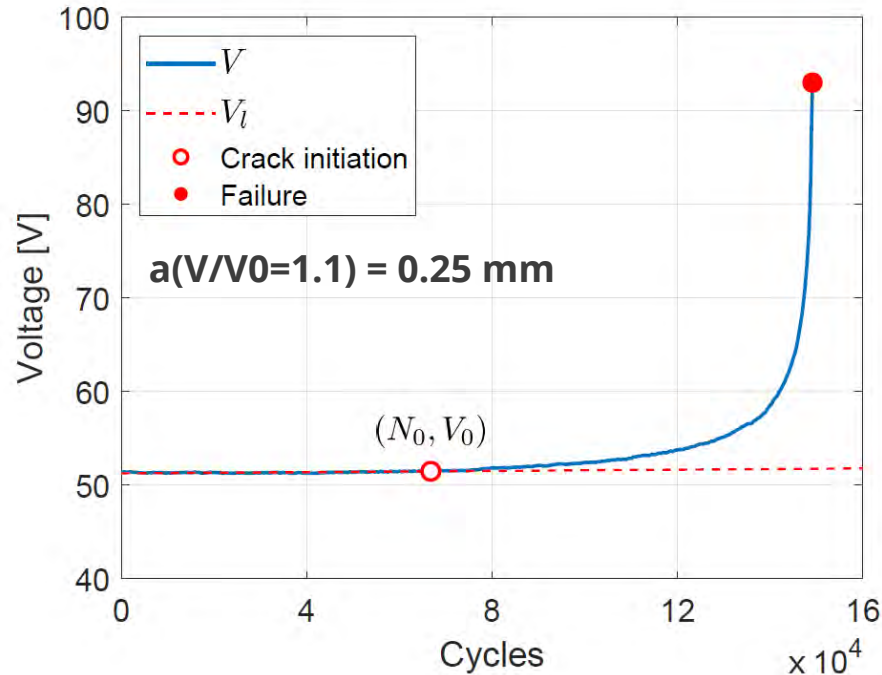
How many specimens were tested?



- Would C&S include crack initiation if we had a higher testing **throughput**?
- How can we improve throughput?



What is crack initiation?



Effect of the crack initiation detection algorithm does not change the conclusions. However, there is **no clear definition of “crack initiation”**.

- What is the most relevant definition (length) for crack initiation?
- Should this be standardized?



Other discussion points

- Smooth vs. notched. Alternative notched geometries, e.g. CNT, transverse circular hole



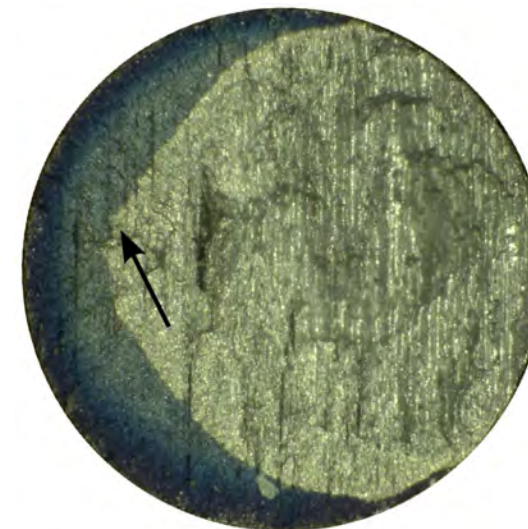
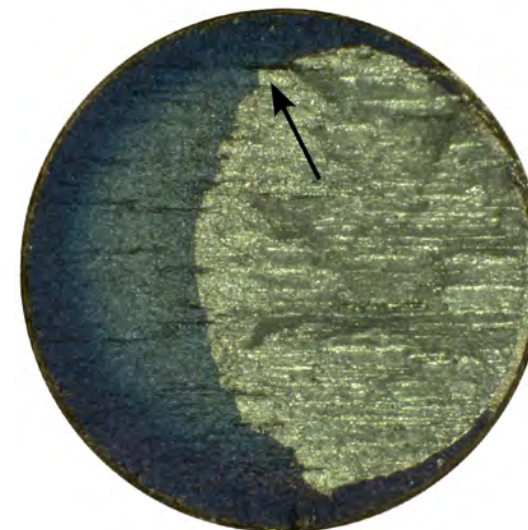
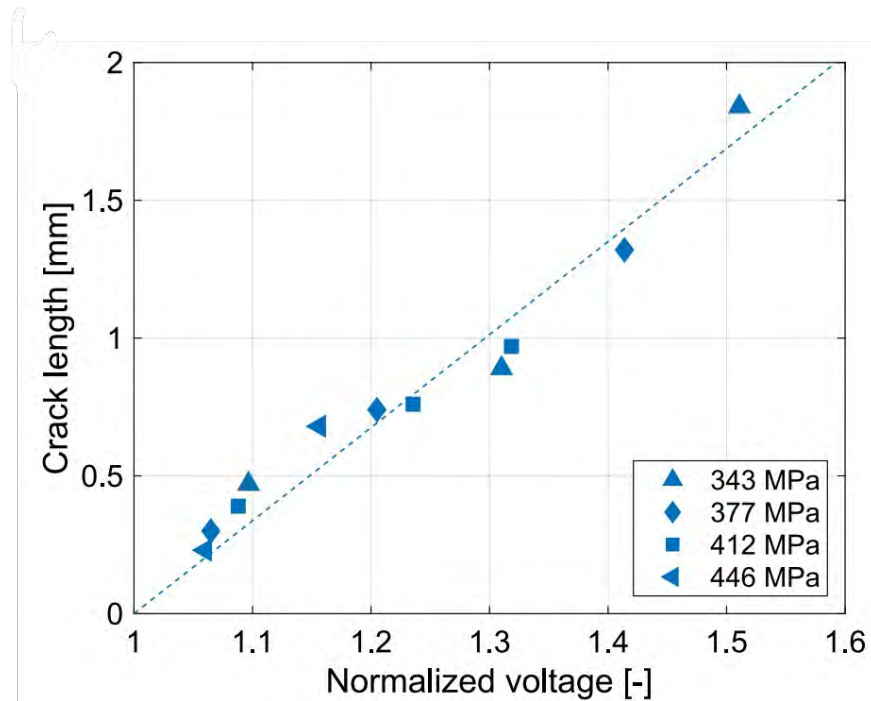
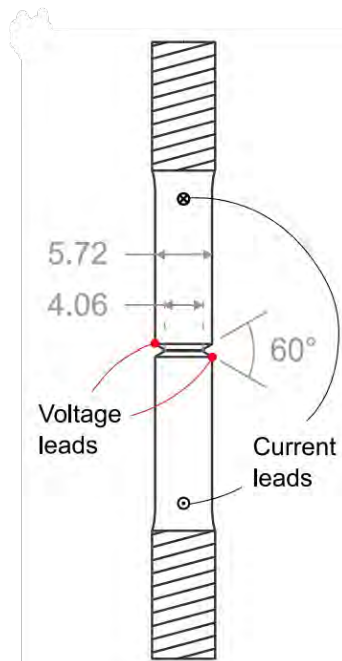
- What other materials/operating conditions we lack data for?
 - Materials
 - Operating conditions
 - Welds
 - Defects (dents, scratches, etc.)
- How to link S-N tests with approaches for fatigue life testing (deterministic and probabilistic)?

Thanks!

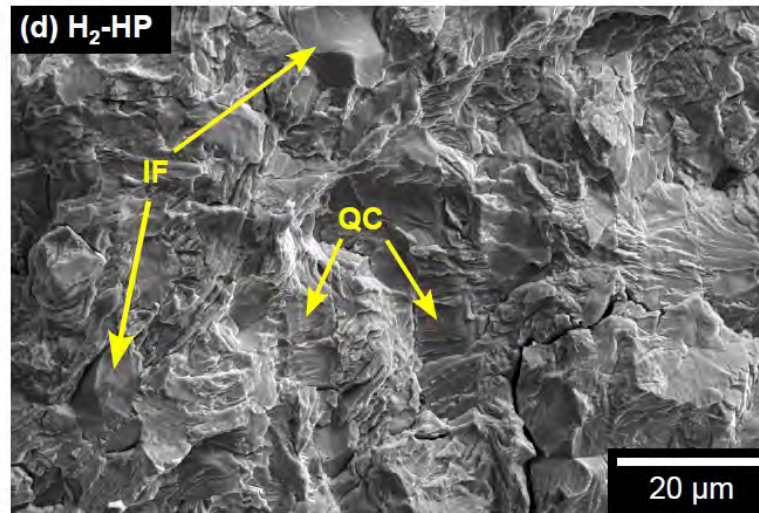
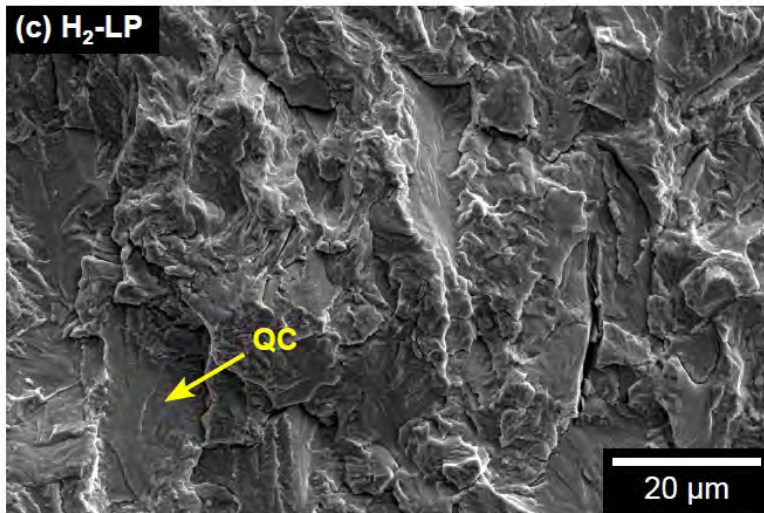
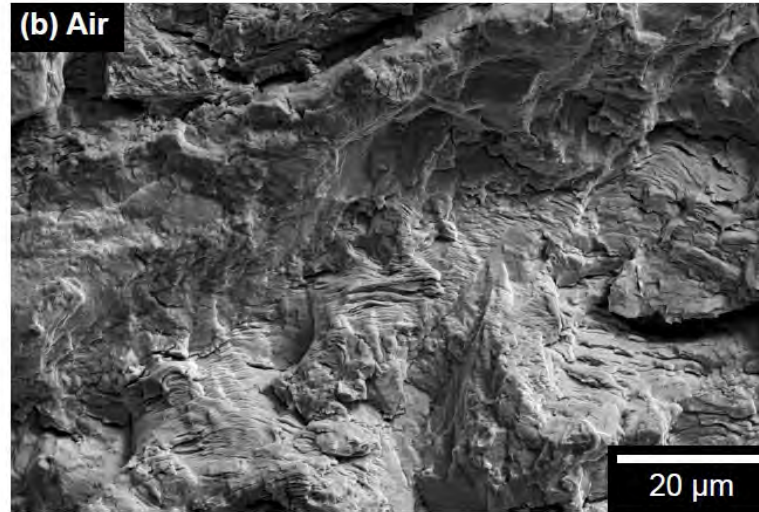
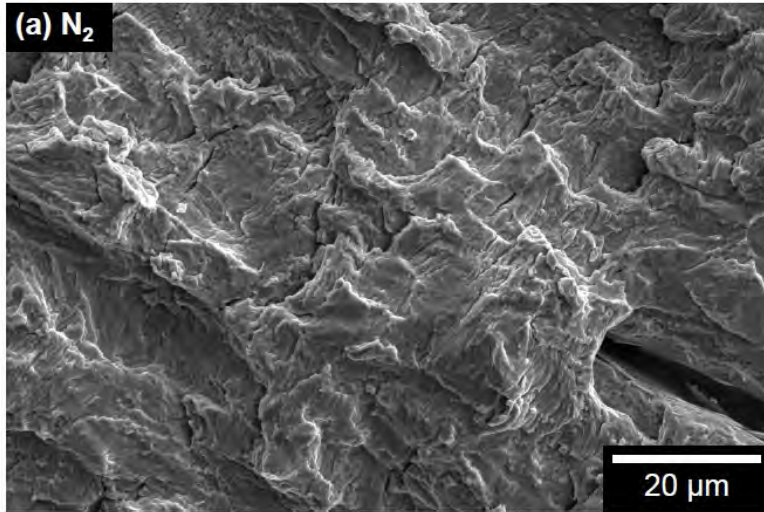
Contact me at: feonca@sandia.gov



Circumferential notch tension (CNT) → interrupted test + heat tinting



Fracture surface is affected by hydrogen



- Tests in N₂ and air are very similar, showing ductile transgranular fracture.
- H₂-LP shows evidence of H-induced quasi-cleavage (QC).
- H₂-HP shows larger amounts of QC and regions of intergranular fracture (IF).

Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn



EPRG Round robin benchmark study on the fracture toughness testing in hydrogen gas

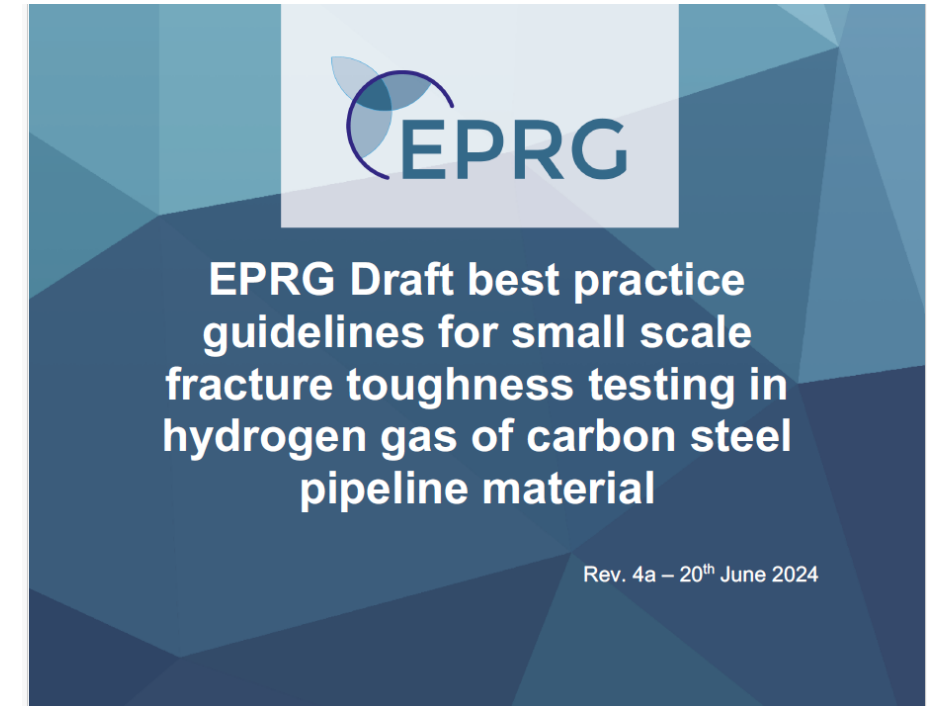
Bostjan Bezensek, Shell ; Neil Gallon, Rosen, Holger Brauer Mannesmann Line Pipe

August 2nd, 2024

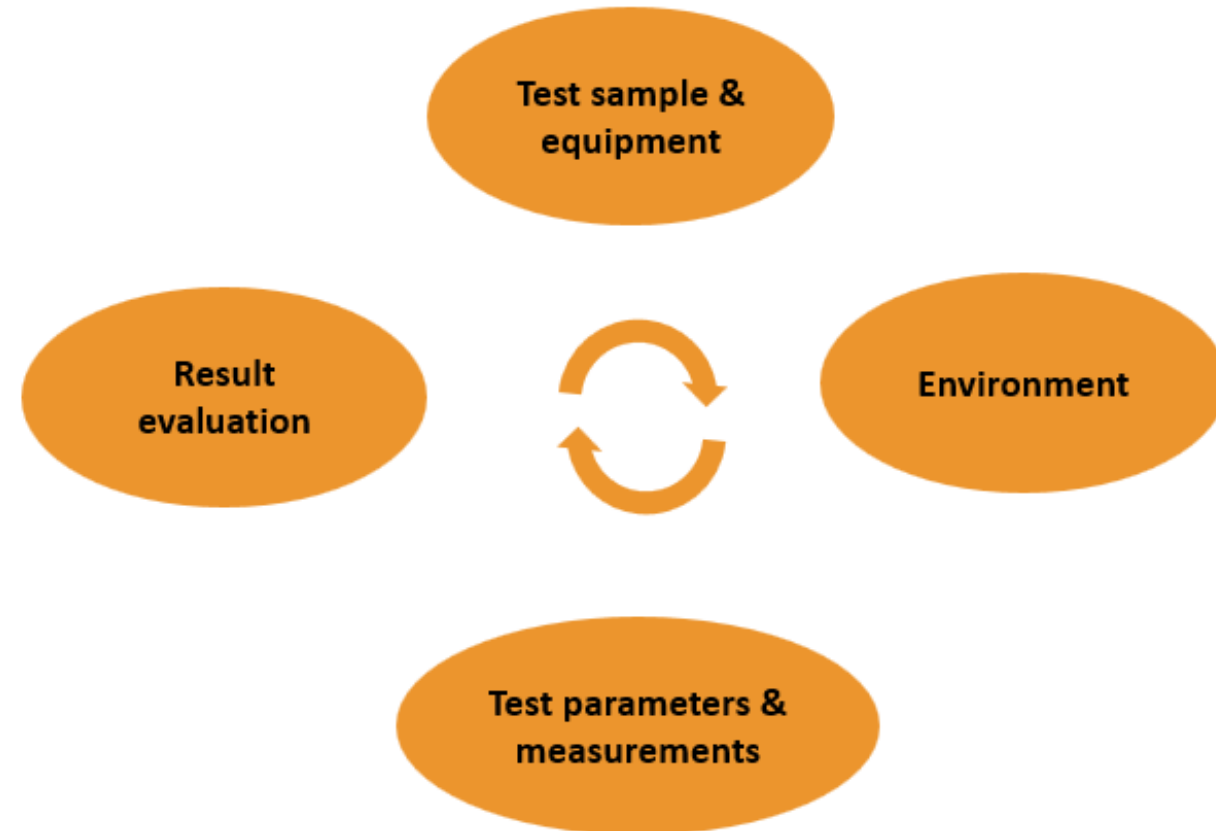
Background

- Move towards elastic plastic ASTM E1820 fracture toughness testing
- Lack of standardisation
 - ANSI / CSA CHMC-1 : 2014 – in update
- Rapid evolution of the understanding
- Still open gaps

- EPRG guidelines for fracture toughness testing in hydrogen gas published July 2024
- Overlay to ANSI / CSA CHMC-1
- Aims
 1. Consistency in the approach to applying ASTM E1820 rising displacement testing across the users and labs
 2. Consolidation of current best practices in executing such testing
 3. Education of the members & industry



- Collation of the current best practices in fracture toughness testing using rising displacement method, noting the ongoing research
- Strong contribution from SNL & DNV experiences + NIST + Uni Wollongong + European members

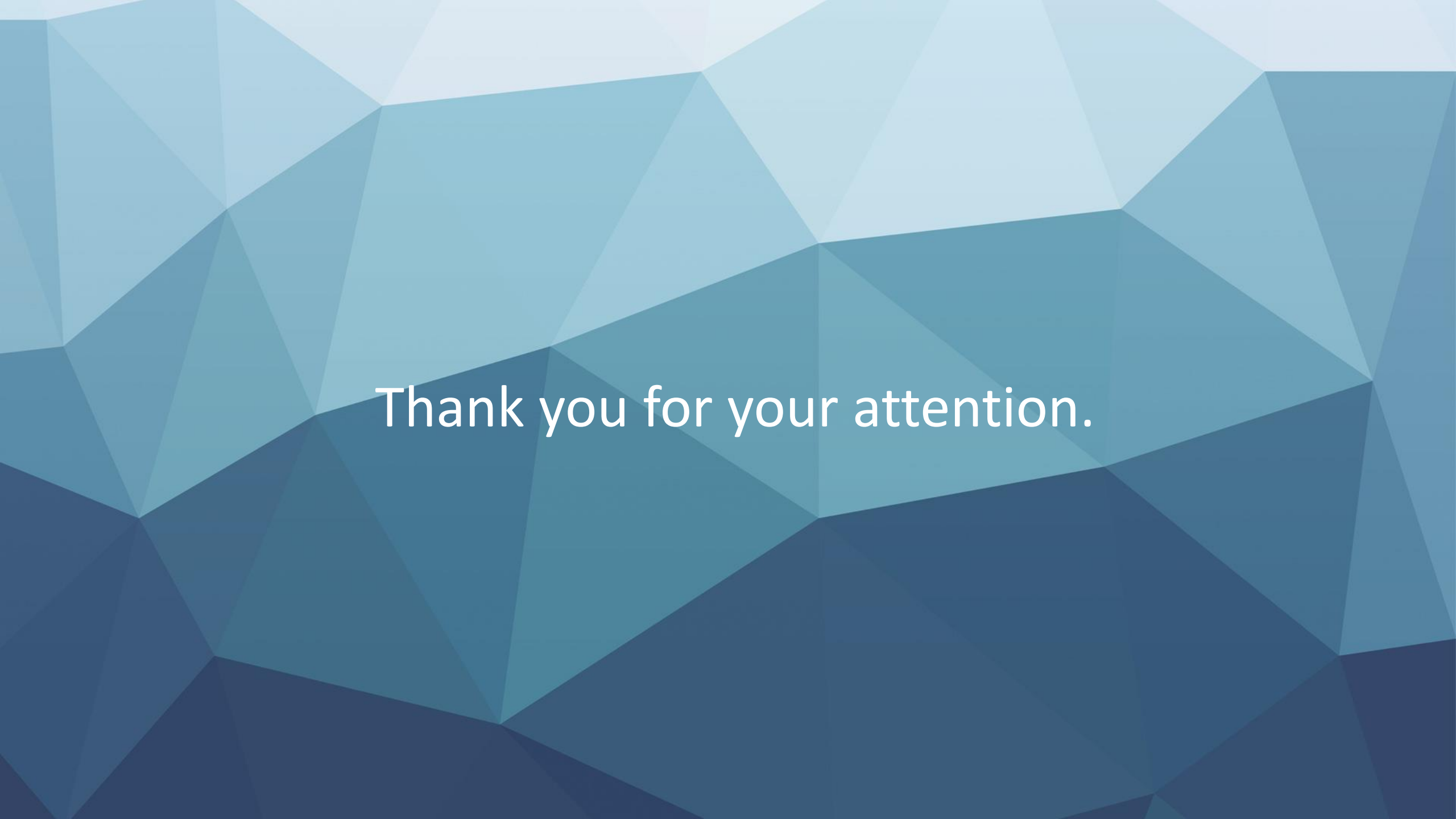


Next step – Industry wide round robin benchmark study



- Apply the EPRG guidelines
- Establish industry baseline performance
 - Springboard for resolving gaps with the member labs
 - Baseline towards closing the open knowledge gaps
- Must be an international effort to be of value !!!
- Lead lab will be contracted by the EPRG
- **All labs are invited to contribute 3off tests (to defined parameters) in-kind in early 2025**
- Data processing will be with considerations for confidentiality and unbiased

- Lead lab contracting process during the 2nd half of 2024
- Info share Teams calls monthly from September - please sign up!
- Project kick-off in January 2025 for 12 months
- Contact - Lead PM: Bostjan Bezensek
Bostjan.Bezensek@shell.com

The background is an abstract geometric pattern composed of numerous triangles in various shades of blue and teal. The colors range from light, almost white, to dark navy blue. The triangles are of different sizes and are arranged in a way that creates a sense of depth and movement, resembling a low-poly landscape or a stylized mountain range.

Thank you for your attention.

Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn

Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn



Exceptional service in the national interest

Microstructural Effects in Fatigue and Fracture in Hydrogen

Milan Agnani*, Joseph Ronevich, Chris San Marchi

ASME Pressure Vessels and Piping Conference

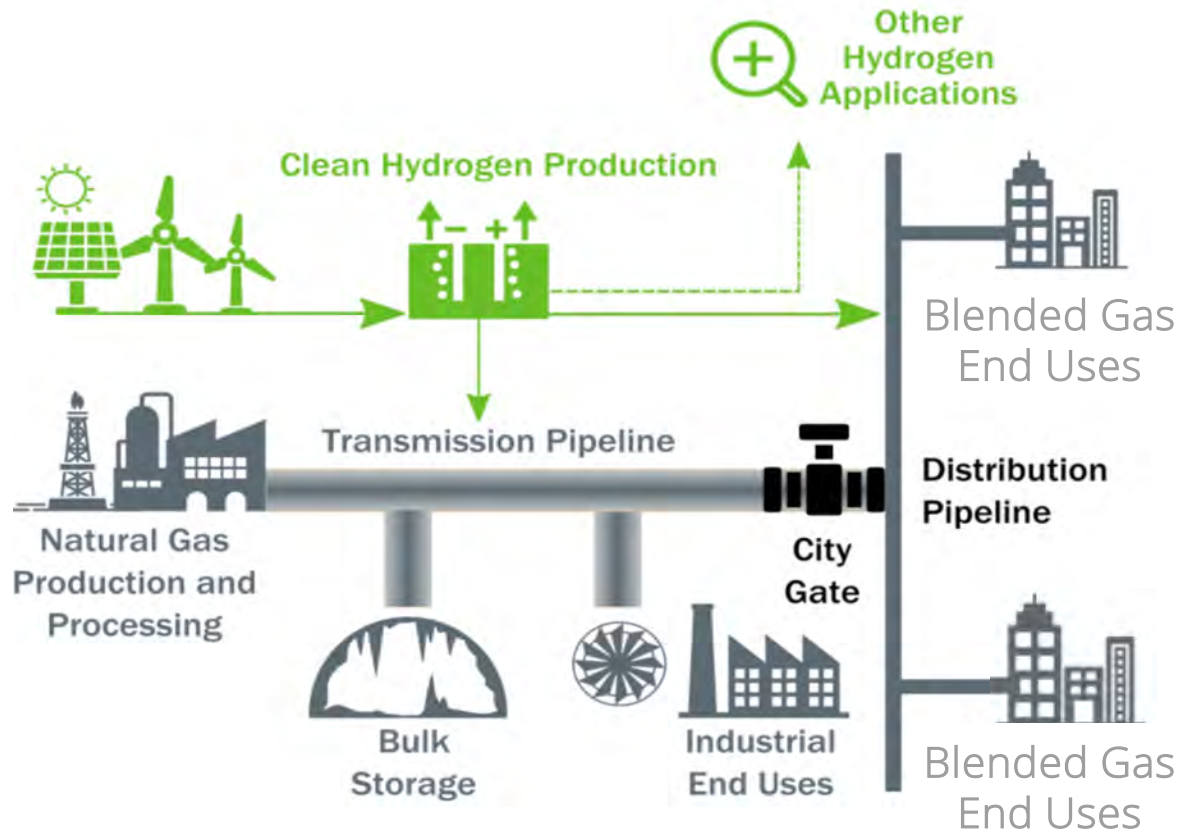
Aug 2nd, 2024

SAND2024-10119PE

Sandia National Laboratories is a multission 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.



Pipeline Blending CRADA

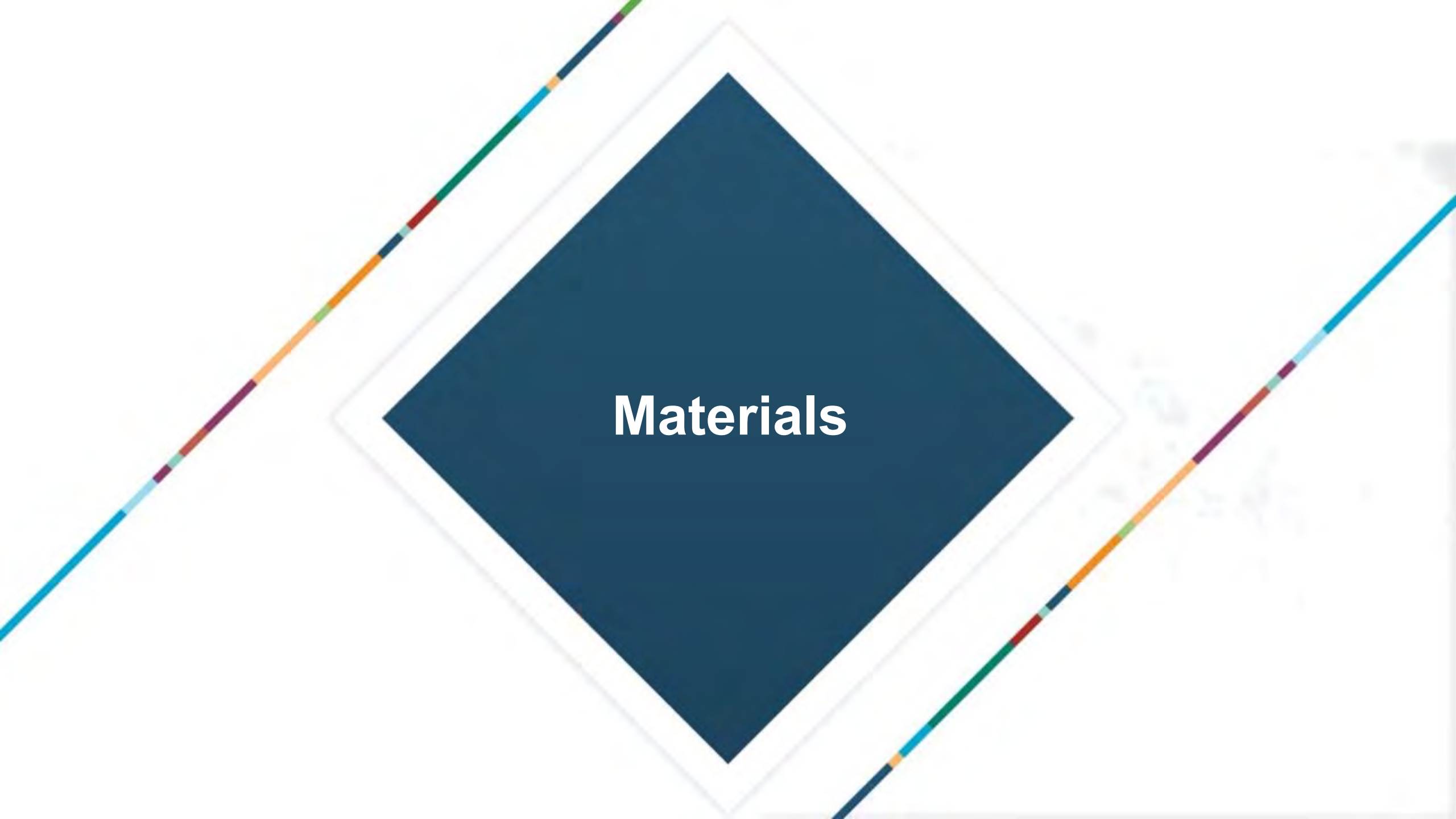


- 13 Vintage Base Metals (X46 to X60 grades)
- 13 Modern Base Metals (X52 to X120 grades)
- 8 Seam Welds
- 4 Simulated High Hardness Microstructures



Outline

- Materials
- Hydrogen Assisted Fatigue Crack Growth
 - Strength
 - Vintage
 - Fracture Surfaces
- Hydrogen Assisted Fracture
 - Modern v/s Vintage
 - Modern (Strength)
 - Modern (Microstructural Constituents)
 - Vintage (Inclusions)
 - Fracture Surfaces
- Summary



Materials



Chemical Composition – Modern vs Vintage

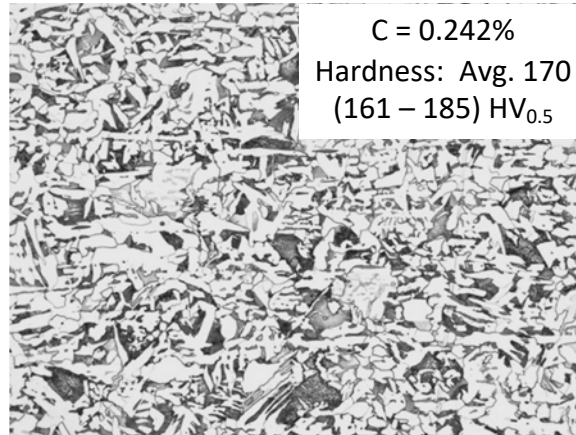
M
O
D
E
R
N

V
I
N
T
A
G
E

Grade	ID	Year	Composition in wt. %								
			C	Si	Mn	P	S	V	Nb	Ti	B
X52	X52J	1990s	0.058	0.12	0.91	0.014	0.006	<0.002	0.027	<0.002	<0.002
X65	X65	1990s	0.08	0.32	1.53	0.01	0.001		0.039	0.002	0.0002
X80	X80E	2000s	0.054	0.15	1.7	0.011	0.002	0.008	0.1	0.015	
X100	X100A	2000s	0.085	0.26	1.69	0.013	0.001		0.05	0.02	
X120	X120	2000s	0.042	0.09	1.97	0.007	0.001	0.008	0.03	0.001	
X52	X52 (1950)	1950	0.242	0.08	1.01	0.021	0.041	<0.002	<0.005	<0.002	<0.002
X52	X52 (1952)	1952	0.26	<0.01	0.94	0.024	0.028	<0.008	<0.008	<0.008	<0.008
X52	X52 (1959)	1959	0.262	0.01	1.06	0.012	0.018	<0.002	<0.005	<0.002	<0.002
X52	X52 (1962)	1962	0.293	0.02	1.17	0.016	0.016	<0.002	<0.005	<0.002	<0.0005
X52	X52 (1964)	1964	0.238	0.064	0.96	0.011	0.021	0.002	0.001	0.002	

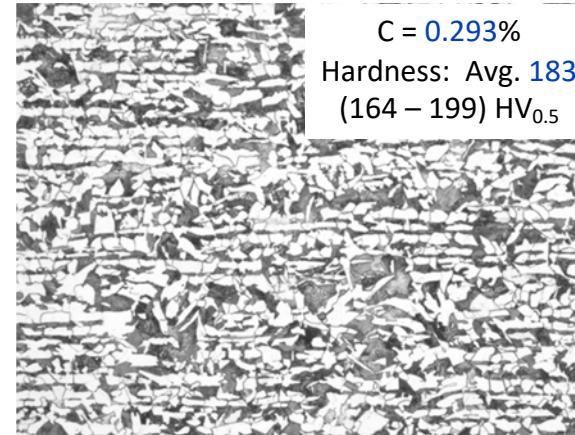
Pipeline Steel Microstructures

Vintage
Ferrite / Pearlite



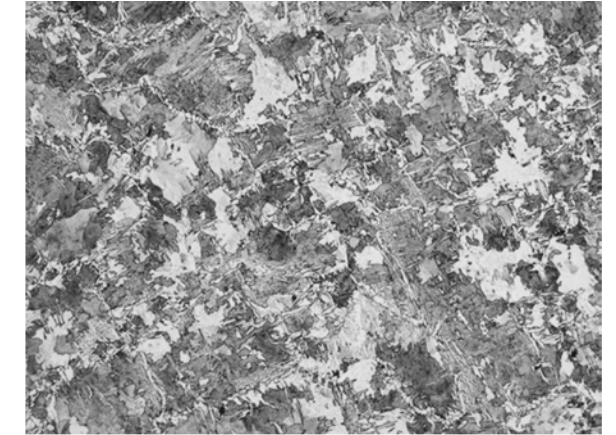
B50

100 μm



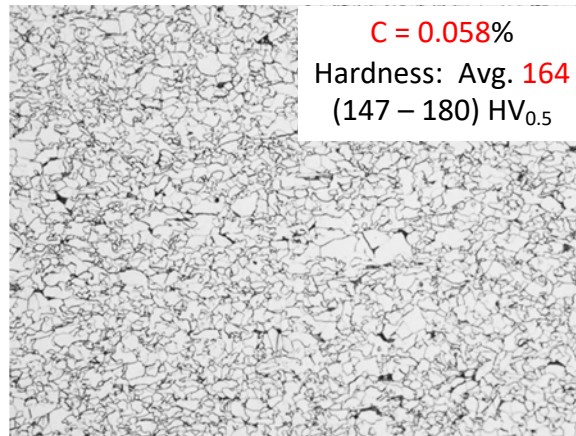
N62

100 μm



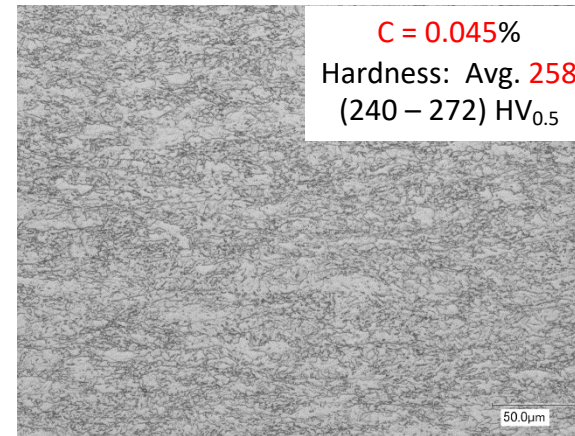
Y59 Weld

100 μm



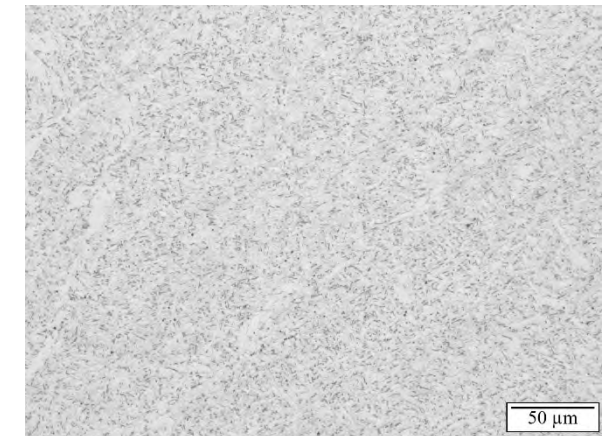
J00

100 μm



X80

50.0 μm



E21 weld

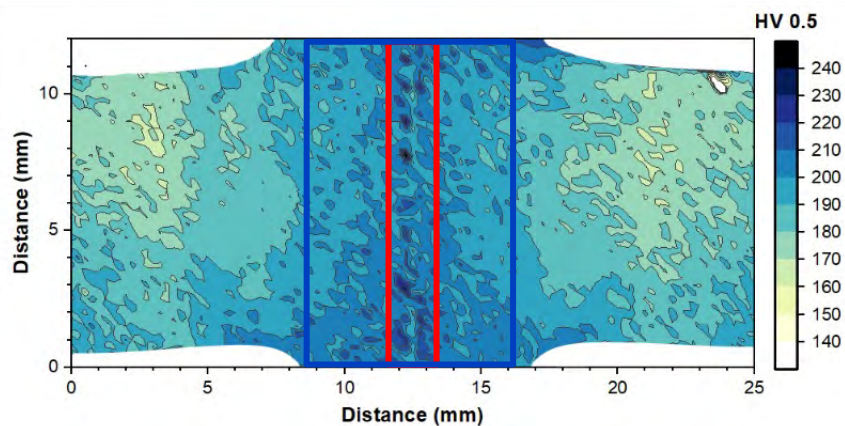
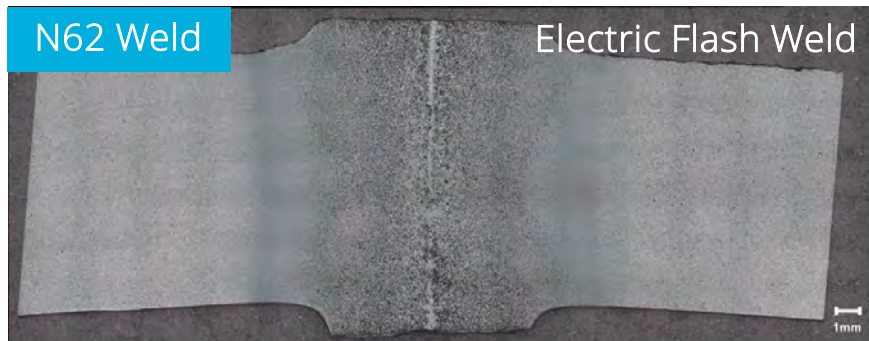
50 μm

Are these microstructures representative / exhaustive?

Pearlite / Inclusions?

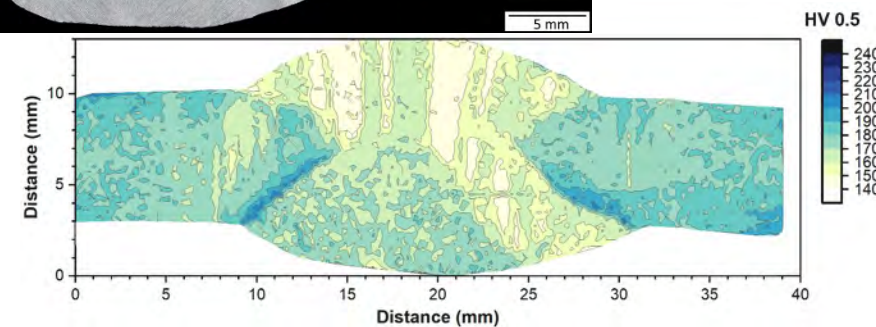
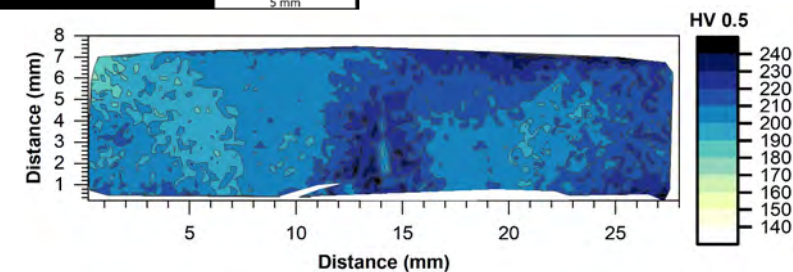
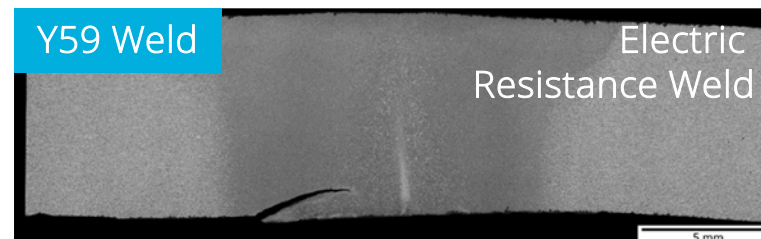


Vintage Weld Regions



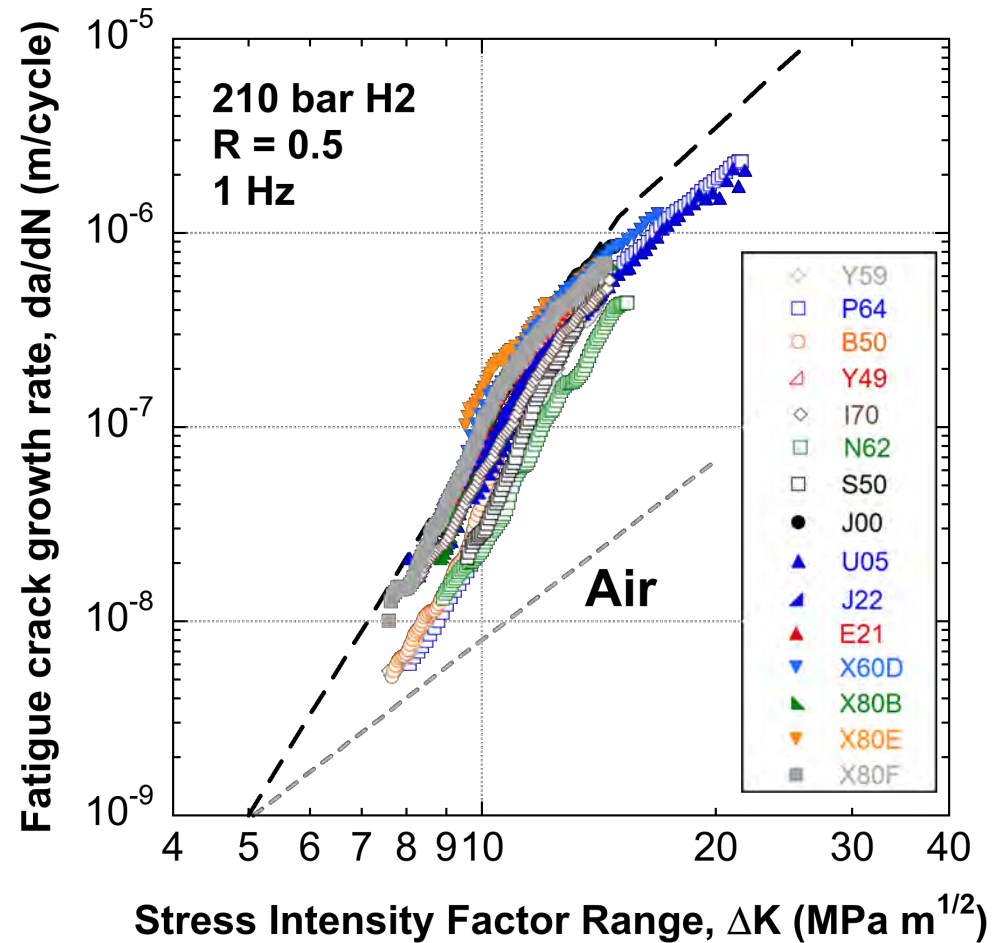
Over 4,500 indents in this case

A Distribution of Hardness Values
Weld Defects and Hard Spots



**Fatigue
Behavior in
Gaseous H₂**

HAFCG Overview



A wide variety of pipeline steels display nominally the same fatigue response in high-pressure gaseous H₂

Material	Microstructure	Vickers Hardness
X52	Ferrite / pearlite	164
X65	Banded ferrite / pearlite	188
X80 (B)	90% PF + 10% AF (coarse)	187
X80 (E)	AF (fine)	222
X80 (F)	70% AF + 30% PF	217
X52 (1950)	Ferrite / pearlite	170
X52 (1952)	Ferrite / pearlite	187
X52 (1959)	Ferrite / pearlite	180
X52 (1962)	Banded Ferrite / pearlite	184
X52 (1964)	Ferrite / pearlite	159



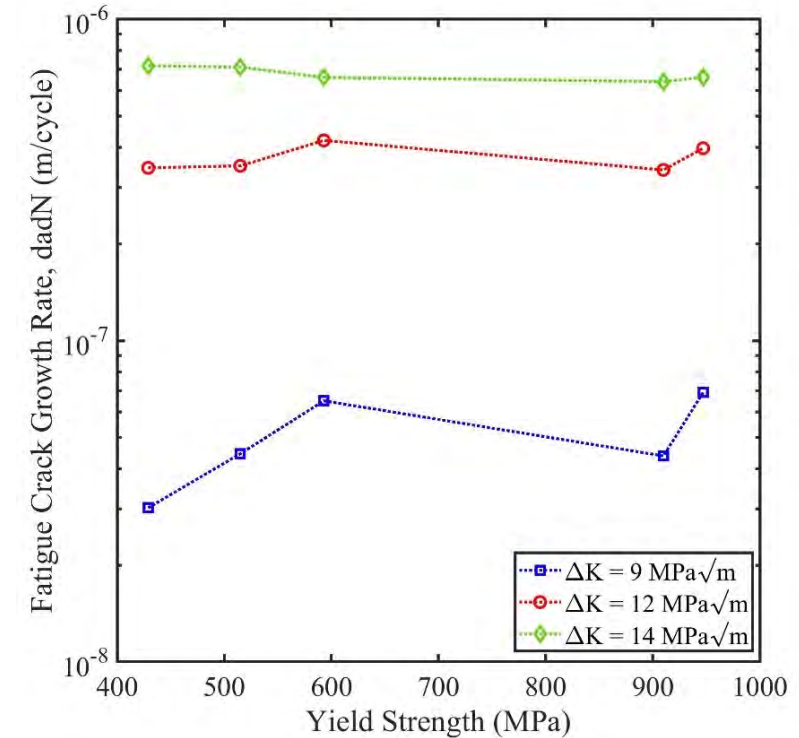
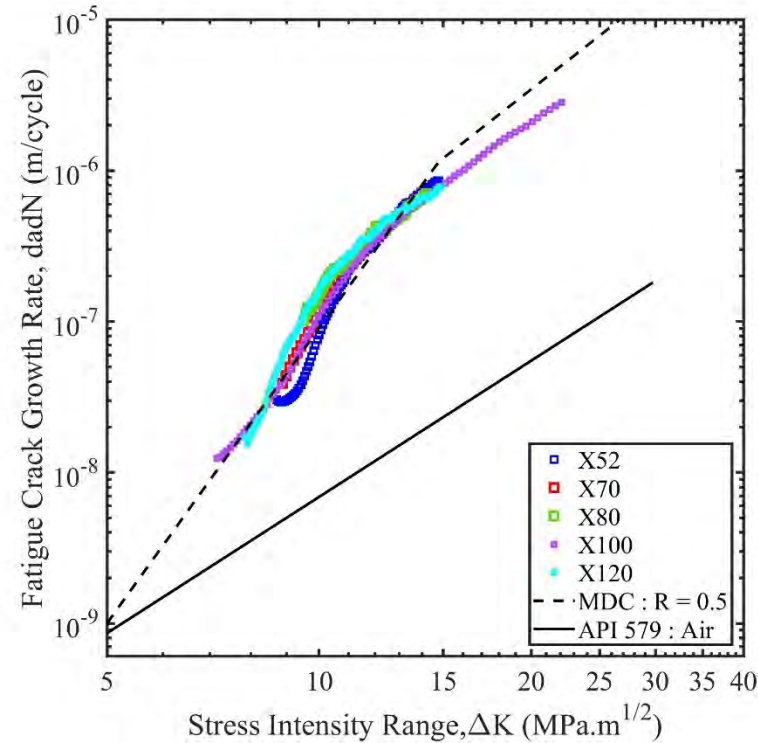
HAFCG - Strength Effects

P = 210 bar GH2

R = 0.5

1 Hz

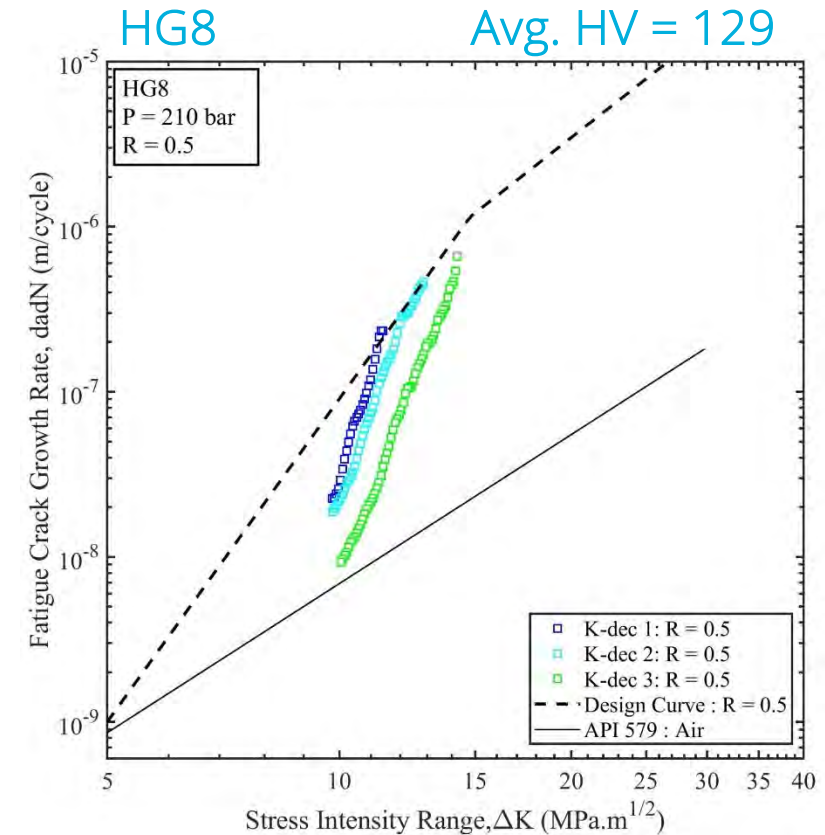
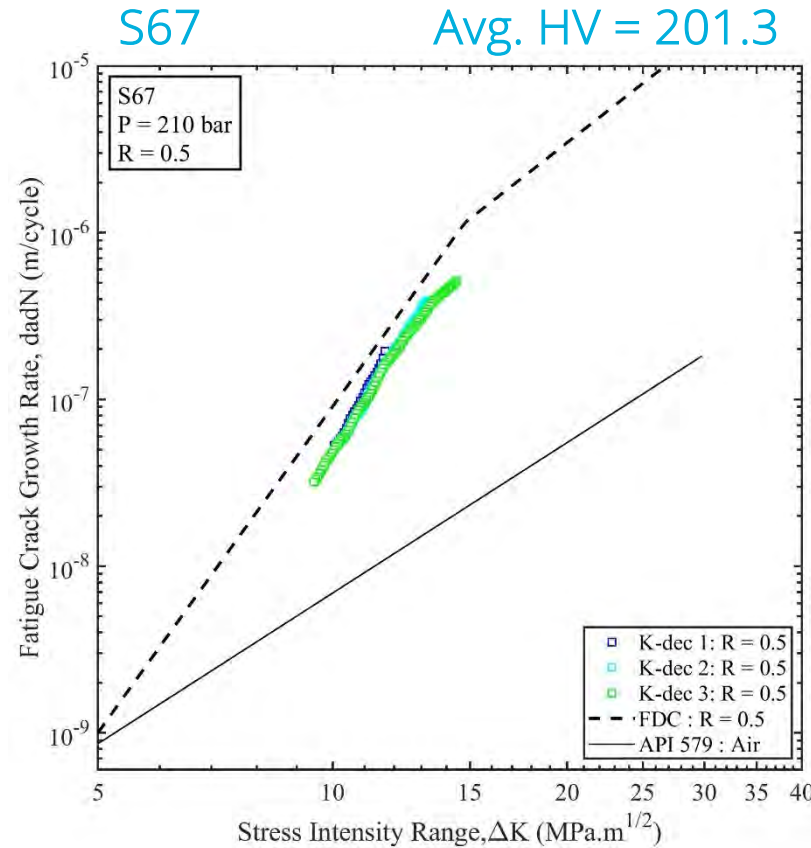
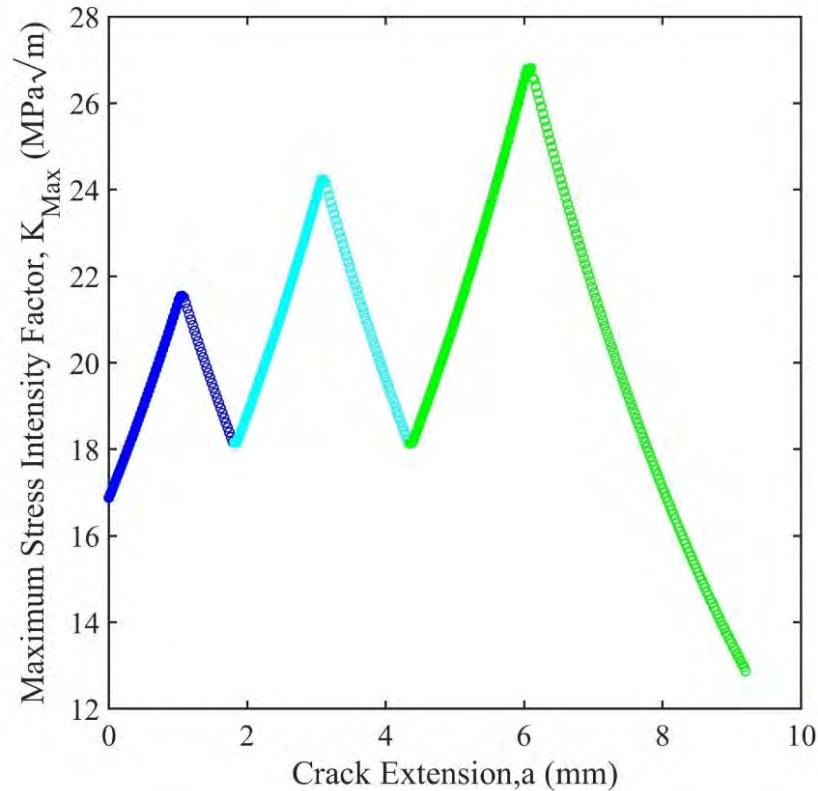
ID	YS (MPa)	UTS (MPa)	Microstructure
X52	429	493	Polygonal Ferrite
X70	515	630	Ferrite/Pearlite
X80	593	710	Acicular Ferrite
X100	910	917	Ferrite/Bainite
X120	947	961	Bainite/Martensite



The HAFCG rates do not directly depend on the strength of the steel

Contradictory observations?

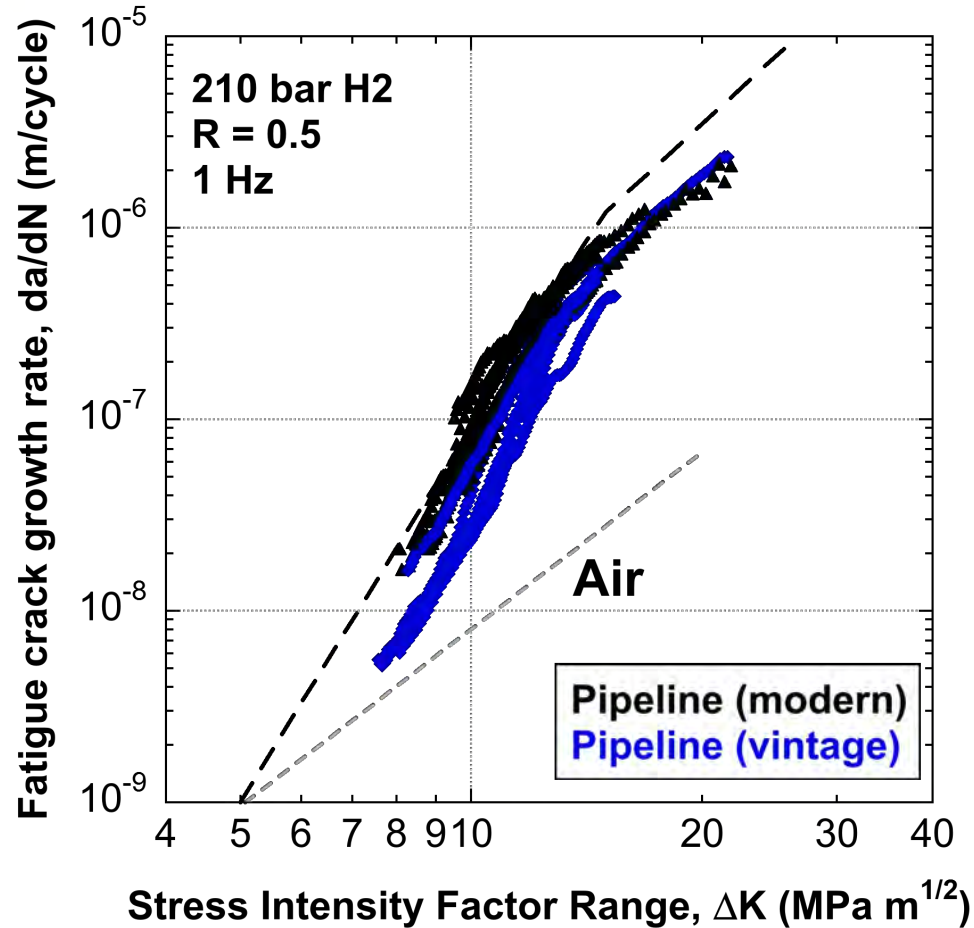
HAFCG - Load History (Effect of Strength)



HAFCG rates depend on prior K_{max} for steel with lower hardness

Implications of prior damage/pressure surge???

HAFCG – Age of the Pipe



- Generally, HAFCG rates are lower in vintage steels (sometimes more than 3 times at low ΔK)
- HAFCG data for modern steels nominally follows FDC
- FDCs serve as upper bound for HAFCG in vintage steels

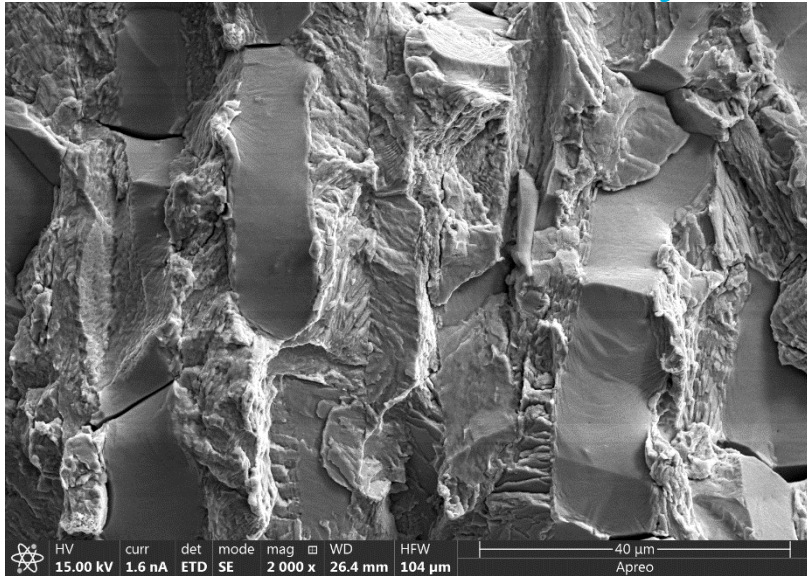


HAFCG – Fracture Surface

$\Delta K = 12 \text{ MPa}\sqrt{\text{m}}$ $P = 210 \text{ bar GH2}$ $R = 0.5$ 1 Hz

U52

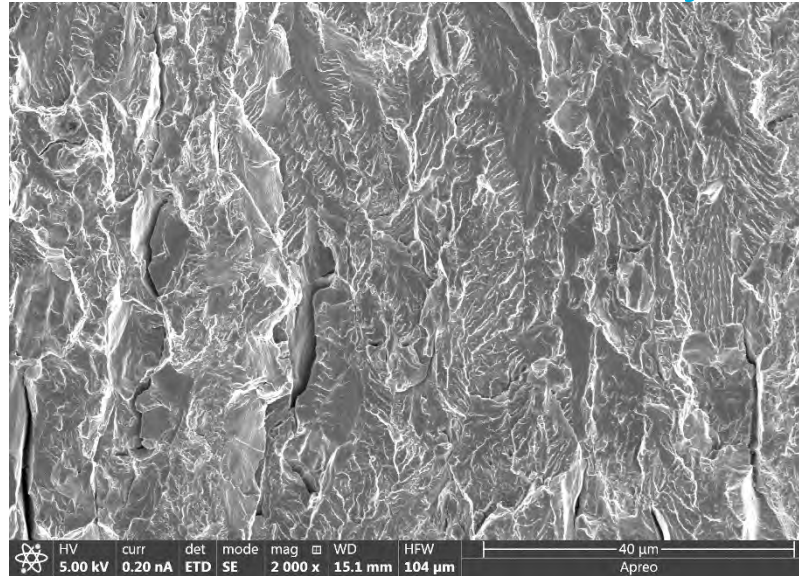
$da/dN: 6e-8 \text{ m/cycle}$



Inter-Granular Ferrite Failure
Trans-Granular Pearlite Failure

E21

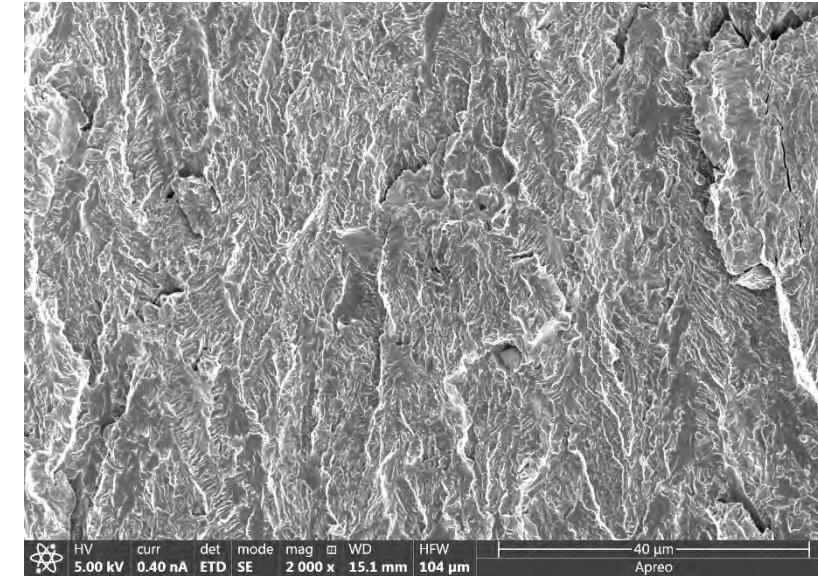
$da/dN: 3.5e-7 \text{ m/cycle}$



Quasi-Cleavage of Ferrite
Inter-Granular Ferrite Failure

X120

$da/dN: 4e-7 \text{ m/cycle}$



Quasi-Cleavage of Bainite/Martensite

Substantial Amount of TG-Pearlite Failure → Lower HAFCG Rates

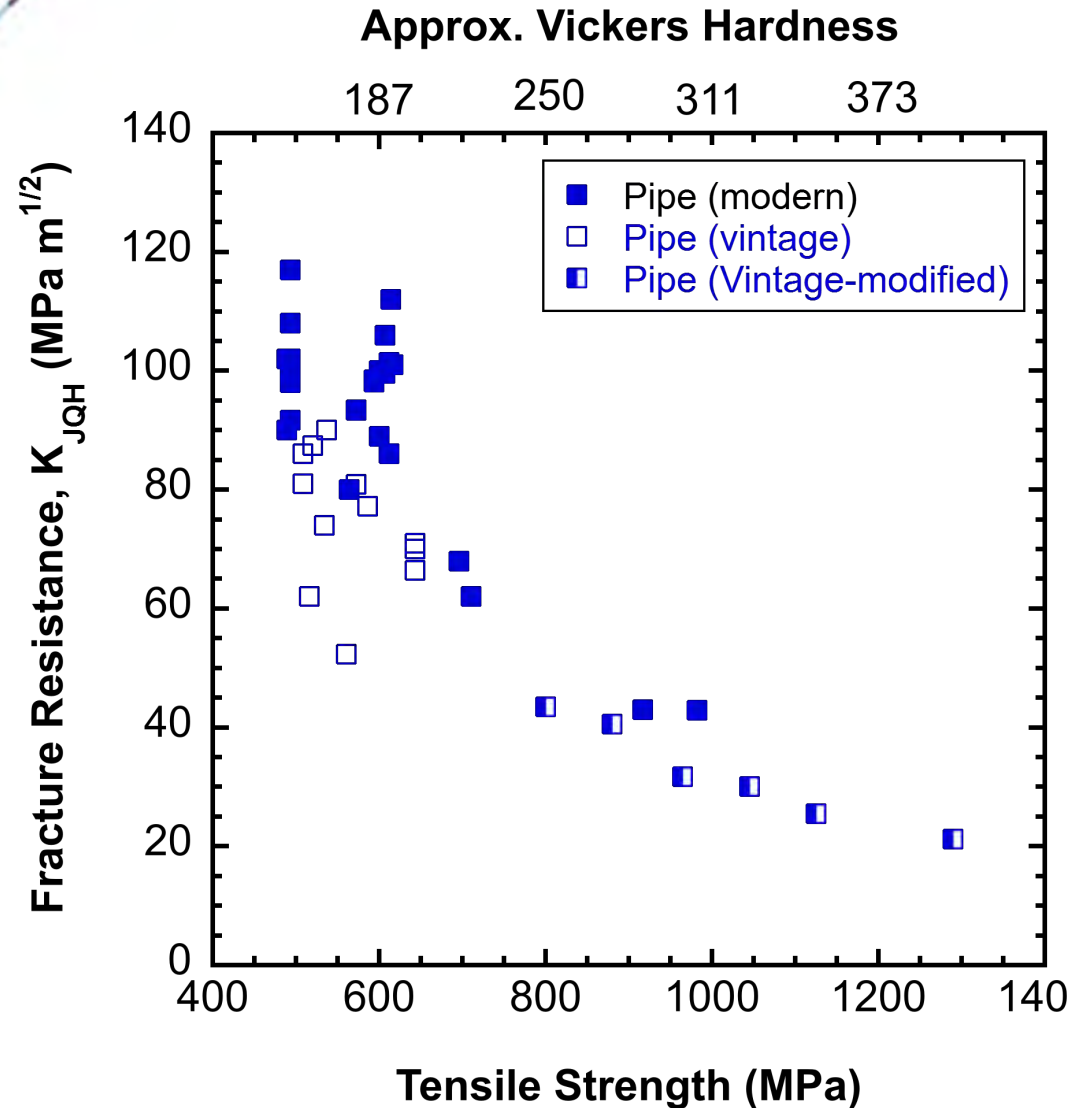
Quasi-Cleavage of Ferrite/Bainite/Martensite → Similar HAFCG Rates

Role of Inclusions?

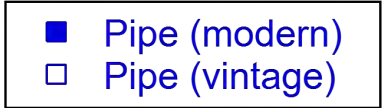
Microstructural Influence on Modern Steels

Trends in
Fracture
Toughness
in H₂

Hydrogen Assisted Fracture (HAF) Overview



- Generally, higher strength steels have lower fracture resistance
- Large scatter in HAF resistance of pipeline steels in low strength regime
- HAF resistance is sensitive to the microstructure

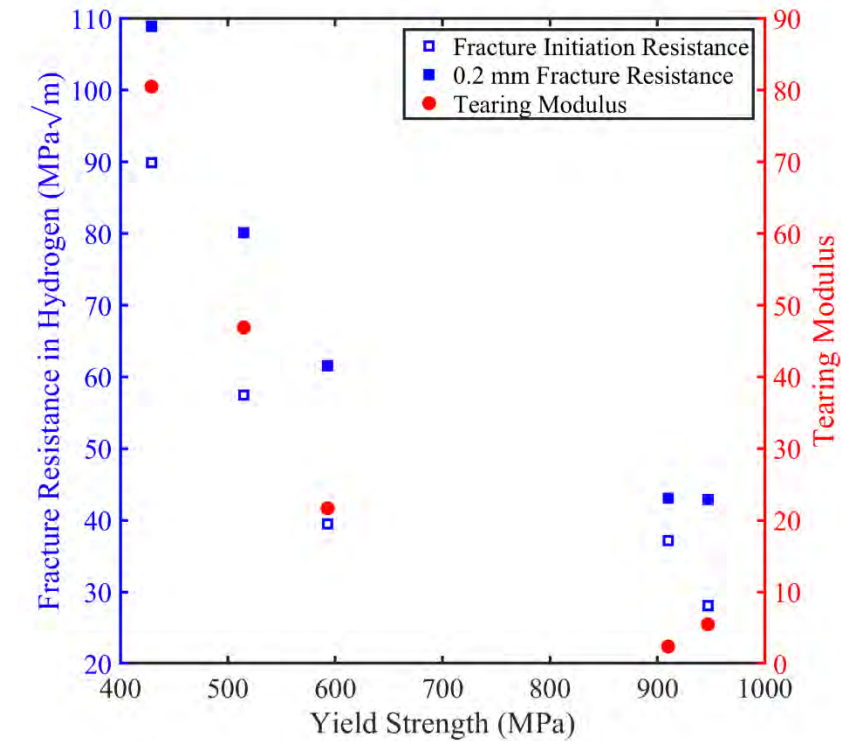
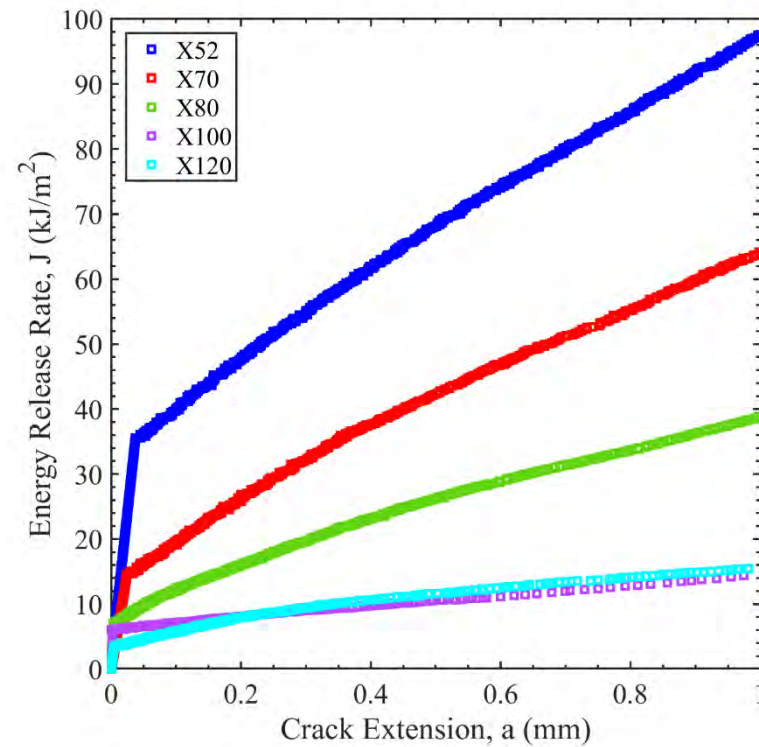


- For a given avg. strength/hardness range, vintage steels typically have lower HAF resistance.
- The difference in HAF resistance of modern and vintage steels is small (compared to air)

HAF – Modern Steel : Strength

P = 210 bar H₂

ID	YS (MPa)	UTS (MPa)	Microstructure
X52	429	493	Polygonal Ferrite
X70	515	630	Ferrite/Pearlite
X80	593	710	Acicular Ferrite
X100	910	917	Ferrite/Bainite
X120	947	961	Bainite/Martensite



Higher Strength Steels have Lower Fracture Initiation and Propagation Resistance

Role of Microstructure?

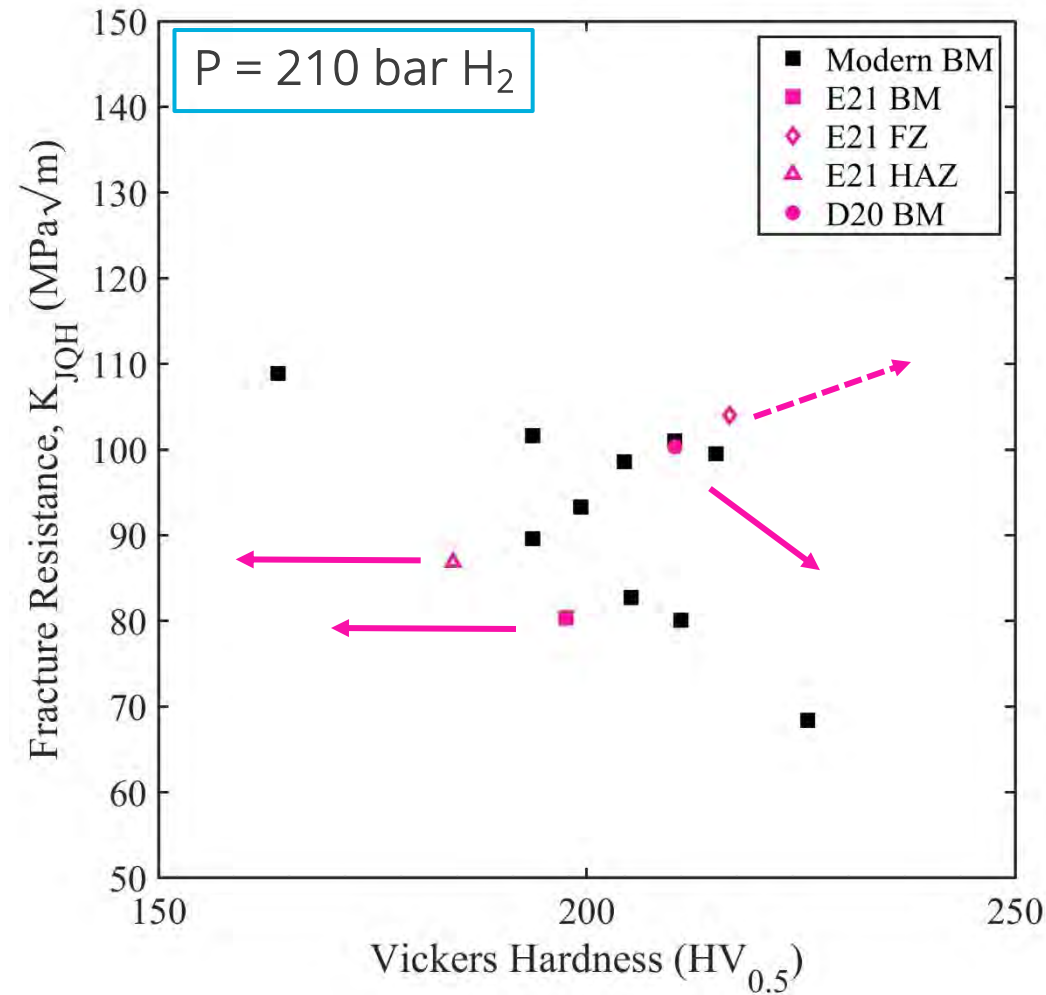
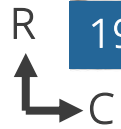
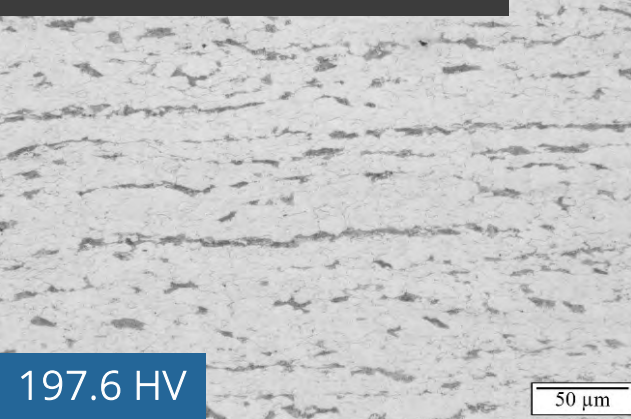
Different H-Concentration or H-Interaction?



HAF – Modern Steel : Microstructure

Comparing
E21 Welded Pipe (DSAW)
& D20 Seamless Pipe

E21 BM : Ferrite/Pearlite

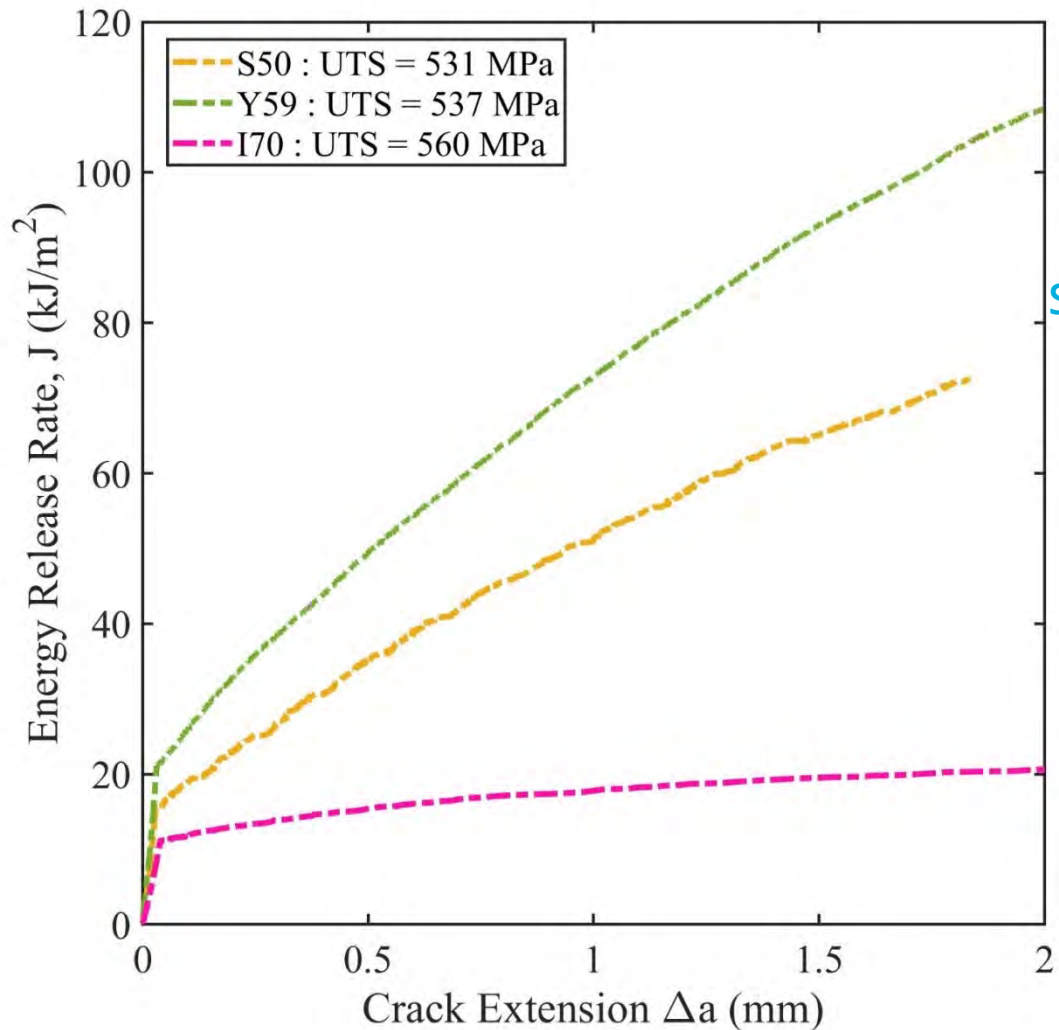


Finer / Uniform Microstructure → Improved HAF Resistance

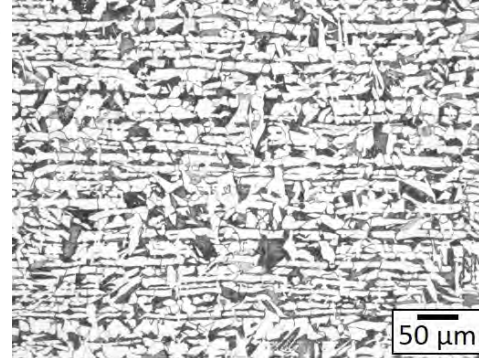
Pearlite is Detrimental

HAF – Vintage Steel : Inclusions

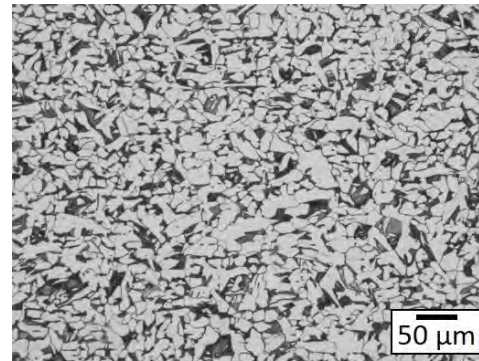
P = 210 bar H₂



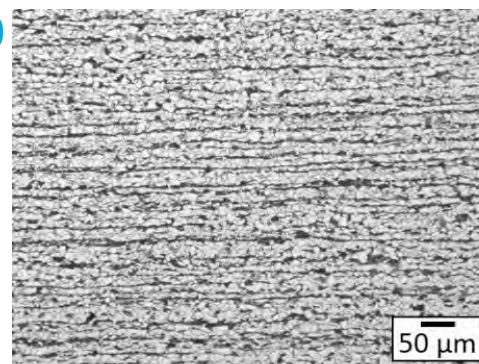
Y59



S50



I70



ID	K_{JQH} MPa $\sqrt{m}$	S content wt.%	Pearlite Fraction
Y59	89.7	0.031	33 %
S50	74.7	0.018	31 %
I70	55.1	0.013	26 %

Role of Microstructure?

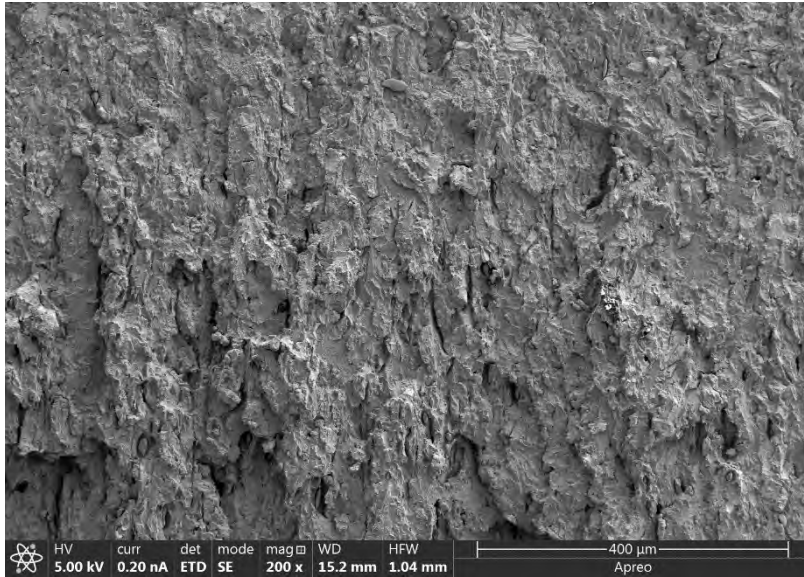
- Inclusions
- Pearlite

HAF – Vintage Steel : Fracture Surfaces

P = 210 bar H₂

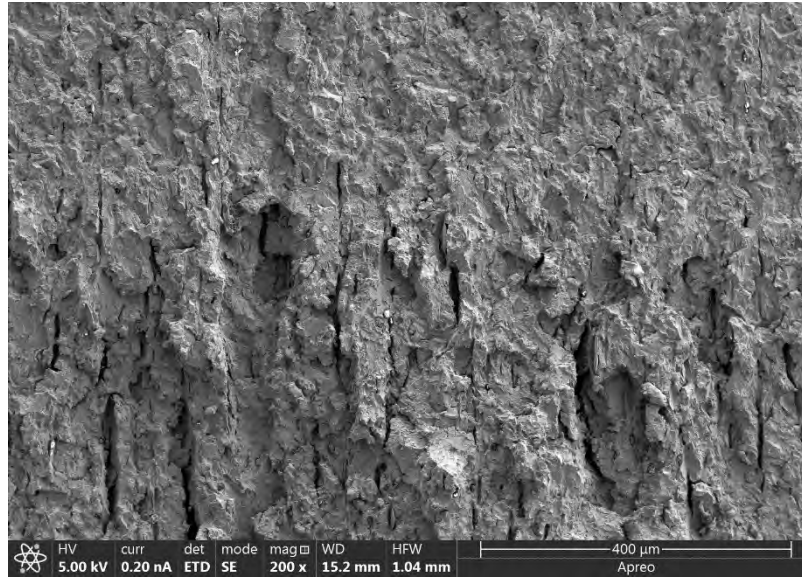
Y59

K_{JQH} : 89.7 MPa√m



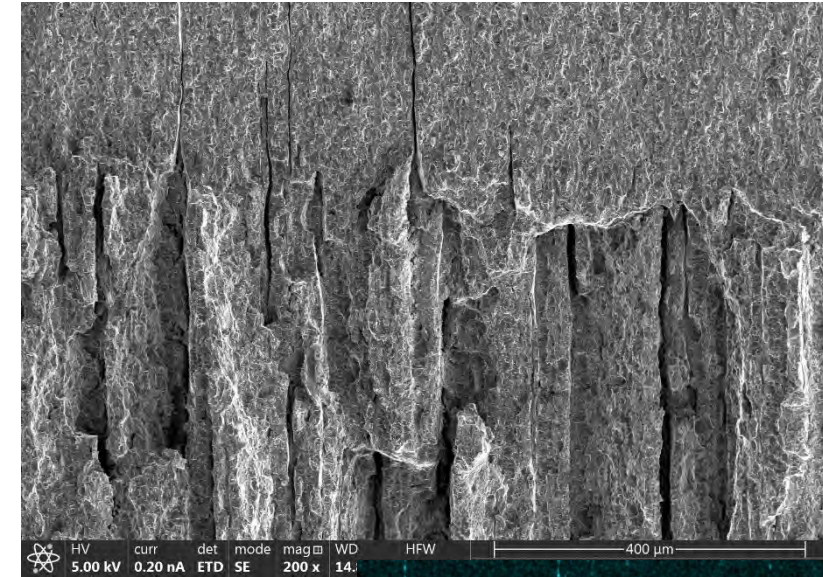
S50

K_{JQH} : 74.7 MPa√m



I70

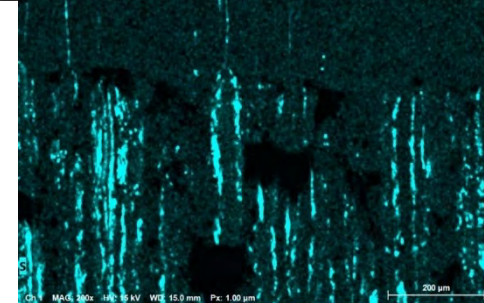
K_{JQH} : 55.1 MPa√m



HAF Resistance of Vintage Steels is Dependent on the Morphology of Inclusions

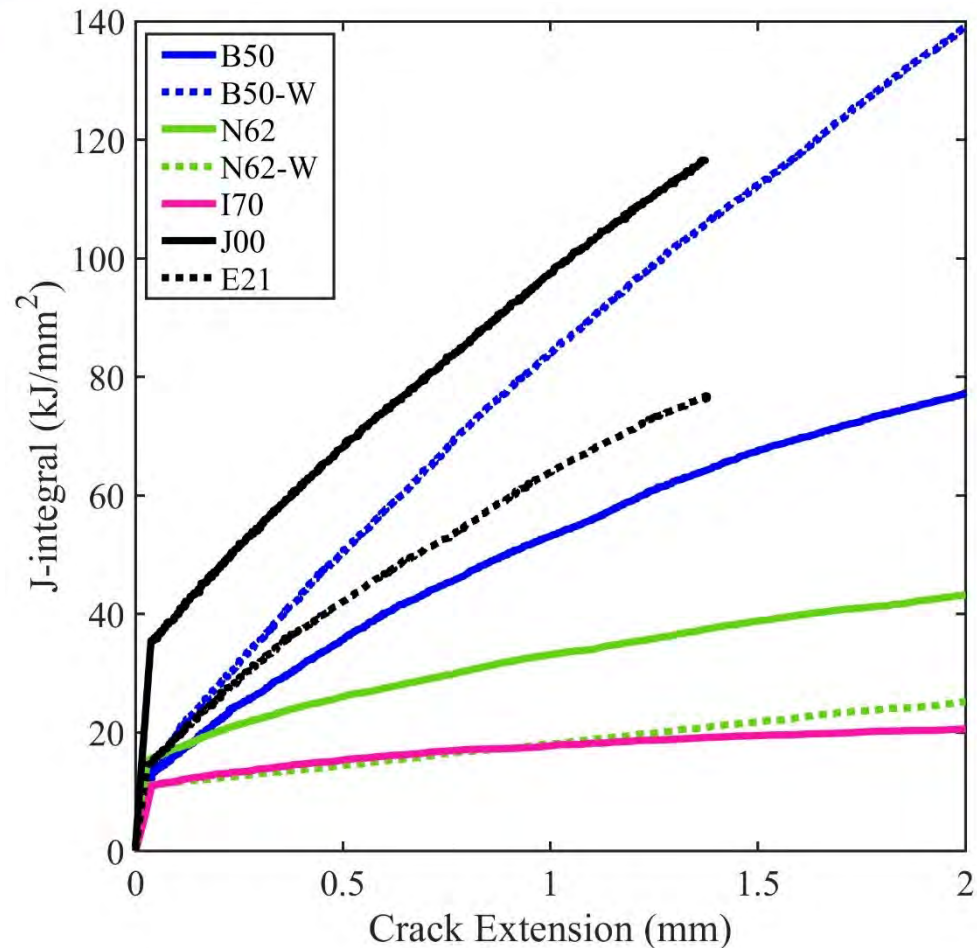
Long Continuous MnS Stringers Promote Delamination and Lower HAF Resistance

The Effects of Pearlite and Inclusions are Coupled



HAF – Welds

P = 210 bar H₂

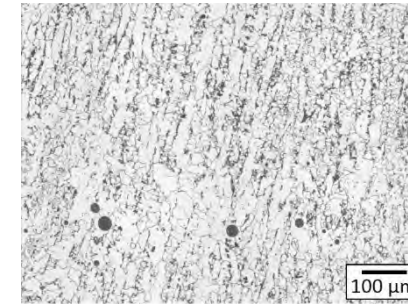


B50



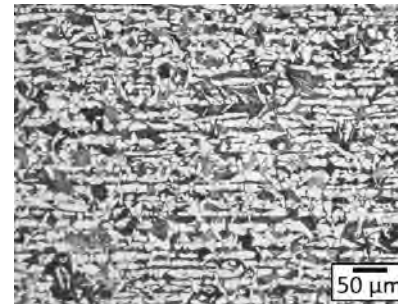
169.9 ± 10.2 HV_{0.5}

Weld Metal

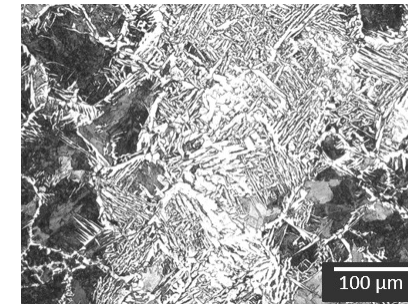


155.6 ± 8.2 HV_{0.5}

N62



183.9 ± 10.2 HV_{0.5}



204.8 ± 11.7 HV_{0.5}

Welds are Similar to Base Metals and Exhibit Same Trends

Inclusion Morphology is Different between BM and Weld



Summary

1. Hydrogen Assisted Fatigue Crack Growth (HAFCG) Behavior

- Consistent HAFCG rates across a range of pipeline steel microstructures
- Strength of the steels does not directly affect HAFCG rates
- HAFCG rates are generally lower in vintage steels due to their higher pearlite content

2. Hydrogen Assisted Fracture (HAF) Resistance

- Higher strength pipeline steels generally have lower HAF resistance.
- Vintage steels tend to have lower HAF resistance than modern steels (similar strength)
- Modern pipelines with finer/uniform microstructures exhibit superior HAF resistance
- Vintage steels with long continuous MnS stringers show lower HAF resistance

Thoughts / Comments?

Study Group on Materials Testing and Qualification for Hydrogen Service

Auditorium - Friday, August 2, 2024

The Hyatt, Bellevue WA
8:00am – 5:00pm (local time)

8:15	Opening Remarks and Introductions
Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.12, Taylor Shie</i>
	<i>Hydrogen-assisted fracture of hard spots, Joe Ronevich</i>
	<i>Brief tutorial on HELPR and discussion of probabilistic tools for fracture assessment, Ben Schroeder</i>
10:00	Break
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe, Bostjan Bezensek</i>
	<i>Subscale testing to simulate full-scale pipe testing, Chris San Marchi</i>
	<i>Fatigue life testing in gaseous hydrogen: crack initiation, Fernando Leon-Cazares</i>
12:00	Lunch (no host)
Test methods for low strength materials	
	<i>Proposed round-robin testing for hydrogen-assisted fracture, Bostjan Bezensek</i>
	<i>Best practices for fracture testing in gaseous hydrogen, Kevin Nibur</i>
15:00	Break
Trends of hydrogen-assisted fatigue and fracture	
	<i>Microstructural effects in hydrogen-assisted fatigue and fracture, Milan Agnani</i>
	<i>Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography, Yazid Madi</i>
Free Discussion/Wrap-up	
17:00	Adjourn



PVP 2024

Hyatt Regency Bellevue, Bellevue, WA
July 29–August 2, 2024



**Study Group on Materials
Testing and
Qualification for
Hydrogen Service**

Auditorium - Friday, August 2, 2024



Strain Rate Effects on Hydrogen Embrittlement in Steel: Insights from X-ray 3D Tomography

**Yazid Madi, L. Meirelles-Santana, V. Okumko,
A. King, T.F. Morgeneyer, J. Besson**

MINES Paris – PSL University - Centre des Matériaux,
UMR CNRS 7633

Motivations

H₂ Tensile tests :

- Multi-cracking at the edge for tests under hydrogen
- Effect of strain rate
- Ductile to quasi-brittle transition fracture

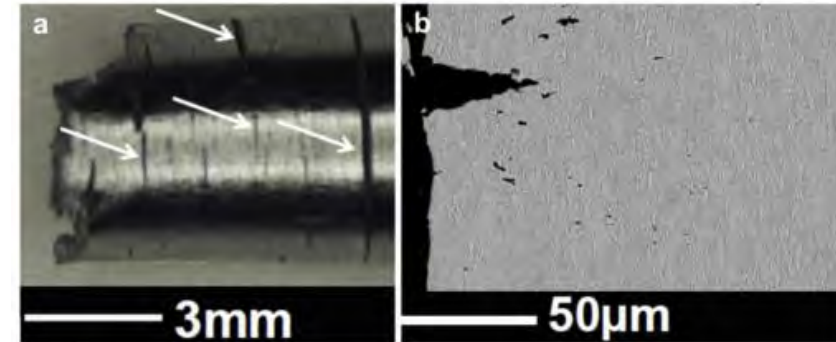
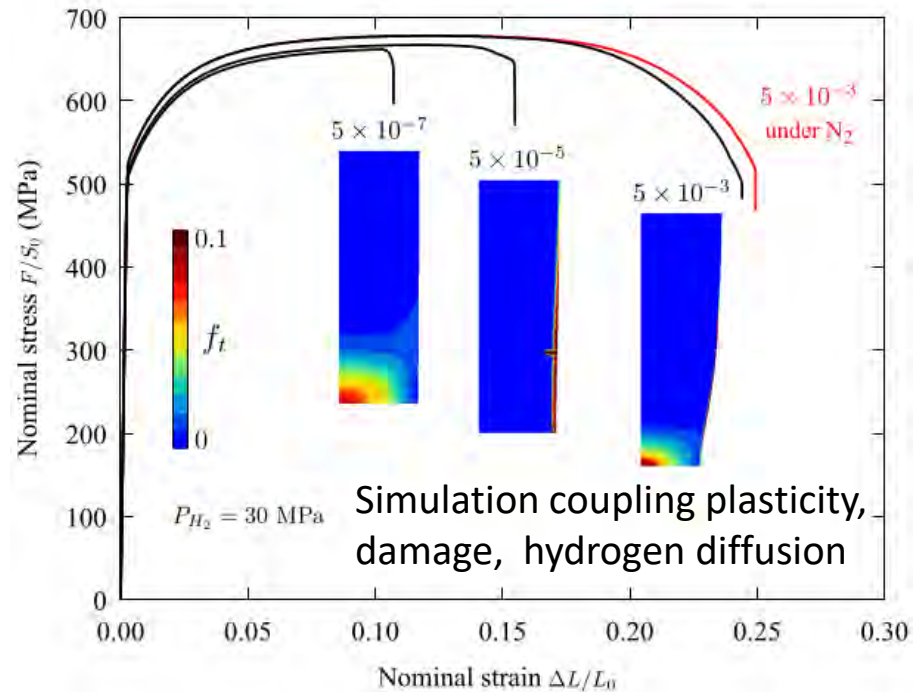
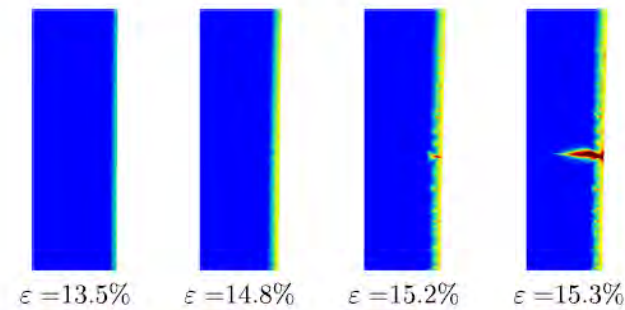


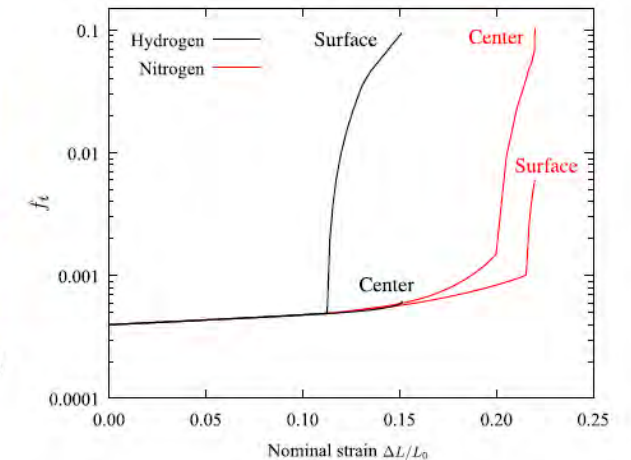
Fig. 9 – Tensile specimen tested in 30 MPa hydrogen at $5 \times 10^{-5} \text{ s}^{-1}$. External surface (a) SEM examination of a longitudinal section (b) [14].

(Experimental data: Briottet *et al.* (2012))

[Pinto et al., EJMS, 2023]



(a)



(b)

Fig. 5. (a) Damage evolution on the surface of the tensile specimen in a H₂ environment. (b) Evolution of the total void volume fraction (f_t) as a function of nominal stress for tensile tests conducted under hydrogen and nitrogen environments. The tests were conducted at a strain rate of $5 \times 10^{-5} \text{ s}^{-1}$.

Geometries and Strain rates employed (Not exhaustive)

NACE TM0198, ASTM G142, ASTM G129, ISO 7539-7 and ANSI/CSA CHMC 1

- Section diameters varies from: 2.5 and 12.5 mm
- Strain rate varies from : $4 \times 10^{-8} \text{ s}^{-1}$ and $2.3 \times 10^{-5} \text{ s}^{-1}$
- NACE TM0198:
 - Diameter of 3.81 mm
 - Strain rate : $1 \times 10^{-6} \text{ s}^{-1}$
- ASTM G142 and ANSI/CSA CHMC 1:
 - Diameter of 6 mm
 - Strain rate : $1 \times 10^{-5} \text{ s}^{-1}$

Open questions:

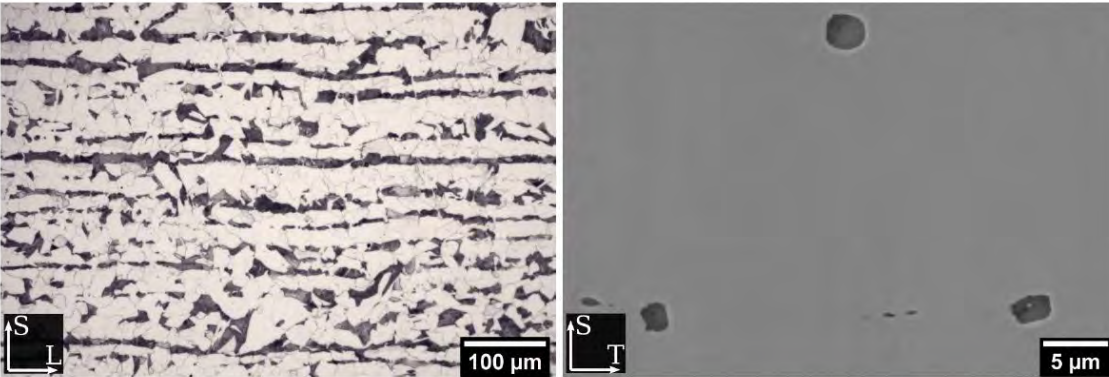
What would be the standard recommendations?

- ✓ Threshold H_2 damage mechanism reached?
- ✓ Material effect?
- ✓ Time test acceptable? $t_c \propto d^2$

Material & Geometry

- E355 Modified 'Modern'
 - Seamless
 - Ø 74.45 mm, thickness 12.7 mm
 - Rolling direction extraction

Microstructure

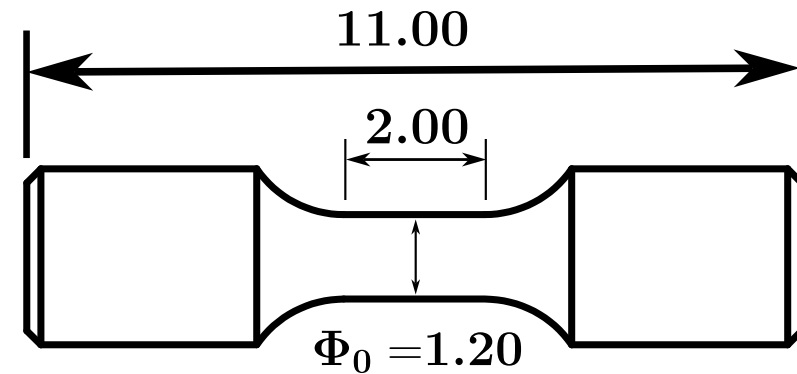


(a) Ferritic matrix with elongated pearlite bands. Average grain diameter is $15.9 \mu\text{m}$.
(b) SEM analysis of unetched specimens reveal few globular inclusions, averaging $0.25 \mu\text{m}$ in diameter,

Chemical Composition

	C	Mn	Si	Cr	Mo	S
E355	0.15	1.38	0.19	0.04	0.01	0.002

Mini-Tensile sample mST12



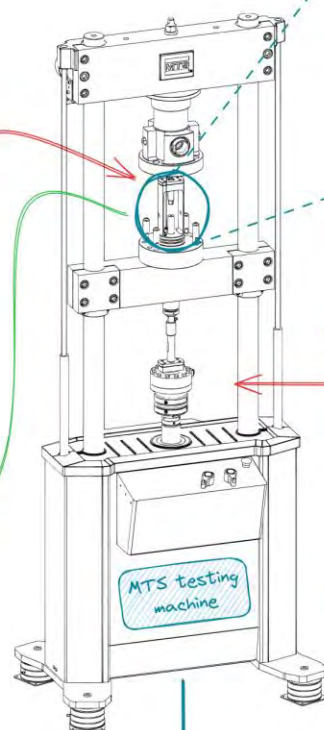
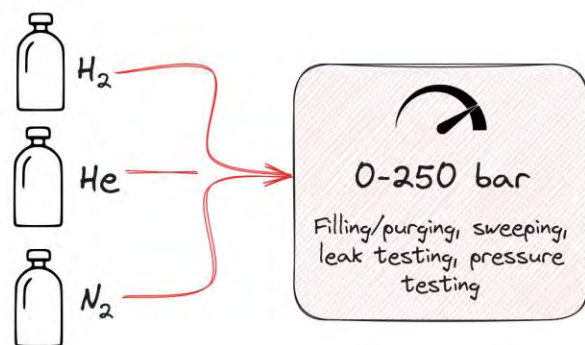
MESSIAH

Hydrogen gas
Testing machine



PSL

Centre des
Matériaux



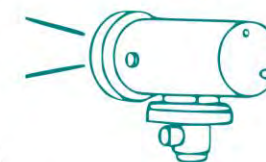
Top industrie
pressure chamber



mST sample
testing



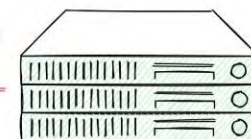
Optical
images



Methodology Mini-samples

Gage, Load
control

MTS
Flextest 40
controller



Transfer of virtual measurements
via EtherCAT communication

Transfer of gage and
load cell informations

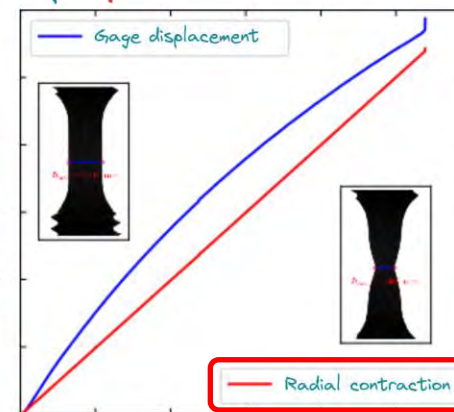
Keyence
controller
Vision



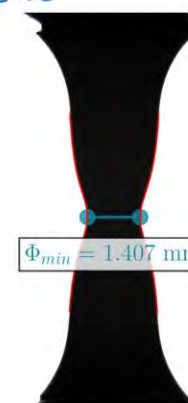
MTS TestSuite
testing program

Sensor
feedback

Gage displacement



Edge tracing
measurements

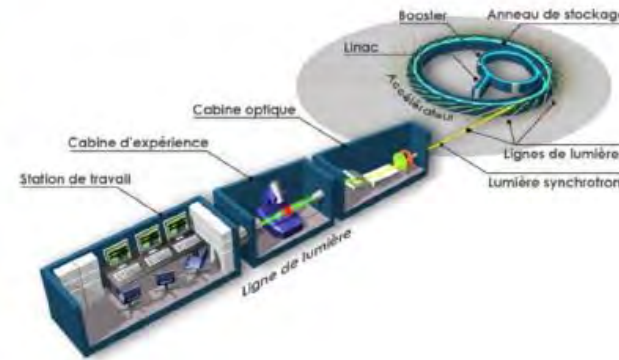


[Madi et al, EFA, 2024]

Gage displacement $\pm 2\text{mm}$ for
small rate control ($0.3 \mu\text{m}/\text{min}$)
5kN Load cell inside the chamber

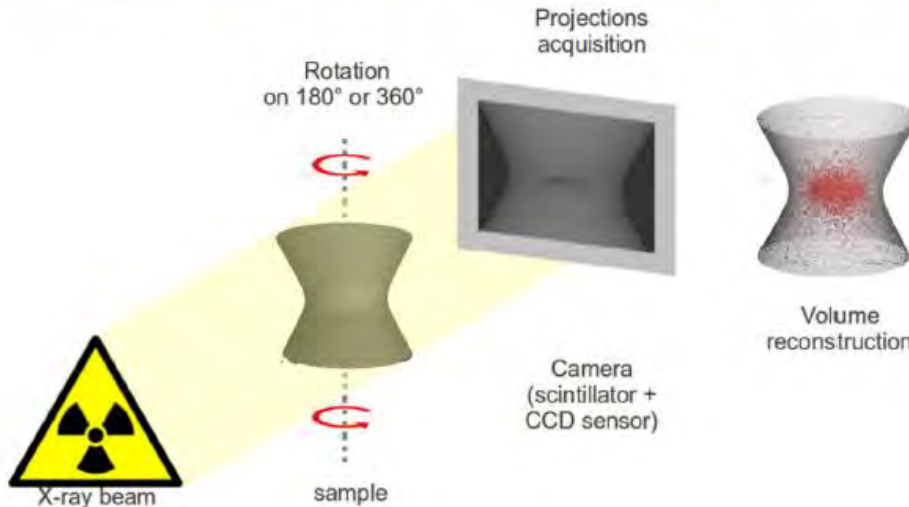
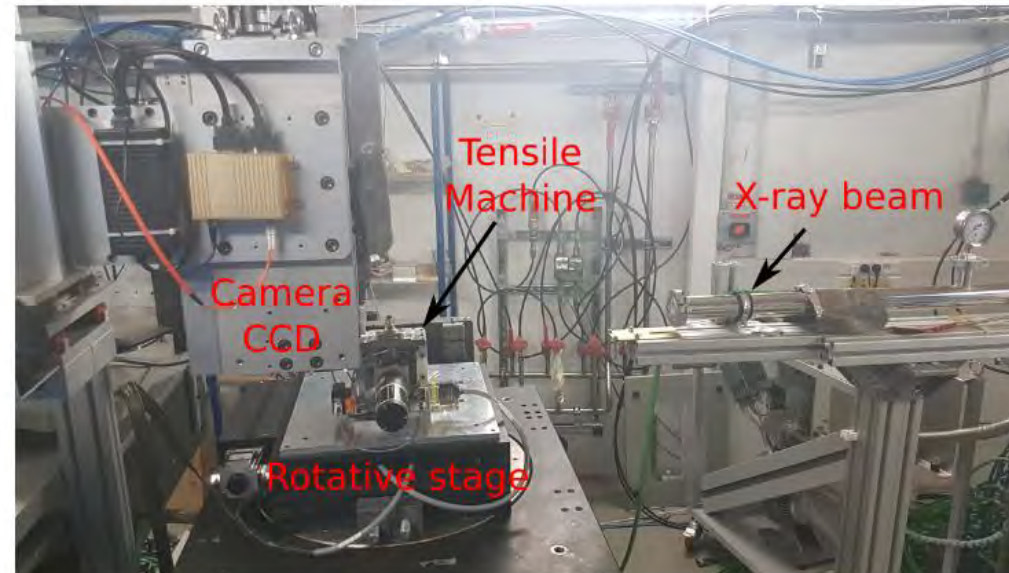
100 bar H₂ external testing stopped, X-Ray tomography observations

In situ experimental device at the PSICHE beamline
(SOLEIL-Paris-Saclay-FRANCE)



mST12

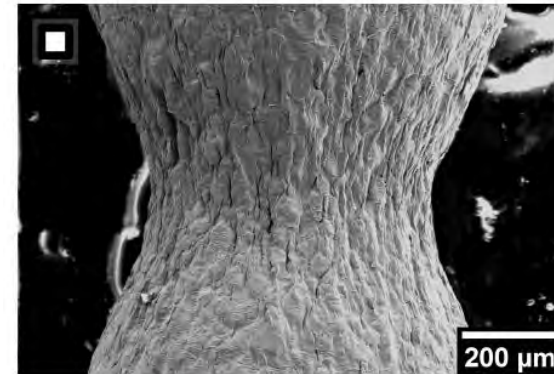
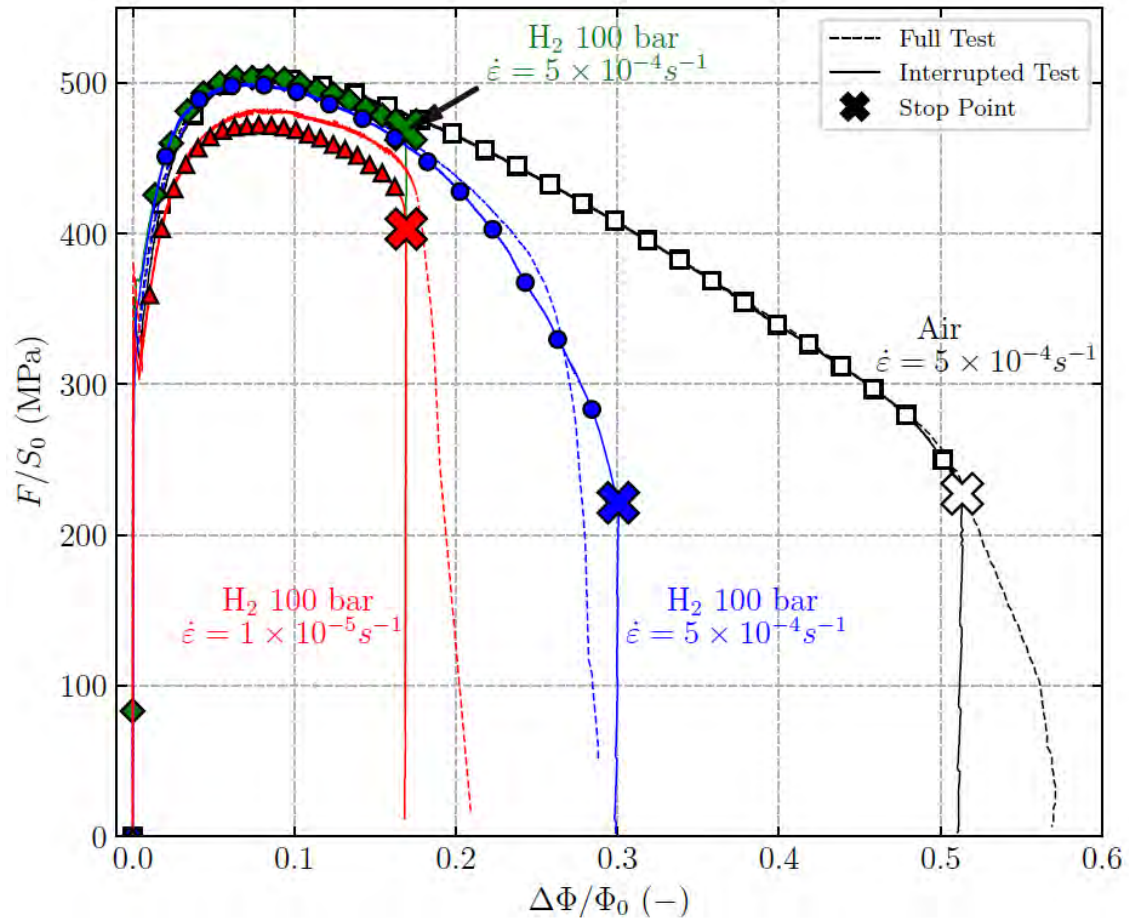
in-situ X-Ray Tomography Setup (Beamline Psiché, Soleil)



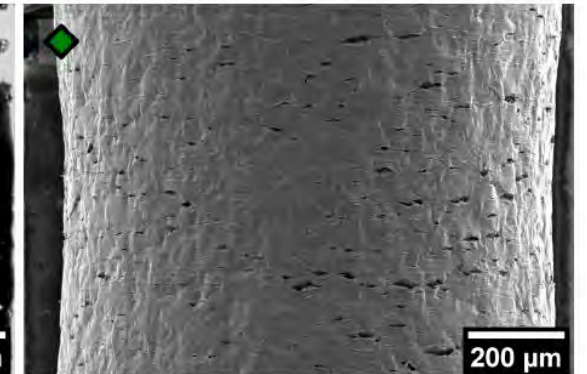
X-Ray tomography Principle

SCAN PROPERTIES	
Energy	65 keV
Pixel size	0.65 micron
Field of view	1.3 mm

Interrupted external 100 bar H₂ Tensile tests



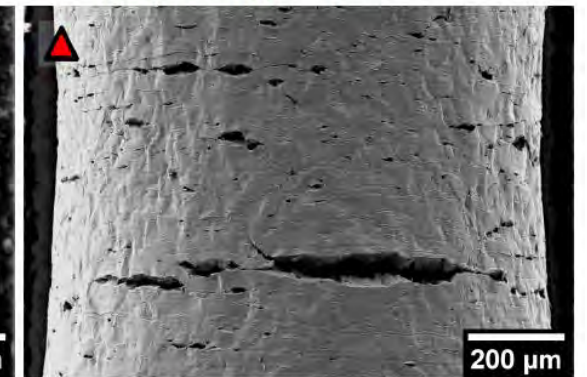
(a) AIR, $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$.



(b) 100 bar H₂, $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$.

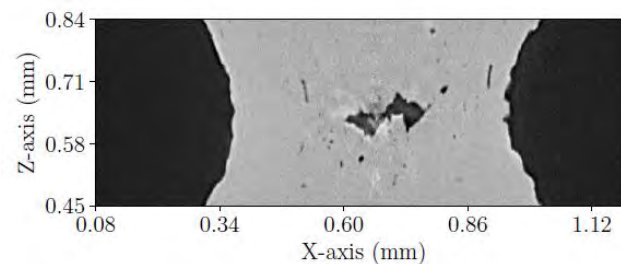
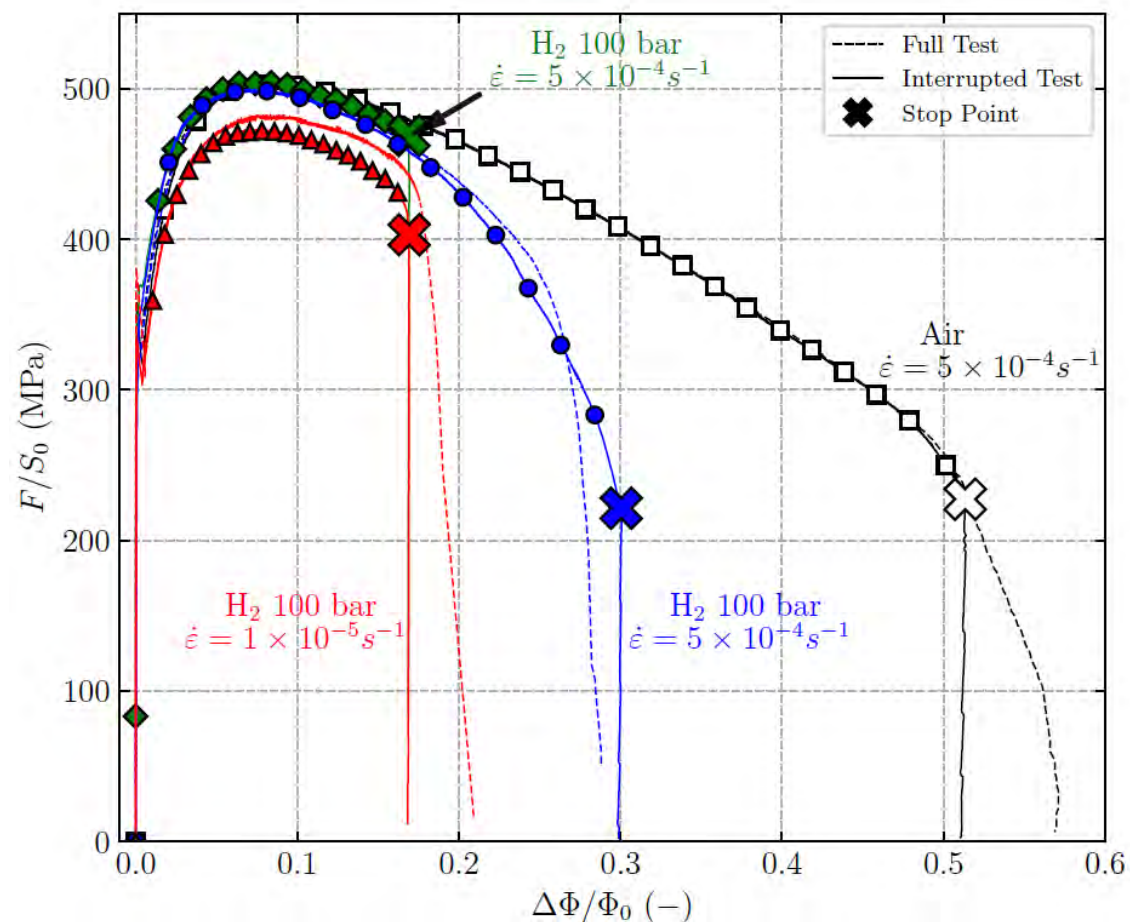


(c) 100 bar H₂, $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$.

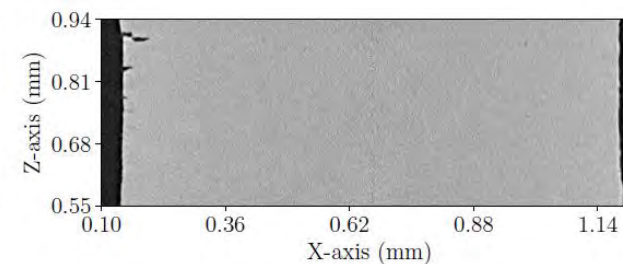


(d) 100 bar H₂, $\dot{\epsilon} = 1 \times 10^{-5} s^{-1}$.

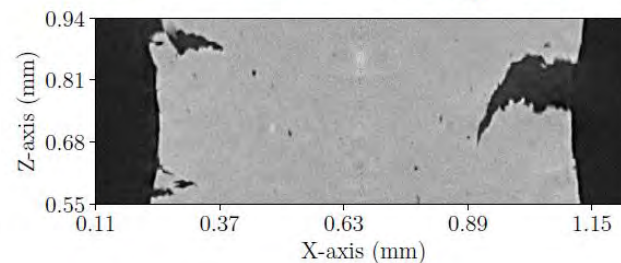
2D X-ray tomography slices



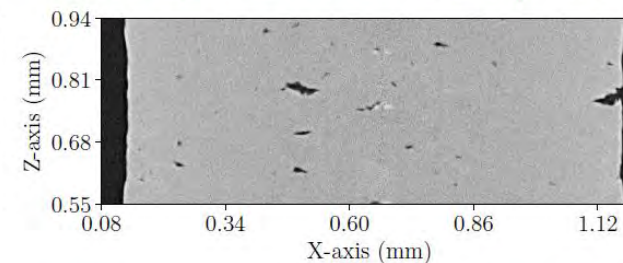
(a) Air - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.51$



(b) 100 bar H_2 - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.17$

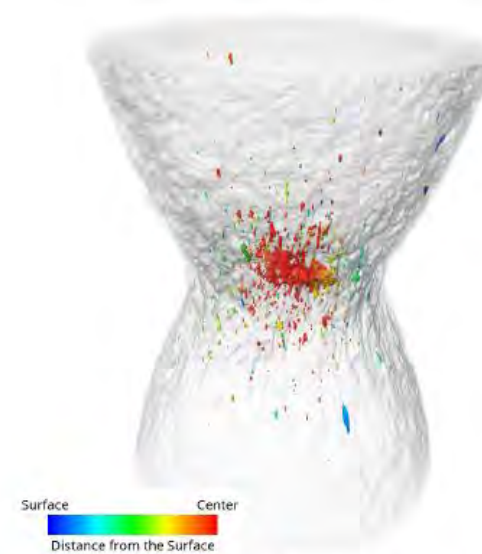
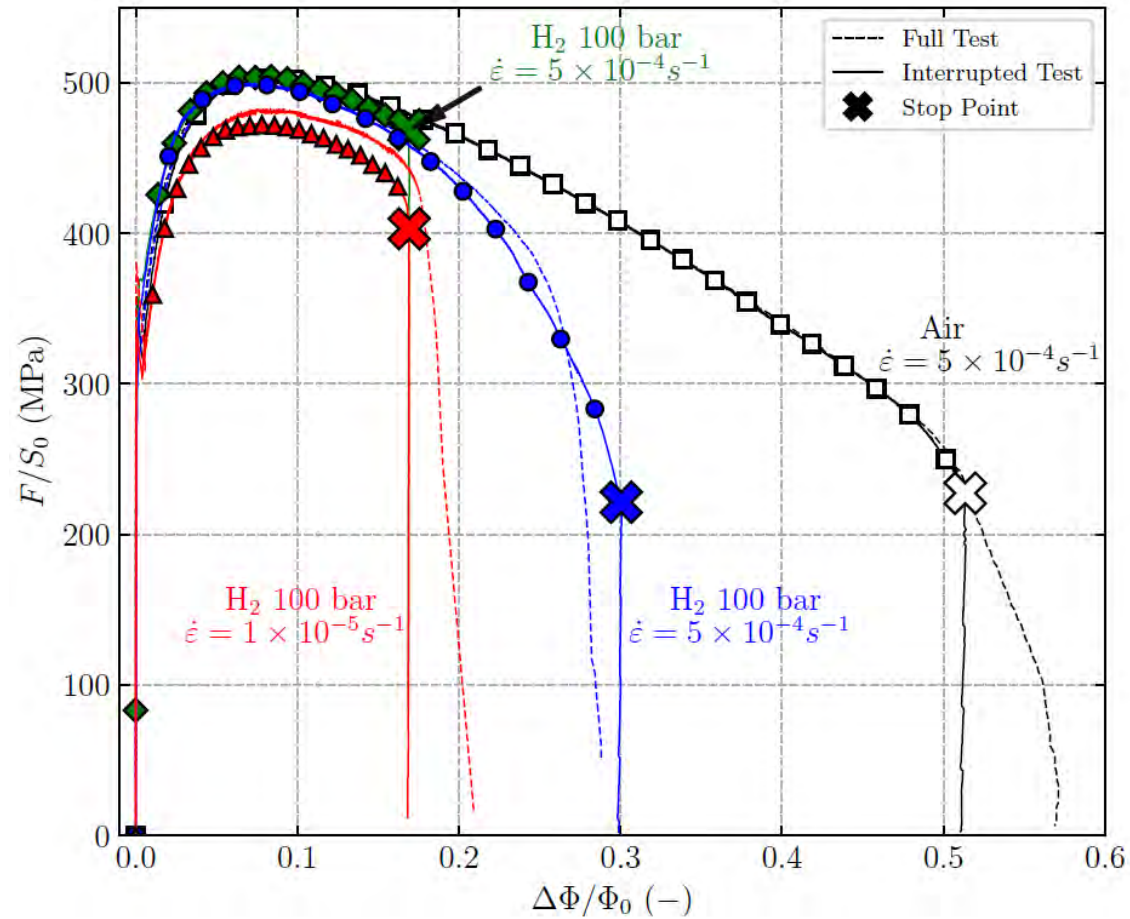


(c) 100 bar H_2 - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.30$

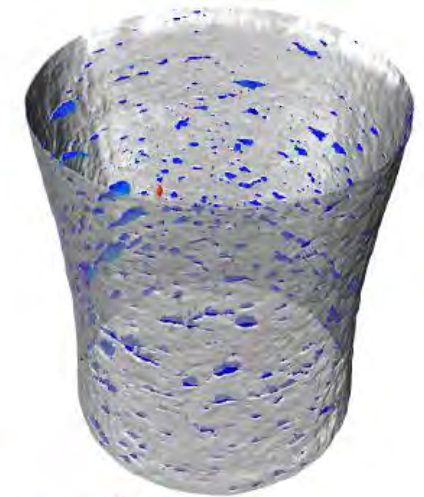


(d) 100 bar H_2 - $\dot{\epsilon} = 1 \times 10^{-5} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.17$

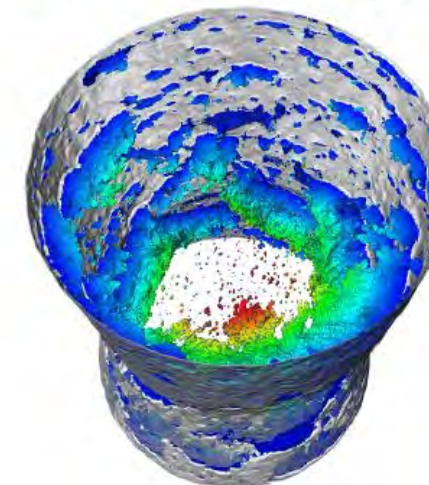
3D damage views



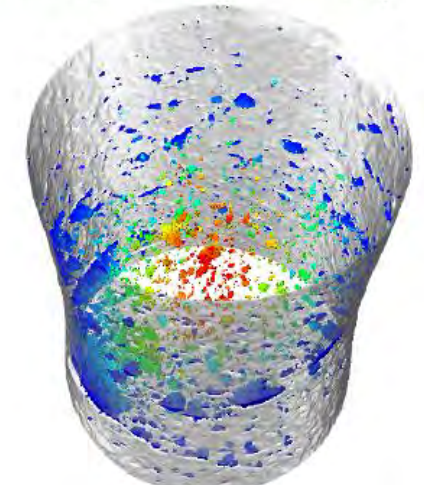
(a) Air - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.51$



(b) 100 bar H_2 - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.17$

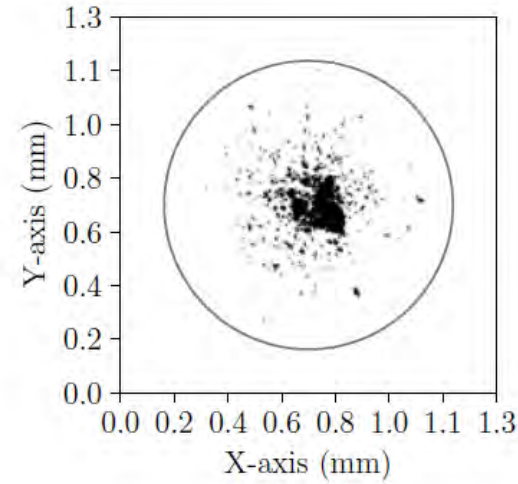
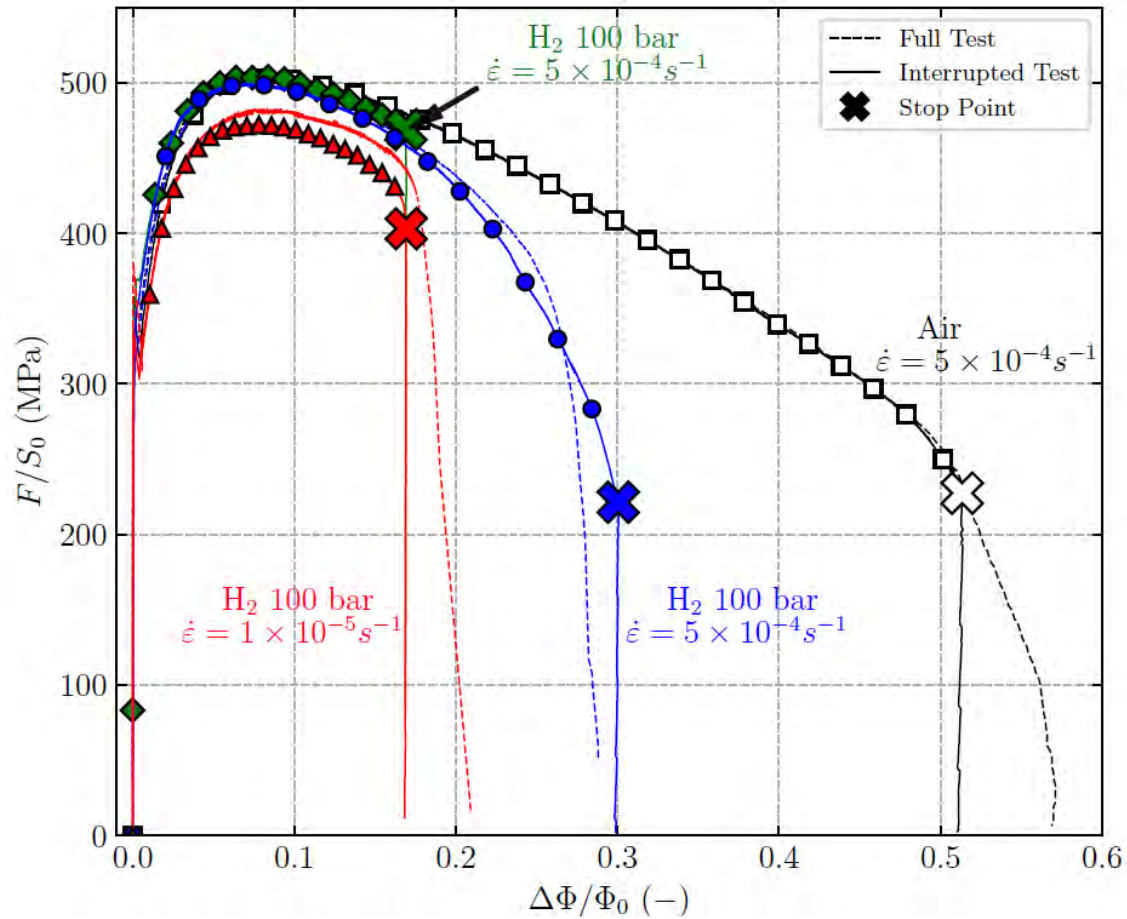


(c) 100 bar H_2 - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.30$

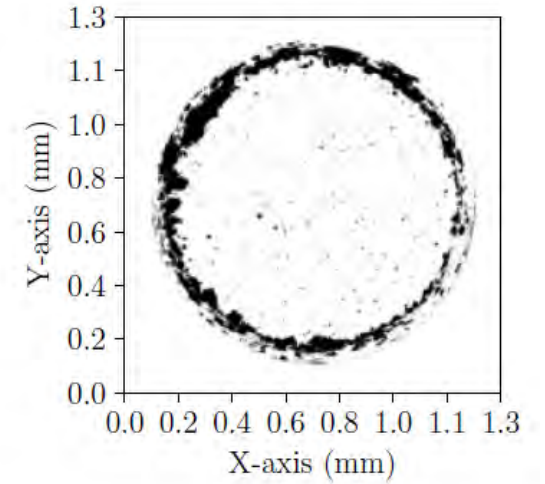


(d) 100 bar H_2 - $\dot{\epsilon} = 1 \times 10^{-5} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.17$

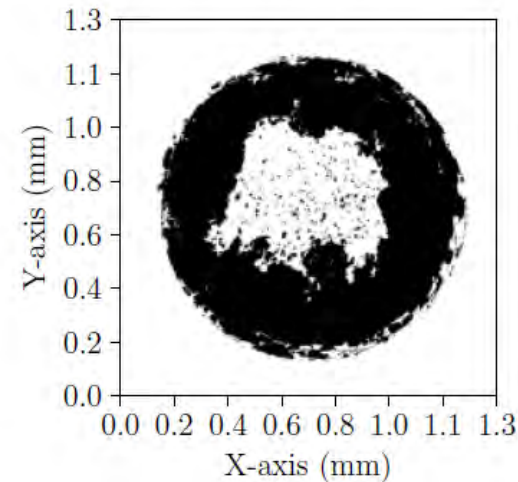
Orthogonal projection of all damage slices



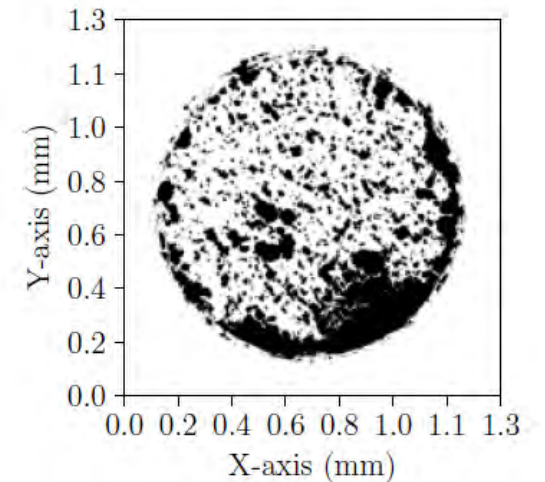
(a) Air - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.51$



(b) 100 bar H_2 - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.17$



(c) 100 bar H_2 - $\dot{\epsilon} = 5 \times 10^{-4} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.30$



(d) 100 bar H_2 - $\dot{\epsilon} = 1 \times 10^{-5} s^{-1}$ - $\Delta\Phi/\Phi_{0f} = 0.17$



PVP 2024

Hyatt Regency Bellevue, Bellevue, WA
July 29–August 2, 2024



This work is funded by ANR
Chair program MESSIAH
(ANR-20-CHIN-0003)

Questions?

yazid.madi@minesparis.psl.eu