

Study Group on Materials Testing and Qualification for Hydrogen Service

Friday, July 25, 2025

Hotel Bonaventure, Montreal 1-3

Montreal, Canada

8:00am – 5:00pm (local time)

Standards for materials testing and hydrogen infrastructure	
	<i>Update on ASME B31.3, B31.8, and other codes</i> open discussion
	<i>Brief overview of ANSI/CSA CHMC1 materials testing standard for hydrogen</i> Chris San Marchi (Sandia National Laboratories)
	<i>Sustained load cracking: fact or myth?</i> Chris San Marchi (Sandia National Laboratories)
Component testing and design methods	
	<i>Full-scale pipeline testing in Europe</i> Bostjan Bezensek (Shell)
	<i>Defect simulation in subscale pipe testing</i> Chris San Marchi (Sandia National Laboratories)
Test methods for low strength materials	
	<i>Round-robin testing for hydrogen-assisted fracture</i> Bostjan Bezensek (Shell)
	<i>ExxonMobil CO₂-H₂ fracture testing efforts to support CCS pipelines</i> Greg Pioszak (ExxonMobil)
	<i>Experience with SENB testing in gaseous hydrogen</i> Lu Sun (C-FER)
	<i>Best practices for fracture testing in gaseous hydrogen</i> Chris San Marchi (Sandia National Laboratories)
Trends of hydrogen-assisted fatigue and fracture	
	<i>Frequency dependence in fatigue testing</i> Fabien Ebling (Fraunhofer)
	<i>Materials selection for hydrogen</i> Chris San Marchi (Sandia National Laboratories)
<i>Addendum: Considerations of Fatigue Design in H₂ Service (PVP2025-152431)</i> Kang Xu (Linde) & Mahendra Rana (Consultant)	



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ANSI/CSA CHMC1 update

Chris San Marchi and Joe Ronevich

Study Group on Materials Testing and Qualification for Hydrogen Service

Montreal, Canada 25 July 2025

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ANSI/CSA CHMC1 – Test methods for evaluating materials compatibility in compressed hydrogen applications - Metals

- **Current status: currently open for public comment**
- **Next steps**
 - Address comments
 - Committee vote
 - If approved, publish – hopefully before end of year



ANSI/CSA CHMC1 – Test methods for evaluating materials compatibility in compressed hydrogen applications - Metals

- **Section 4 – General requirements**
 - Hydrogen gas purity
 - Measurement and instrumentation
 - Test temperature
 - H₂ test pressure
 - Soak time
- **Section 5 – Test methods**
 - Slow strain rate tensile testing
 - Hydrogen-assisted cracking threshold stress intensity factor
 - Fatigue crack growth rate (FCGR)
 - Fatigue life tests



ANSI/CSA CHMC1 – Section 4.3: Hydrogen gas purity

- Purity of the test gas “shall not be assumed to equal to that of source gas”
- “test chamber gas shall be evaluated after each test ”
 - Oxygen ≤ 1 vppm – required; ≤ 0.2 vppm - recommended
 - Moisture/water ≤ 10 vppm - recommended

- Test gas purity is critically important and should not be underestimated
- Oxides do not prevent hydrogen-assisted fatigue and fracture, although they can influence measurements by affecting hydrogen uptake
- Oxygen does not change long-term static fracture behavior (100s of hours)



ANSI/CSA CHMC1 – Measurement and instrumentation (4.4), Temperature (4.5), Pressure (4.6)

- **Transducers** – both internal and external transducers can be acceptable with proper characterization
 - **Standard Test Temperature:** 20-25 °C
 - **Pressure:** “Testing results are valid for all pressures equal to or less than the target test pressure”
-
- **Internal transducers are recommended and robust methods exist for both internal load and displacement (on the sample) measurements**
 - **Room (laboratory) temperature is generally considered ‘worst-case’ for fatigue life testing**
 - **Hydrogen effects depend on pressure – as a general rule**

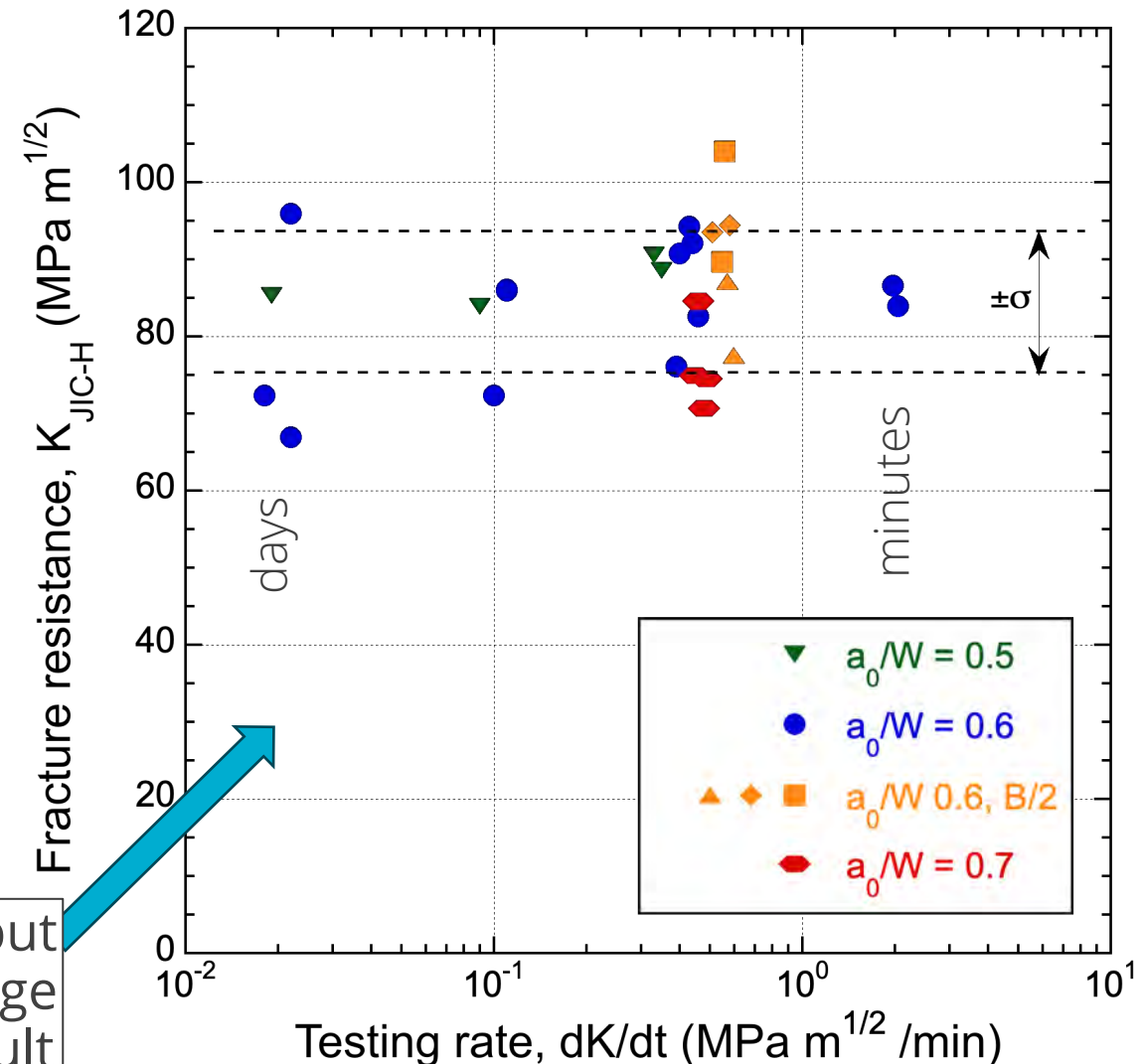


ANSI/CSA CHMC1 – Section 4.7: Soak time

- **Soak time:** soaking is not necessary except to ensure stability of pressure, temperature and instrumentation

- **Fatigue crack growth and fracture tests clearly demonstrate that soaking has no benefit if state-of-the-art procedures are used**

Tests conducted without “soaking” but at different rates representing a range of test times and showing same result





ANSI/CSA CHMC1 – Section 5.3 Hydrogen-assisted cracking threshold intensity factor

- **Method should be consistent with ASTM E1820**
 - **No restriction on methods for crack monitoring – both DCPD and compliance methods are acceptable**
 - **Precracking in air or in hydrogen**
 - **Displacement control between 0.1 to 1 MPa m^{1/2} /minute (defined in elastic region)**



ANSI/CSA CHMC1 – Section 5.4 Fatigue crack growth rate (FCGR)

- **Method should be consistent with ASTM E647**
 - Description generalized to allow user to define test parameters
 - Frequency = 1 Hz recommended

- **K-control tests (e.g., using C or $C_{\text{norm}}^{\dagger}$) greatly enhance testing efficiency and access to broader FCGR ranges**

[†]Nibur and Somerday: “Evaluating methods to reduce duration of near-threshold fatigue crack growth rate measurements for low-alloy steels in hydrogen gas” International Journal of Fatigue 201 (2025) 109150.

<https://doi.org/10.1016/j.ijfatigue.2025.109150>



Closing thoughts

- **CHMC1 is the best available test method description**
 - Captures important aspects of testing (e.g., gas quality and transducers)
 - Generally provides flexibility in test hardware and transducers (perhaps too much)
- **CHMC1 does not mention ASTM E1681 – constant load/displacement fracture methods**
- **As noted, no requirements for soak time**



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SAND2025-94650

Sustained load cracking: fact or myth?

Chris San Marchi and Joe Ronevich

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Montreal, Canada 25 July 2025

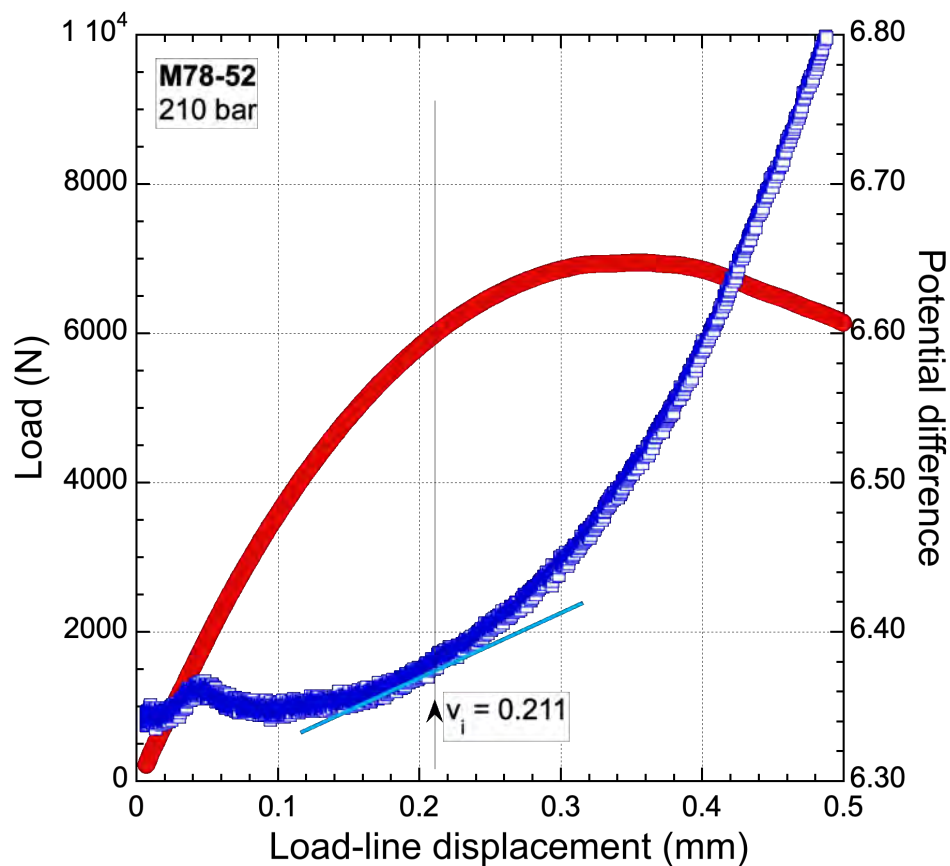
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Background: *Fracture mechanics is the transfer function that converts laboratory tests into materials behavior that can be used in design*

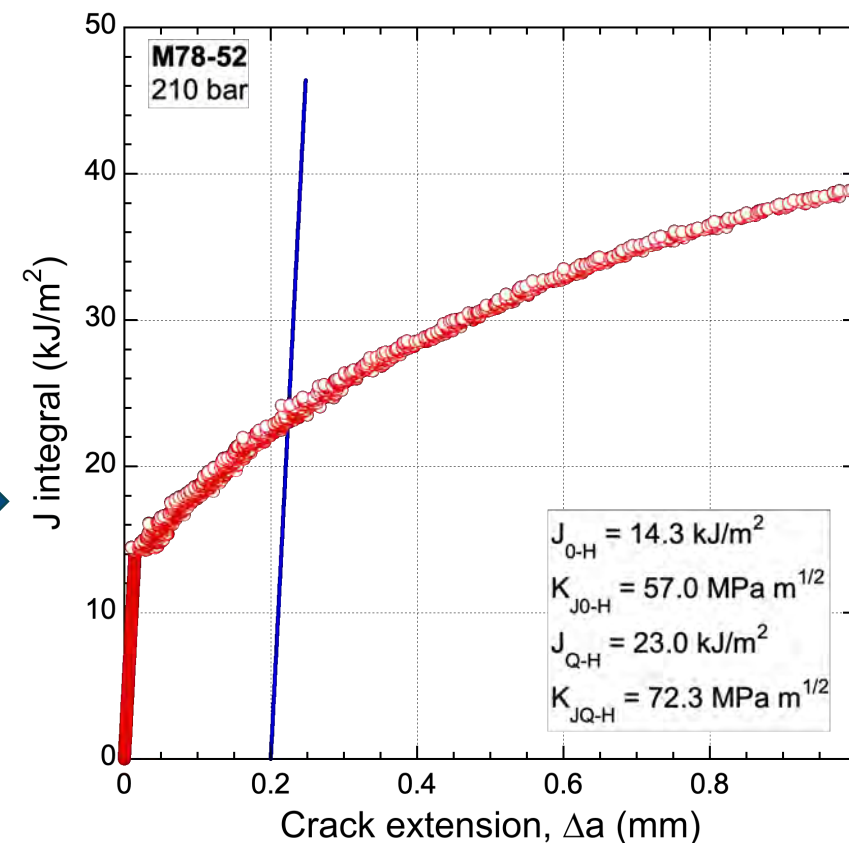
Load-displacement curve



Geometry specific

Fracture
Mechanics

Fracture resistance curve

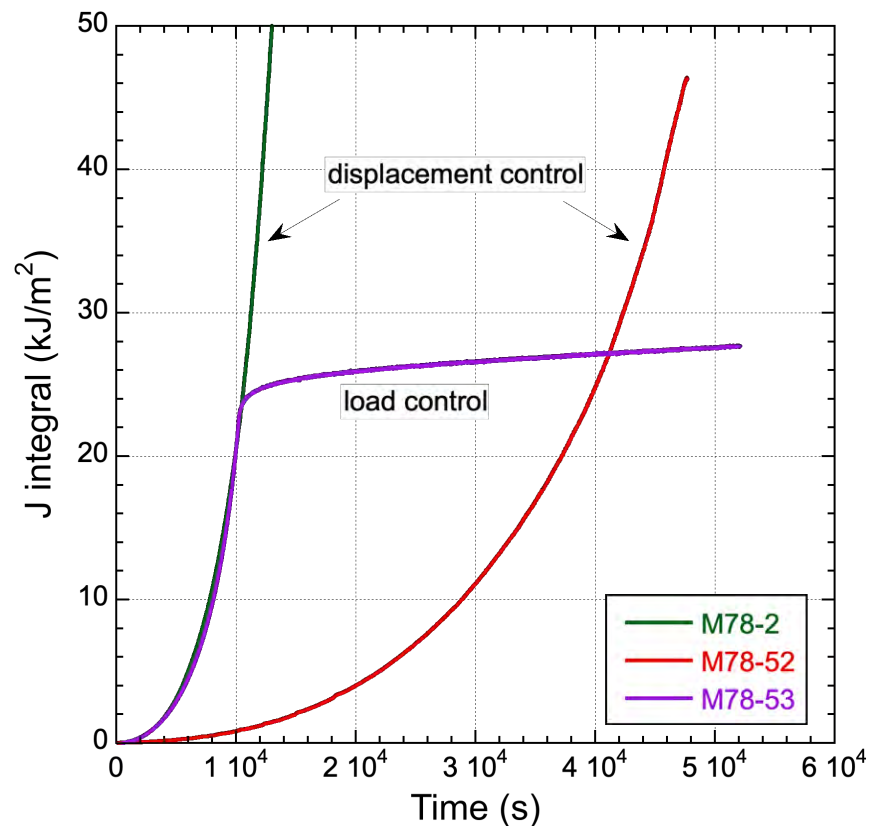


*Geometry independent
materials property*



Background: *Fracture mechanics is the transfer function that converts laboratory tests into materials behavior that can be used in design*

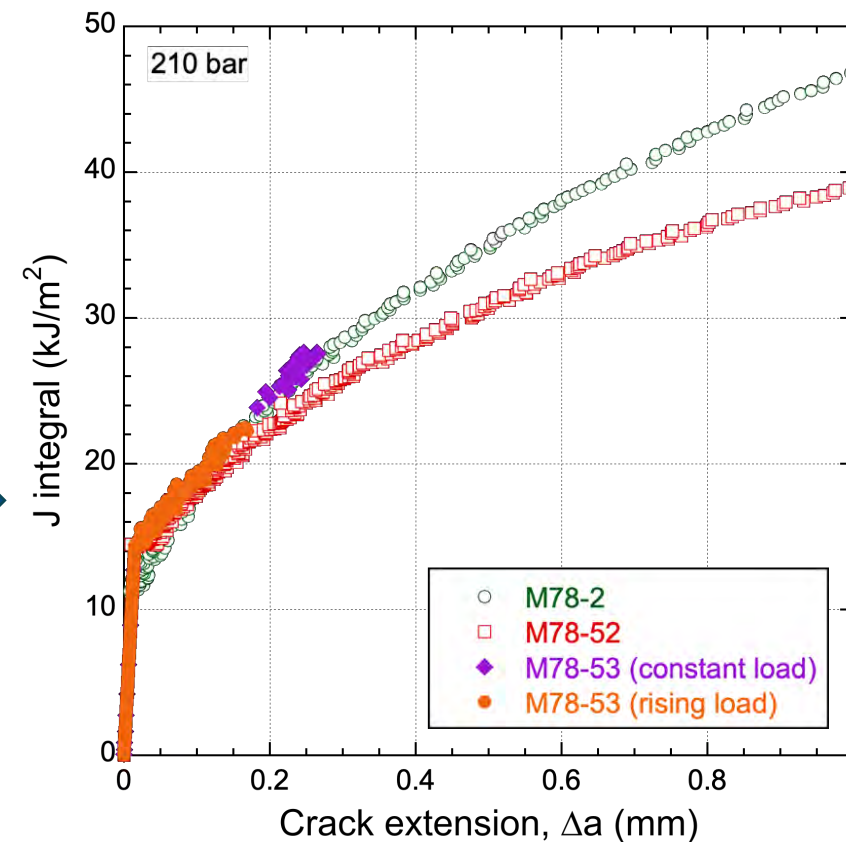
Loading rate curves



Test control specific

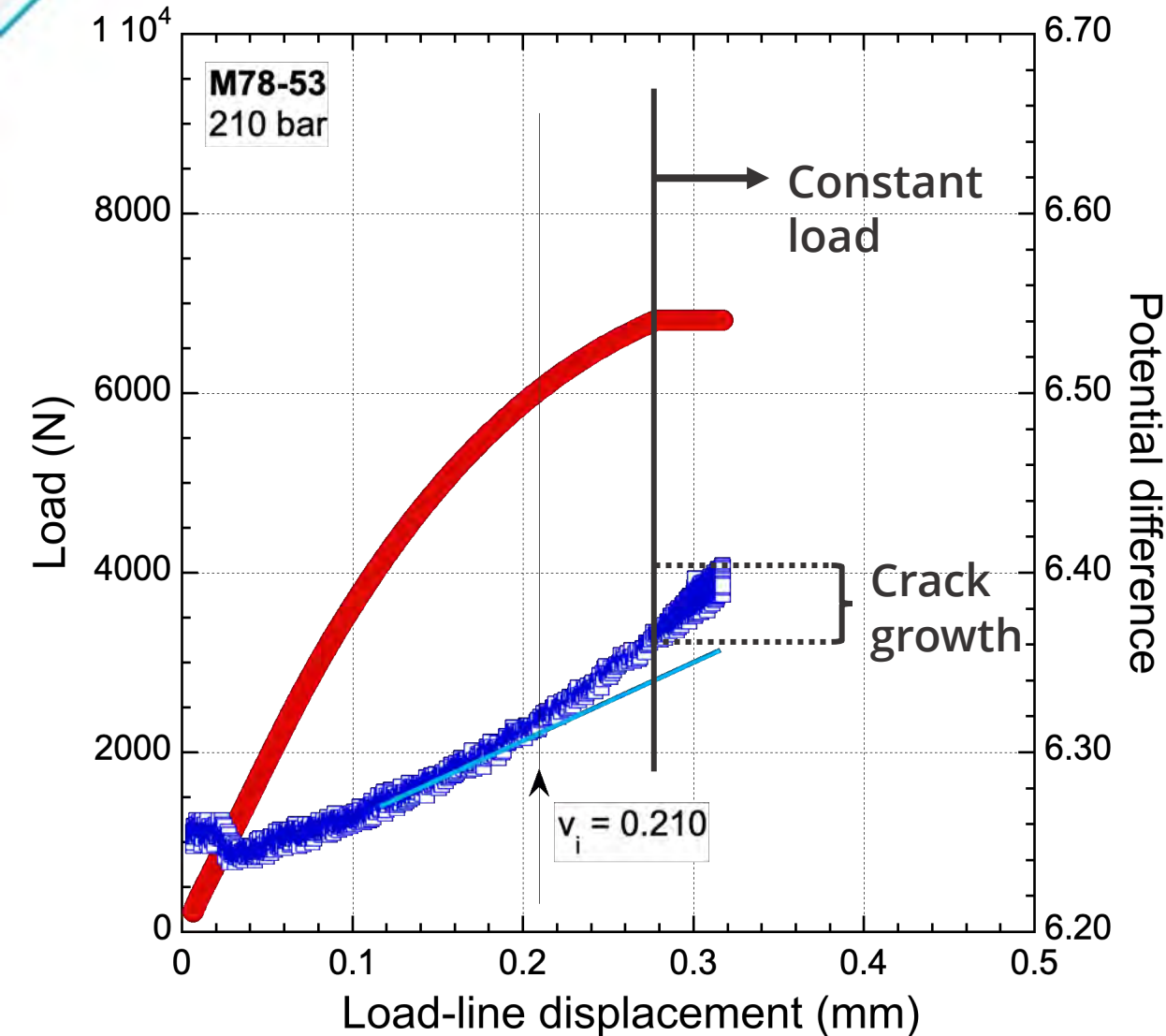
Fracture
Mechanics

Fracture resistance curves



*Geometry independent
materials property*

Background: What is “sustained load cracking”?



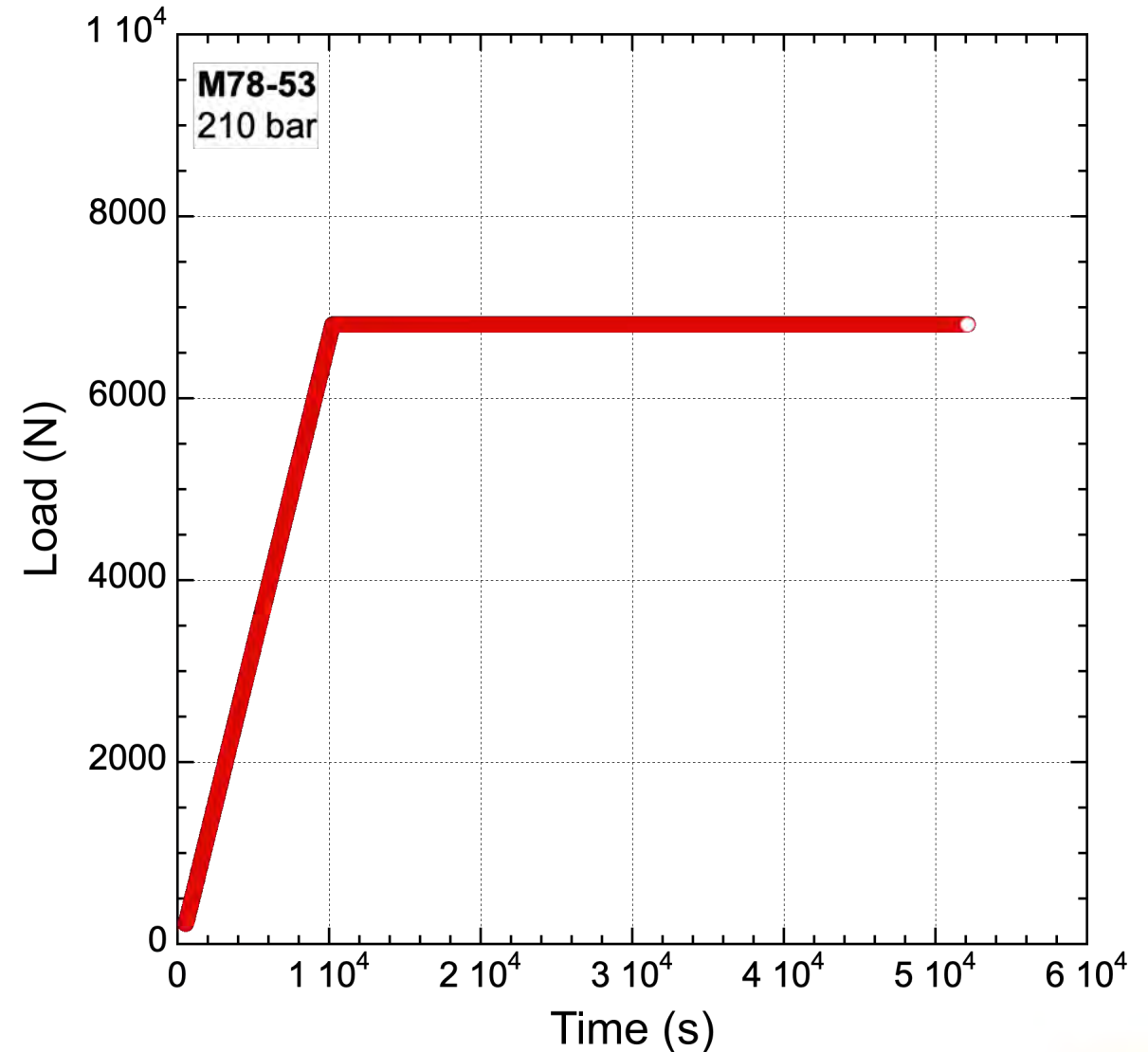
Concept: specimens subjected to constant load show crack extension, sometimes over long timeframes

- Is this phenomenon subcritical crack growth?
- Is it time dependent crack growth?
- Does observation of crack extension in a test specimen imply that cracks will grow in a pressurized structure?
- Can a critical J (or K) be defined where cracks will not grow under “sustained load”?

Example of constant load test (M78-53)

M78-53

- $W = 26.42$ mm
- $B = 12.70$
- $B_N = 11.09$
- $P = 210$ bar
- Constant loading rate:
 $dP/dt = 0.68$ N/s (40.8 N/min)
 $dK/dt \sim 0.37$ MPa $m^{1/2}/min$
- Fracture
 - Start: $a/W = 0.6040$
 - End: $a/W = 0.6153$
 - $\Delta a = 0.297$ mm

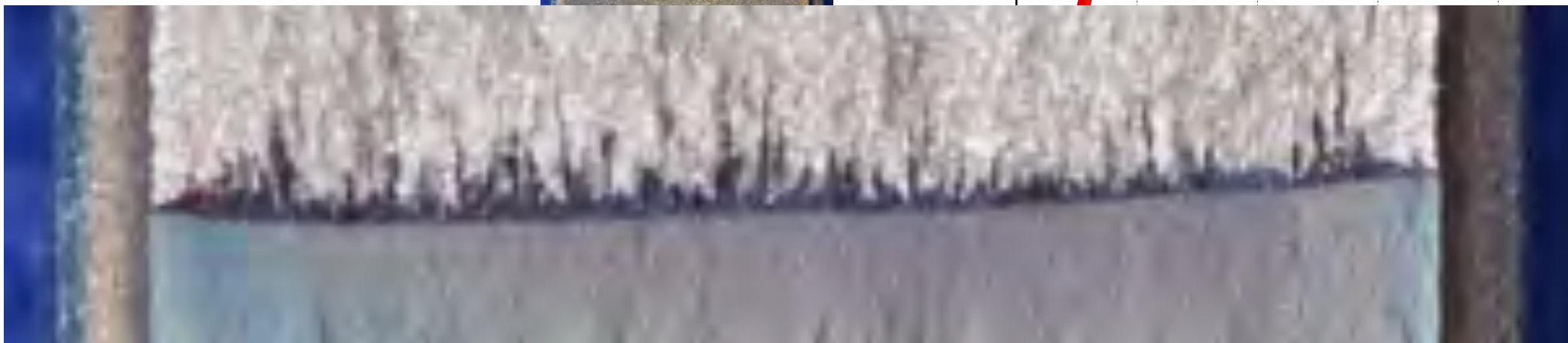
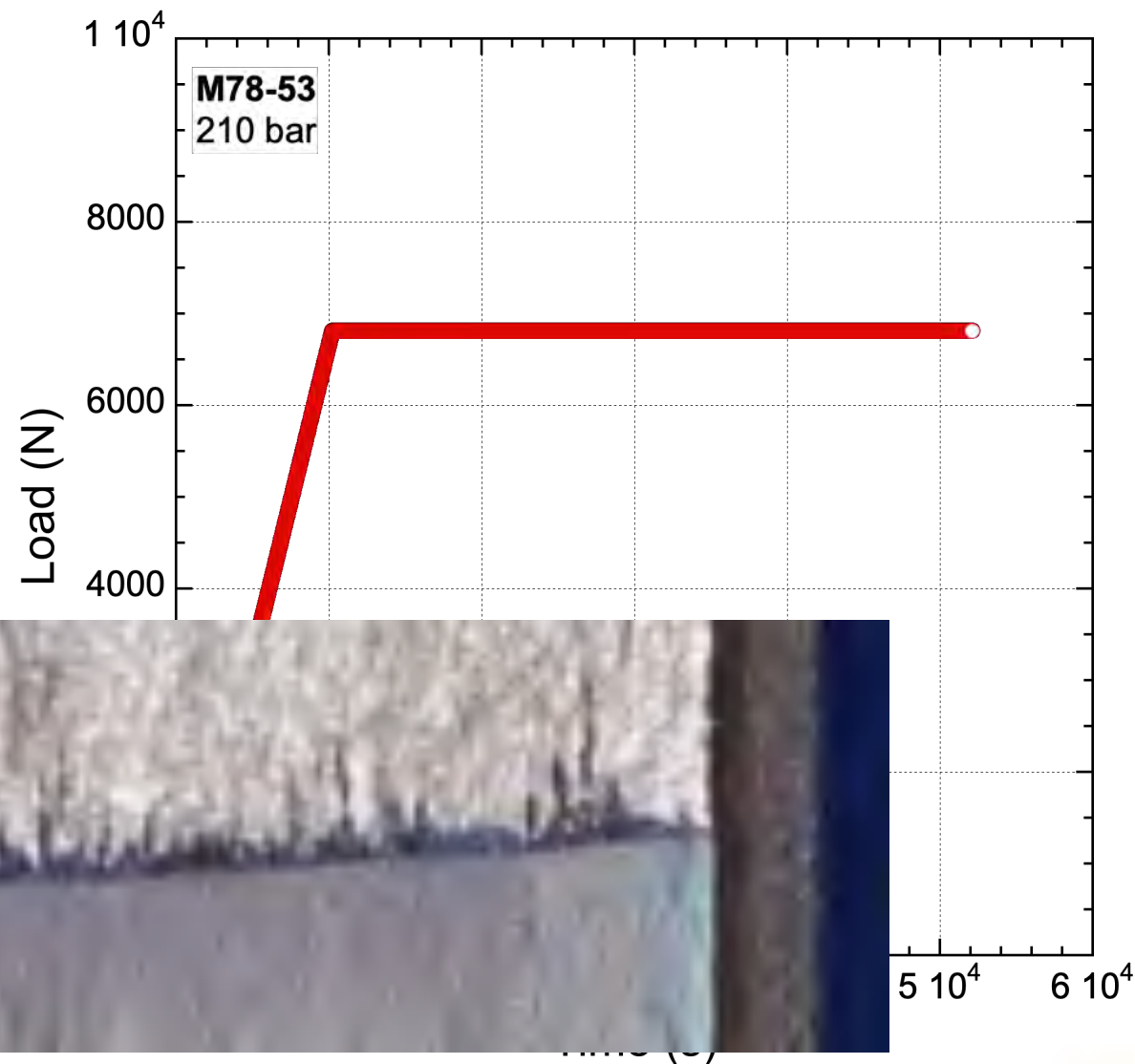




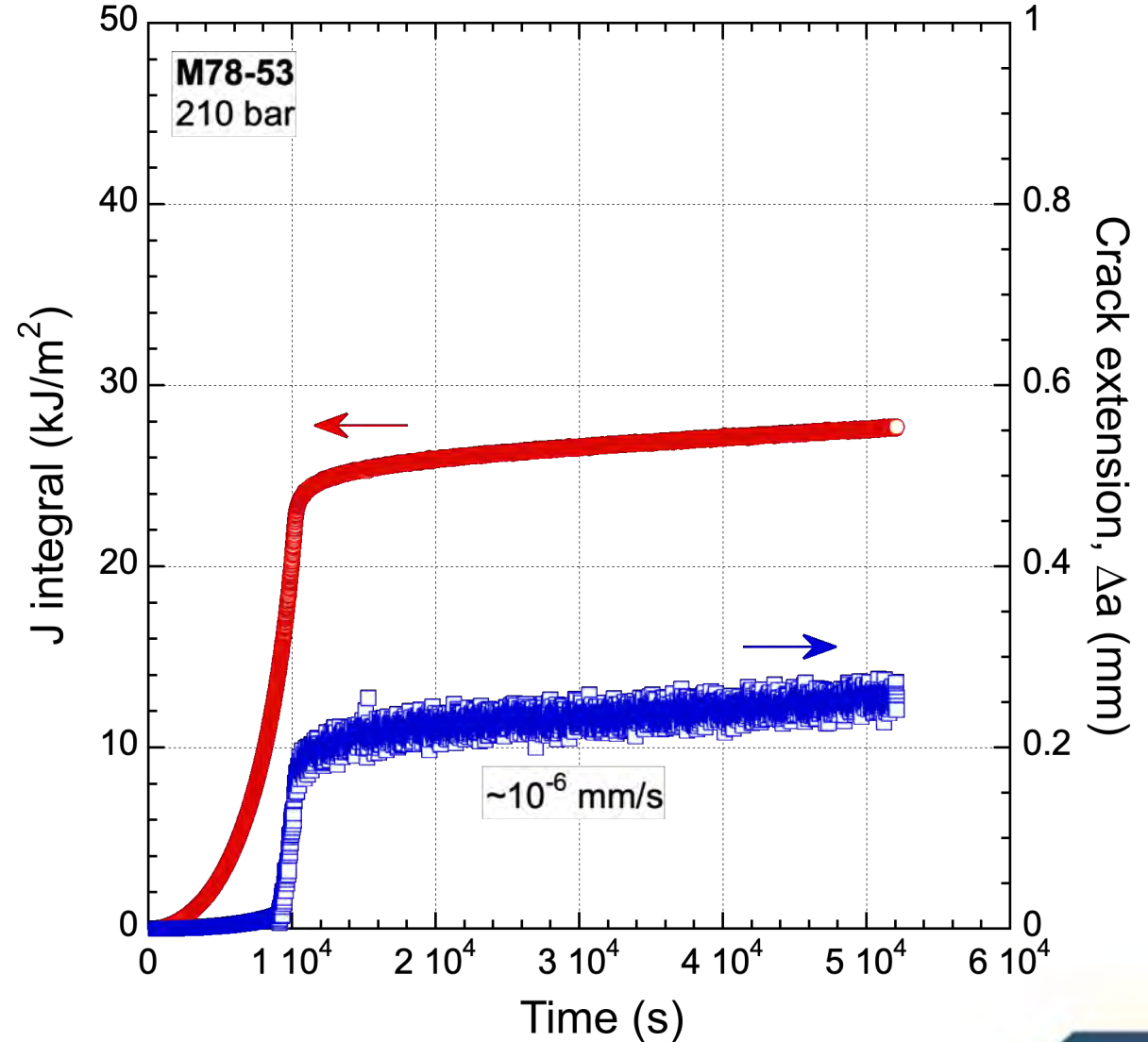
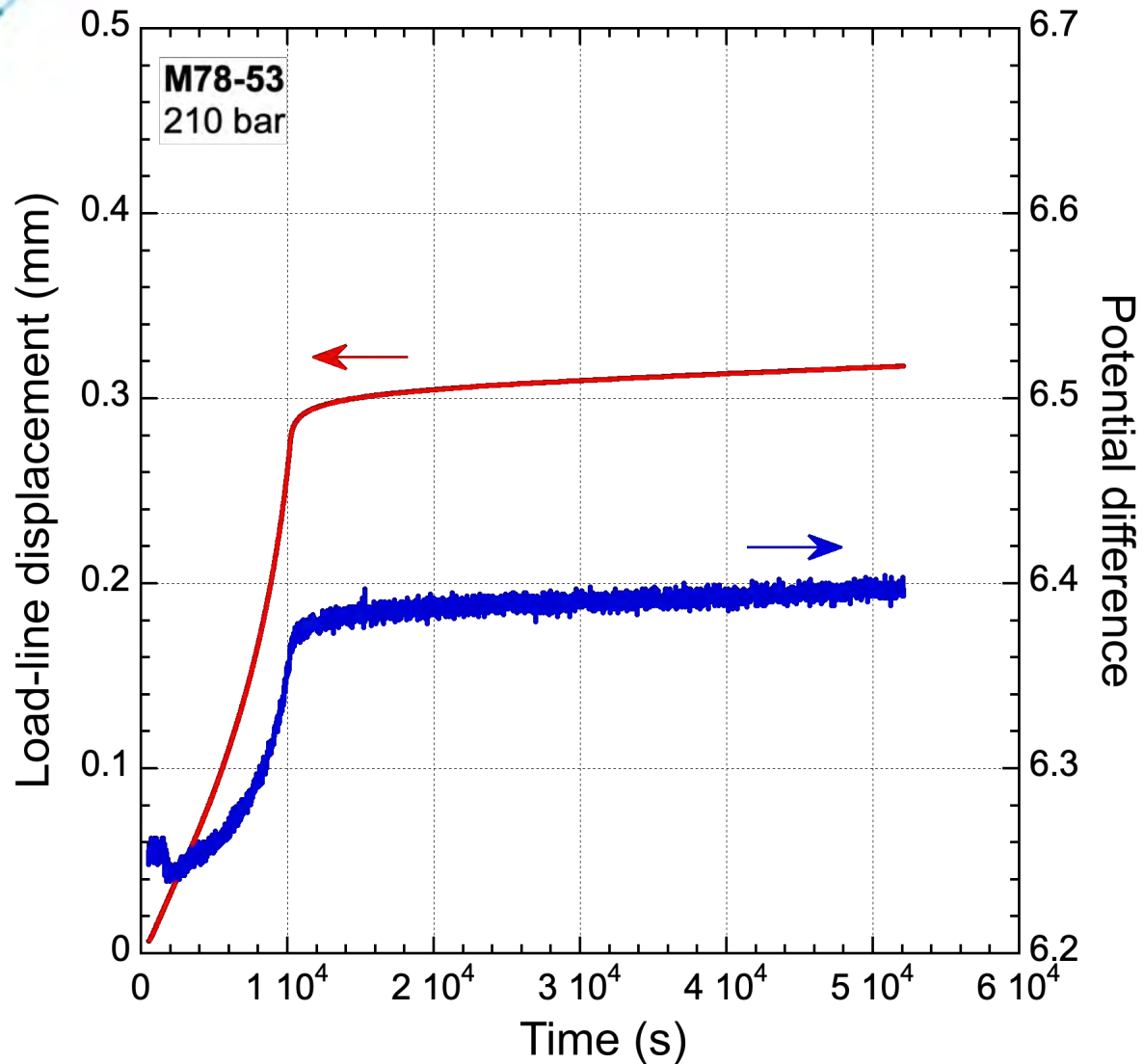
Example of constant load test (M78-53)

M78-53

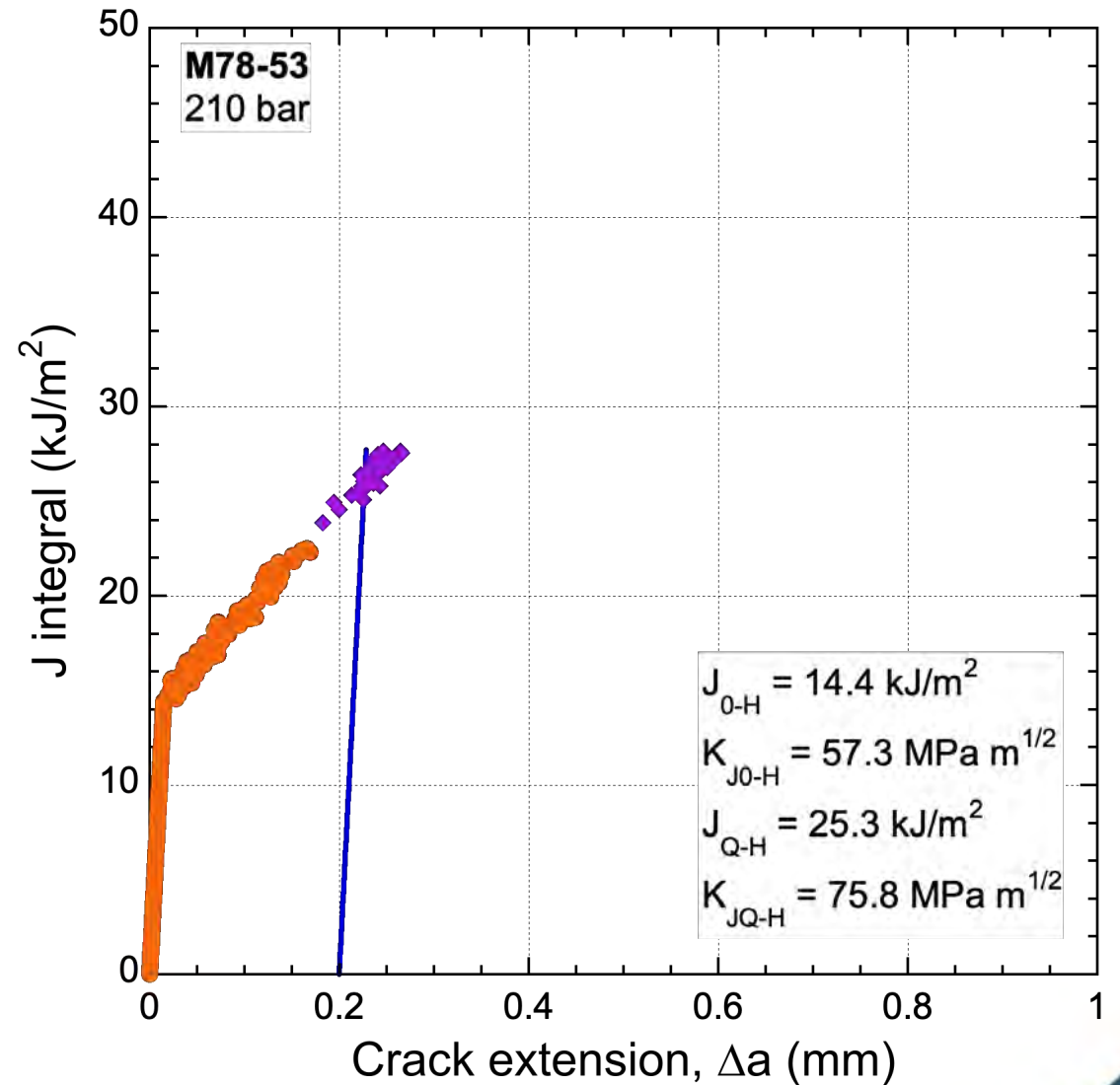
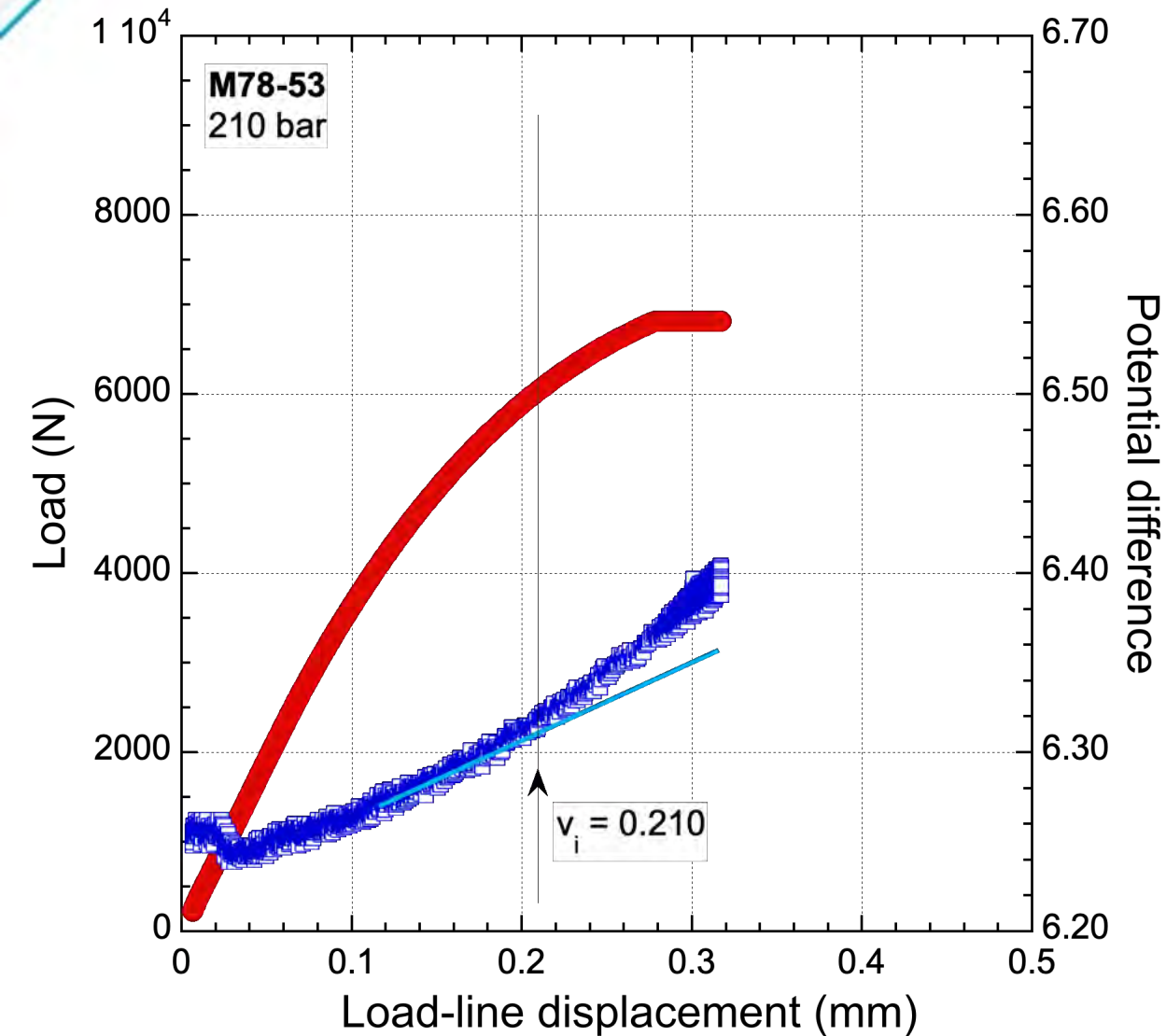
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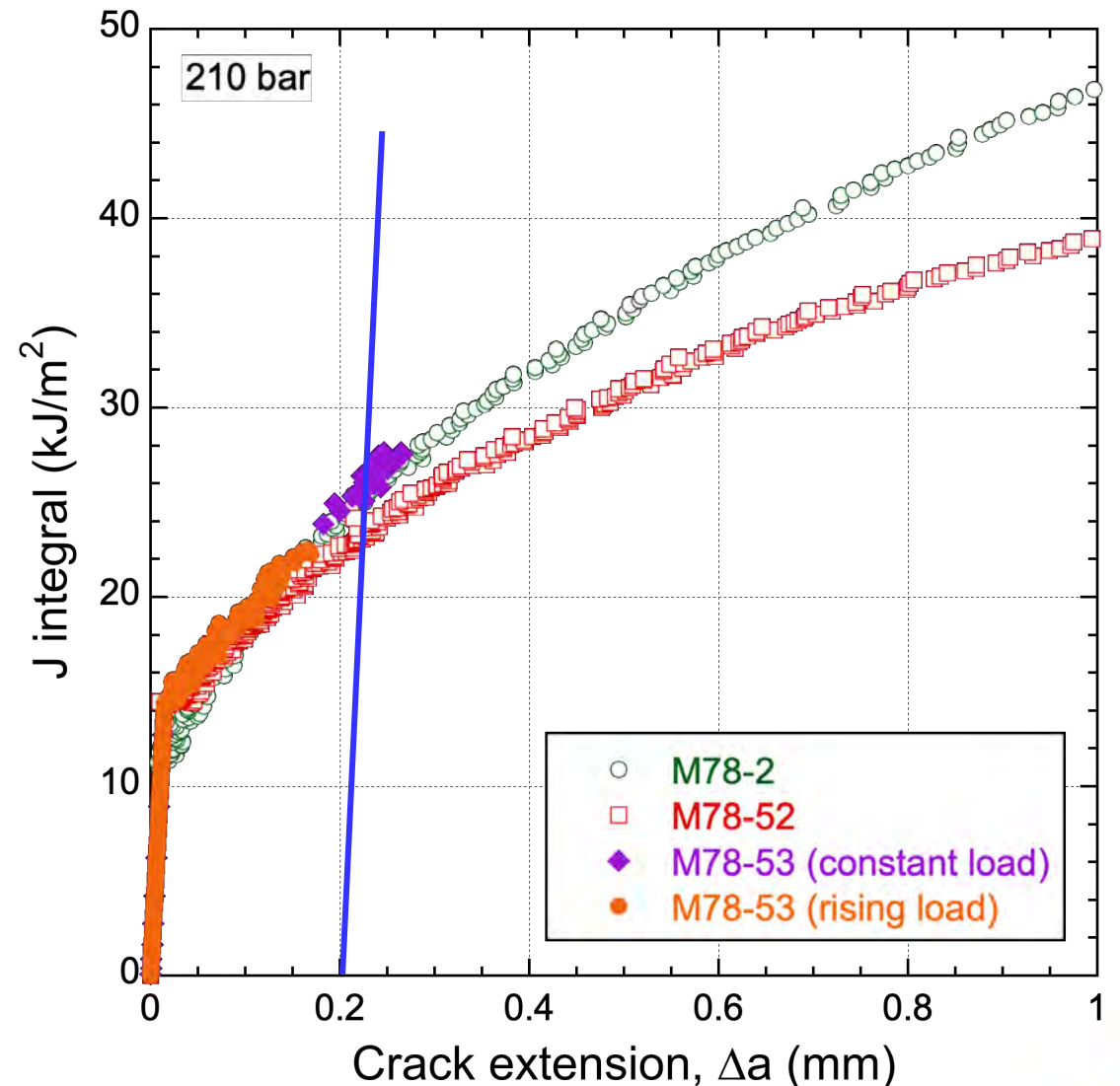
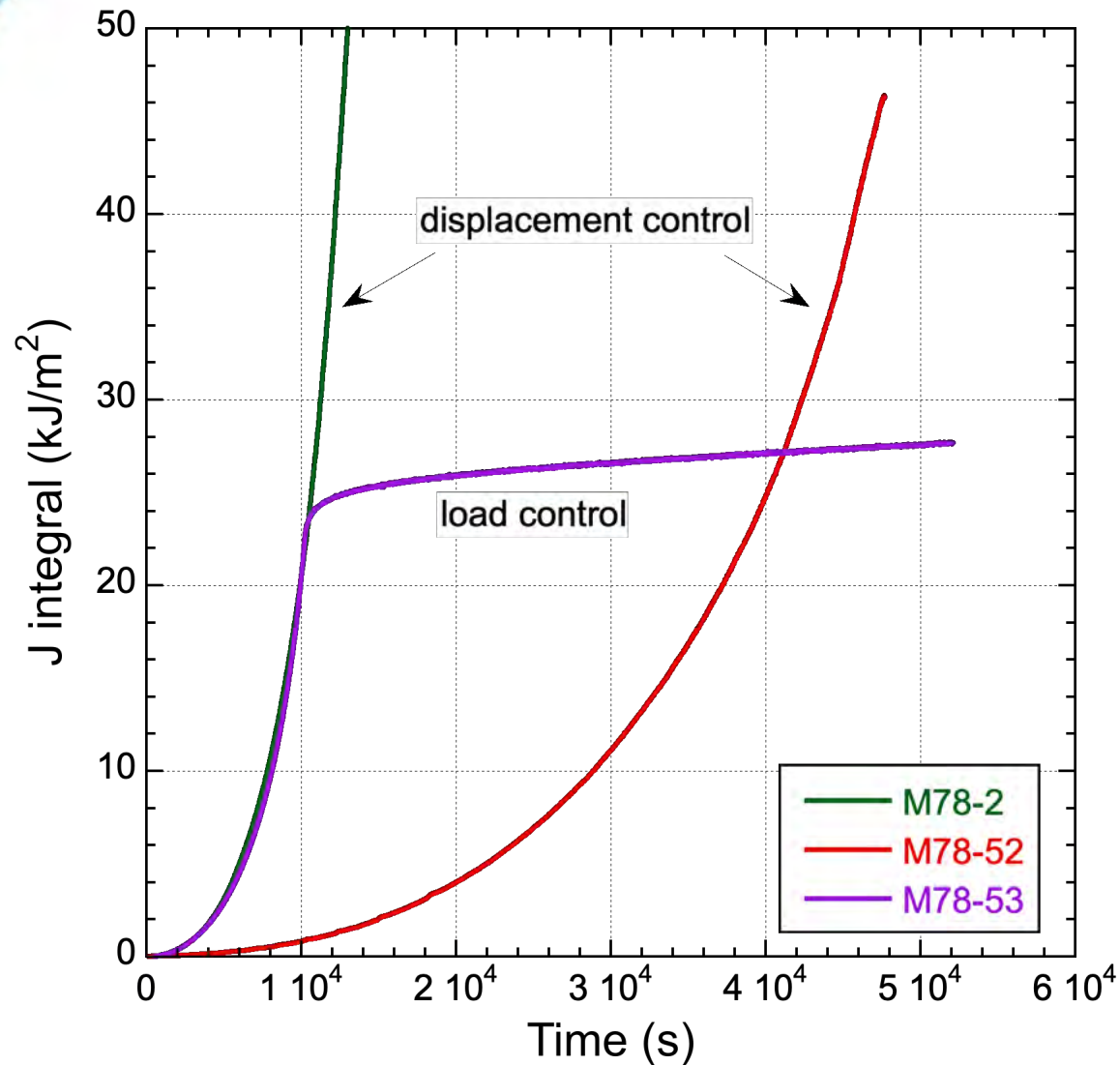
Example of constant load test: crack extension



Example of constant load test: J- Δa evolution



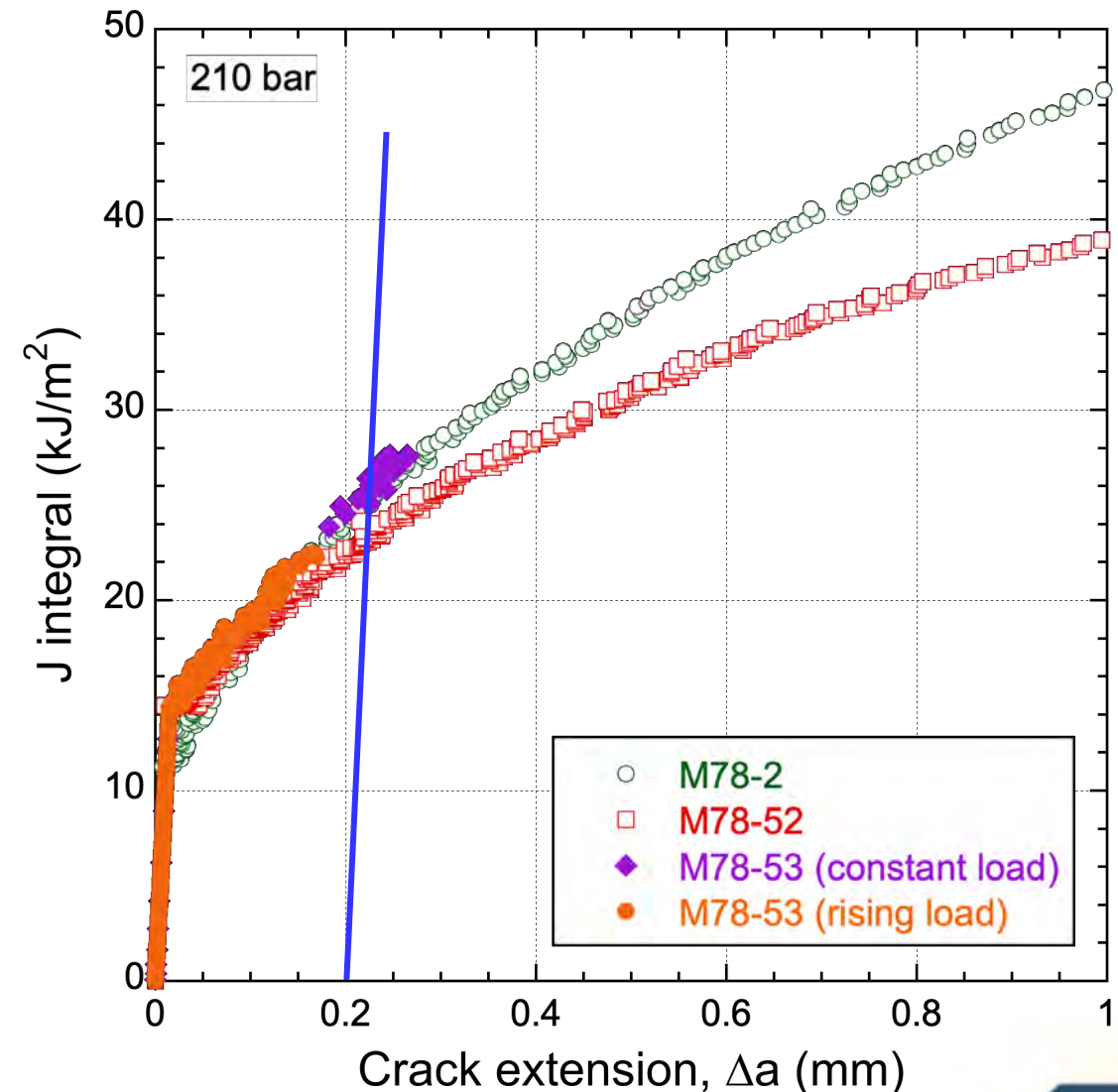
Comparison: Standard fracture tests and load hold test (M78-2 & M78-52 at two different rates and M78-53, respectively)



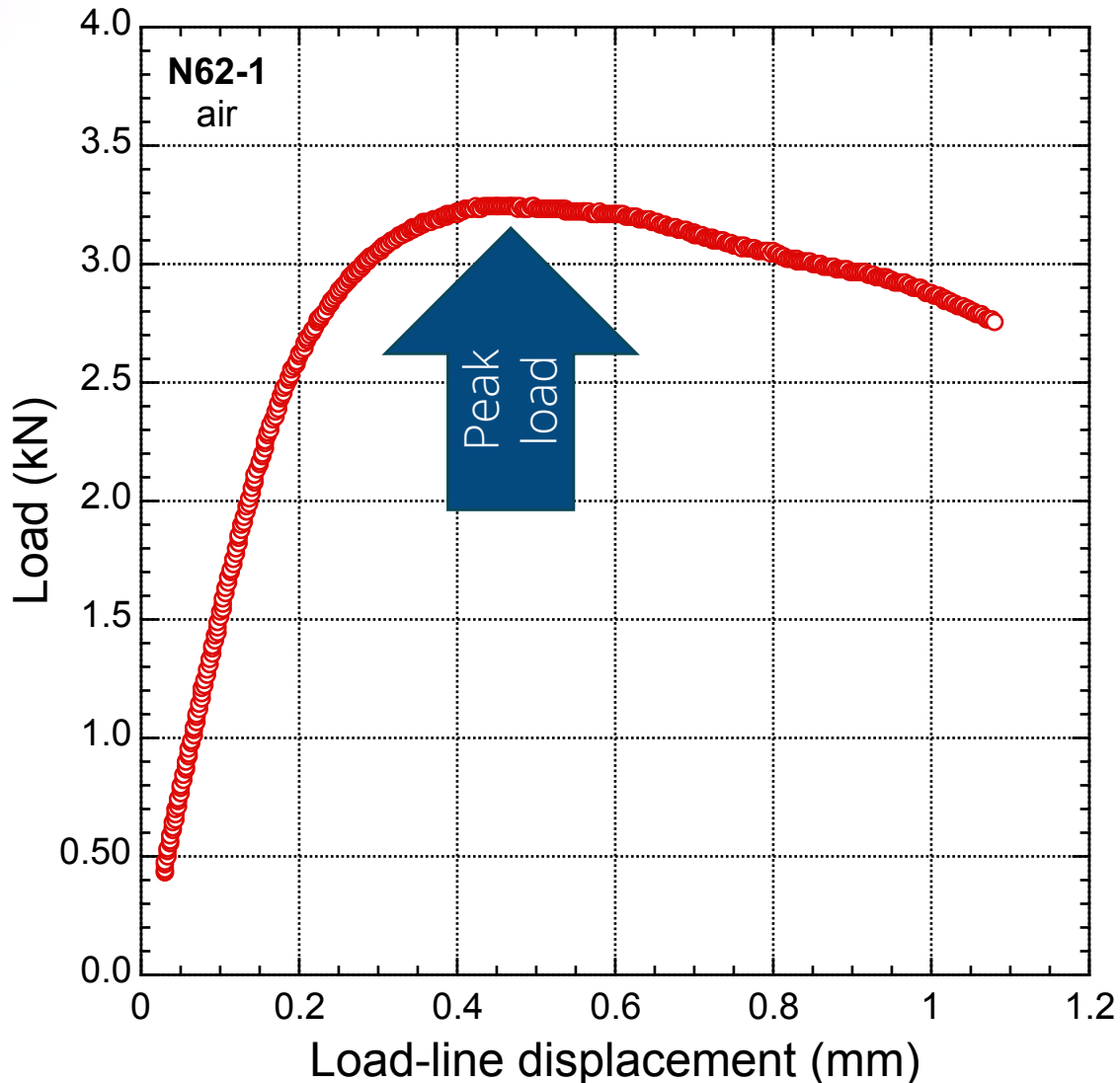


The constant load test reproduces the J-R curve

- Is 'sustained load cracking' subcritical crack growth?
 - Yes, like the rising load test in hydrogen, the result is 'subcritical' (with respect to a measurement in air, i.e. classic definition of subcritical)
 - From a materials behavior perspective, constant load tests measure the same 'materials response' as a standard fracture test
 - In other words, the constant load test measures the J-R curve
- Is it time dependent crack growth?
 - Arguably no. The intent is to measure a J-R curve that is time **independent**
 - The rates of these three tests differ by orders of magnitude



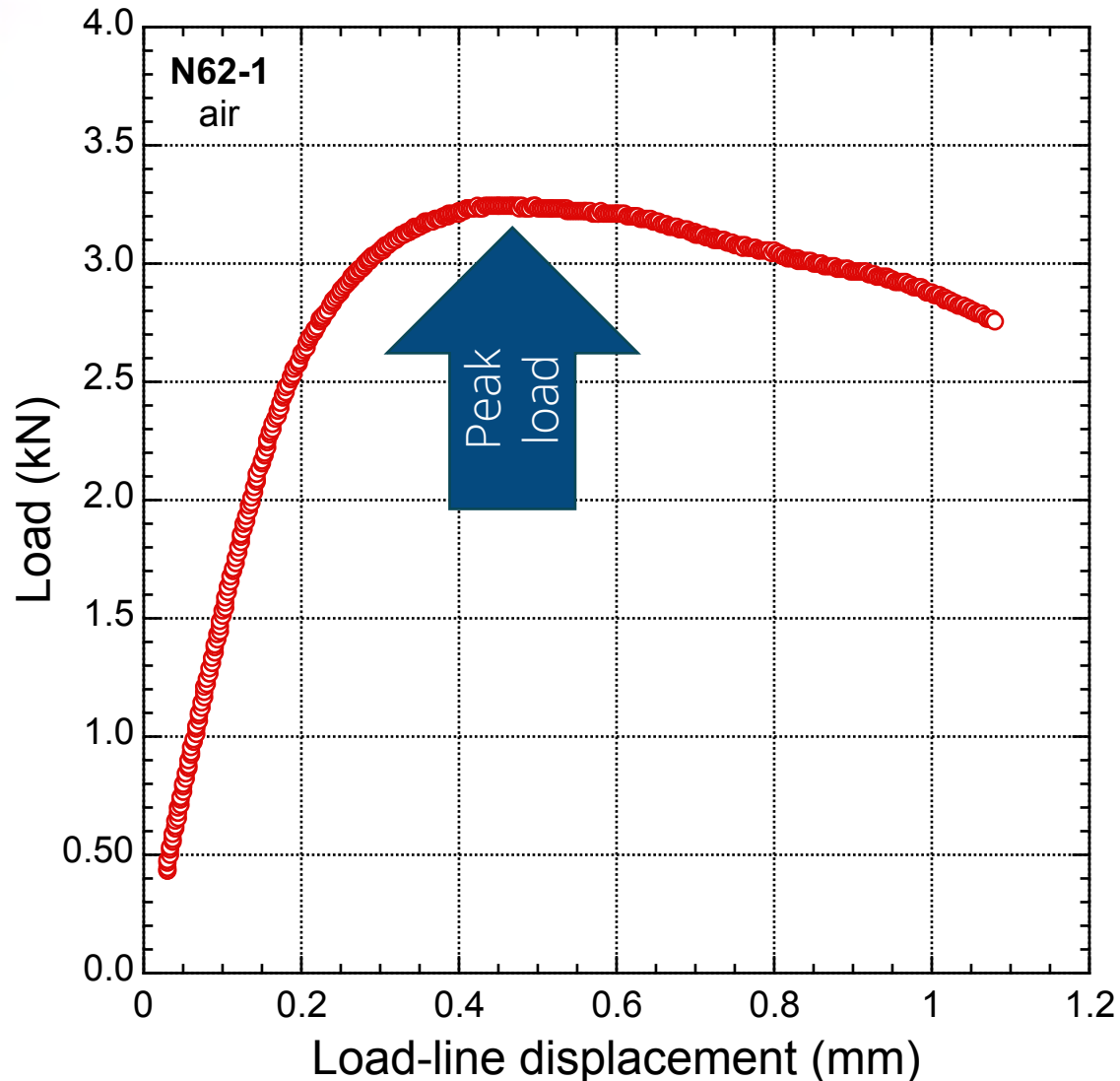
Why does a crack grow under constant load?



Consider the load displacement curve for a standard fracture test in air (ie, displacement-controlled test)

- What happens if we load an identical specimen specimen to the peak load under load control?
- Or 'just past' peak load?

Why does a crack grow under constant load?



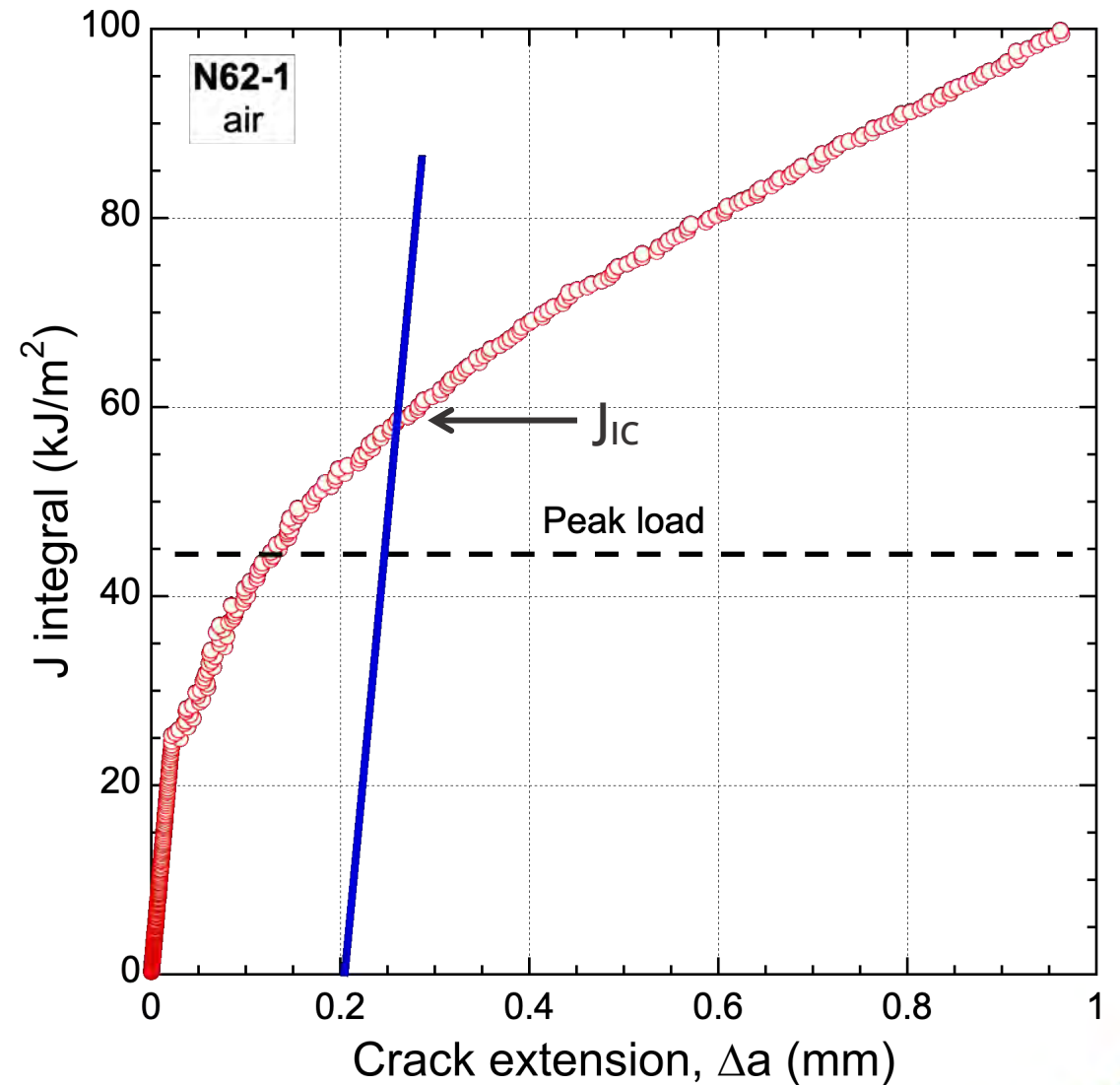
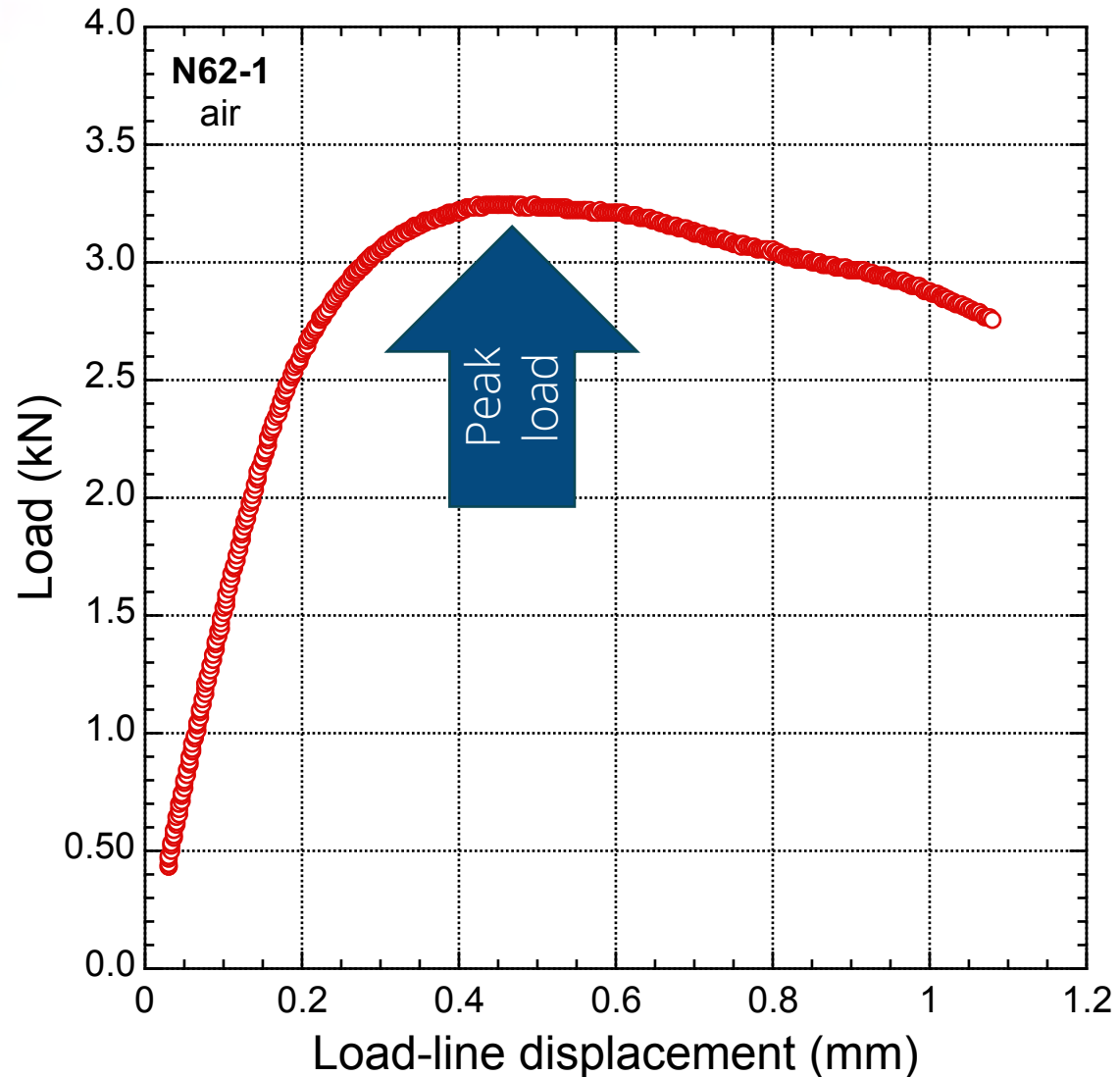
Consider the load displacement curve for a standard fracture test in air (ie, displacement-controlled test)

- What happens if we load an identical specimen specimen to the peak load under load control?
- Or 'just past' peak load?

The crack will grow

- In displacement control, a crack grows stably in air under decreasing load
- In load control, the specimen will "fail" because it cannot exceed the peak load: *this is a geometric instability!*

A crack can grow under constant/sustained load, well before J_{IC}





Consider the tensile analog for geometric instability

- In a test specimen, can the load be greater than the peak load?
 - 'Stability' is limited by the specific geometry of the test specimen
 - Necking occurs due to geometric instability of the specimen
 - If we change the specimen dimensions, we can achieve a higher load
 - The stress, on the hand, is the transfer function from the test specimen to the structure
- In a structure, can the stress be greater than the UTS?
 - Absolutely, the component geometry can 'stabilize' the stresses, enabling very high stress in a component - *for example, at a crack tip or stress concentration*
 - We accommodate/understand high stresses through analysis, and we can 'predict' plastic collapse

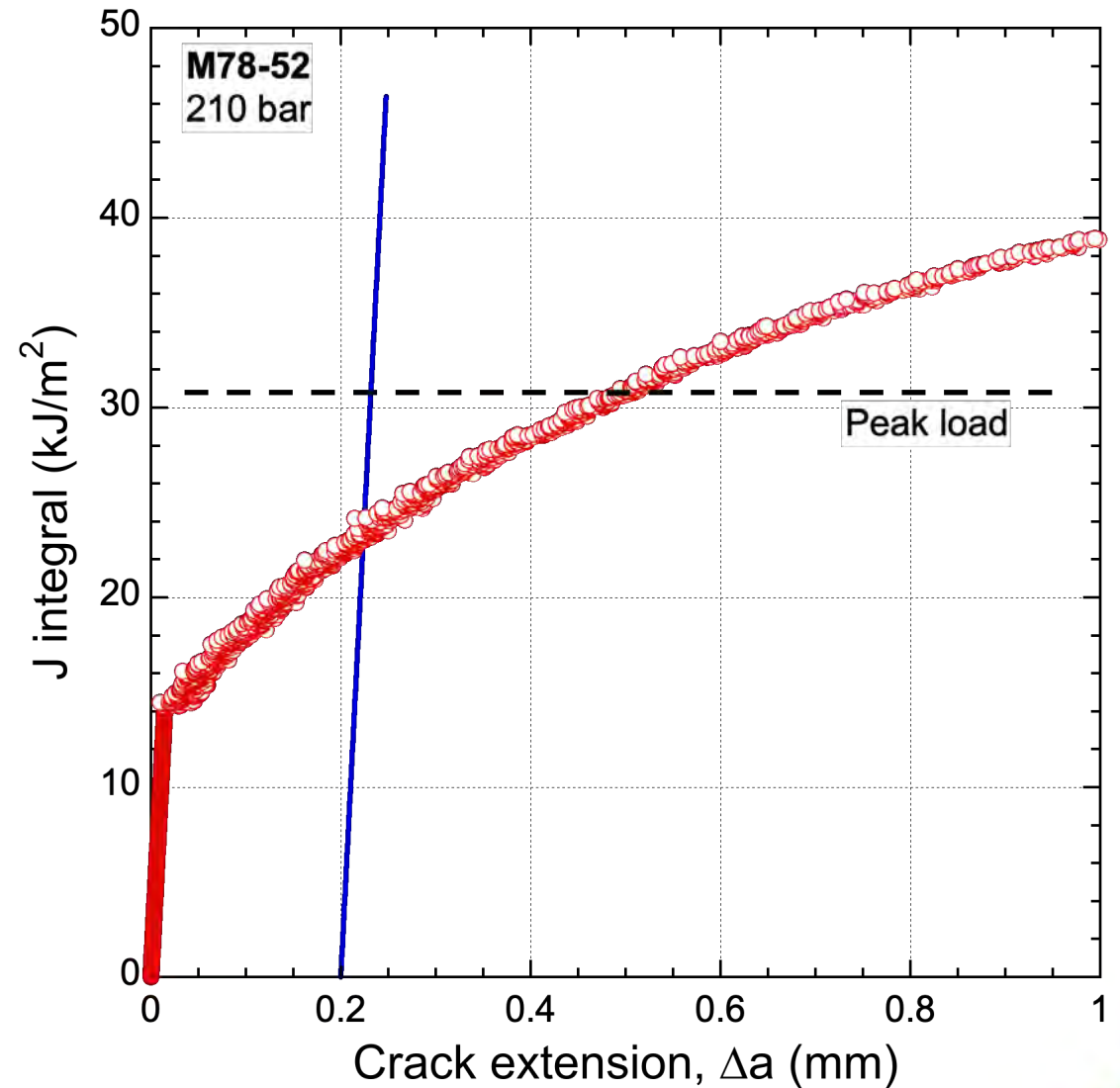
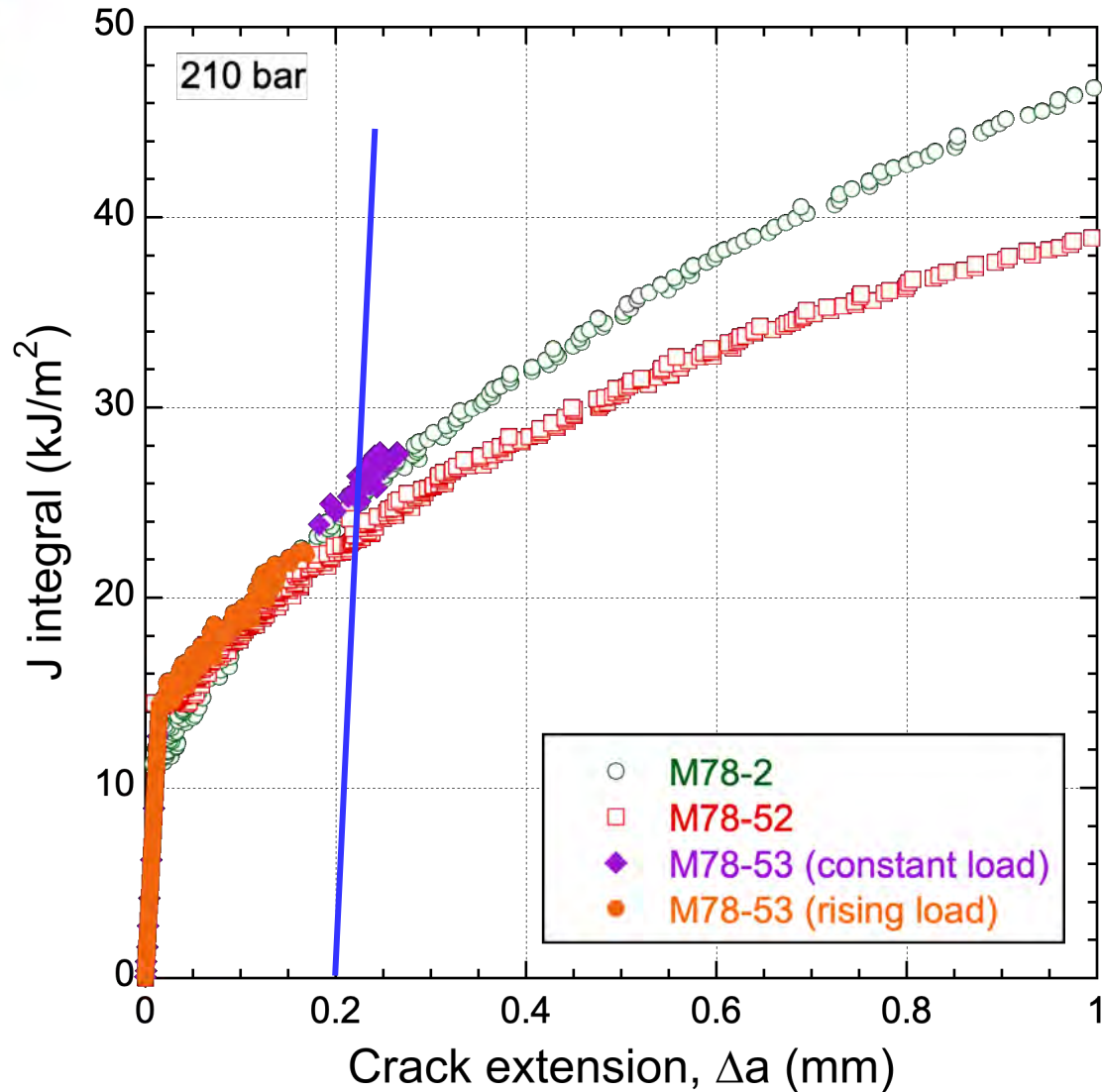


Does observation of geometric instability imply that cracks will grow in a pressurized structure?

- Fracture measurements are limited by the geometry of the test specimen (and the boundary conditions of the test)
 - As in for the tensile case, a “geometric instability” for crack extension is associated with peak load (the peak load depends on a/W , for example)
 - This is not a crack instability as the crack may or may not grow depending on the configuration:
 - load control versus displacement control – *same as a tensile specimen*
- In a structure, we understand the driving forces on a crack through analysis
 - A condition that achieves “geometric instability” in a laboratory test specimen does not necessarily imply the same behavior in a component – *because of the geometry*
 - Analogous to assessment of stress concentrations in a structure, assessment of cracks in structures requires analysis



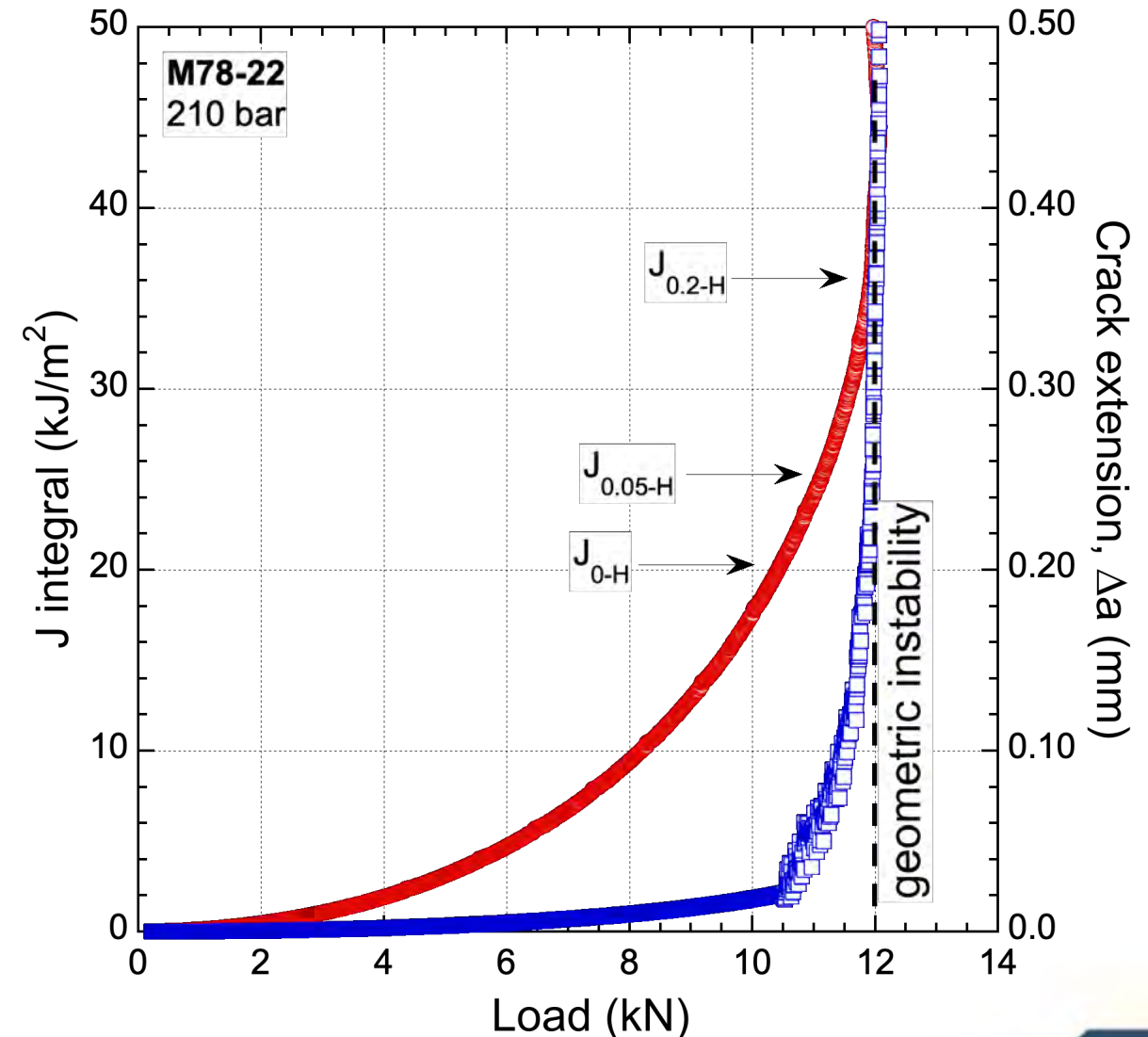
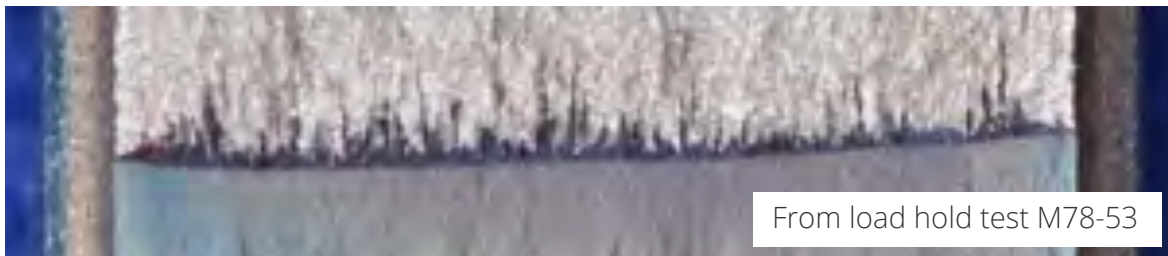
Why does a crack grow under constant load? (when load is less than expected peak load)



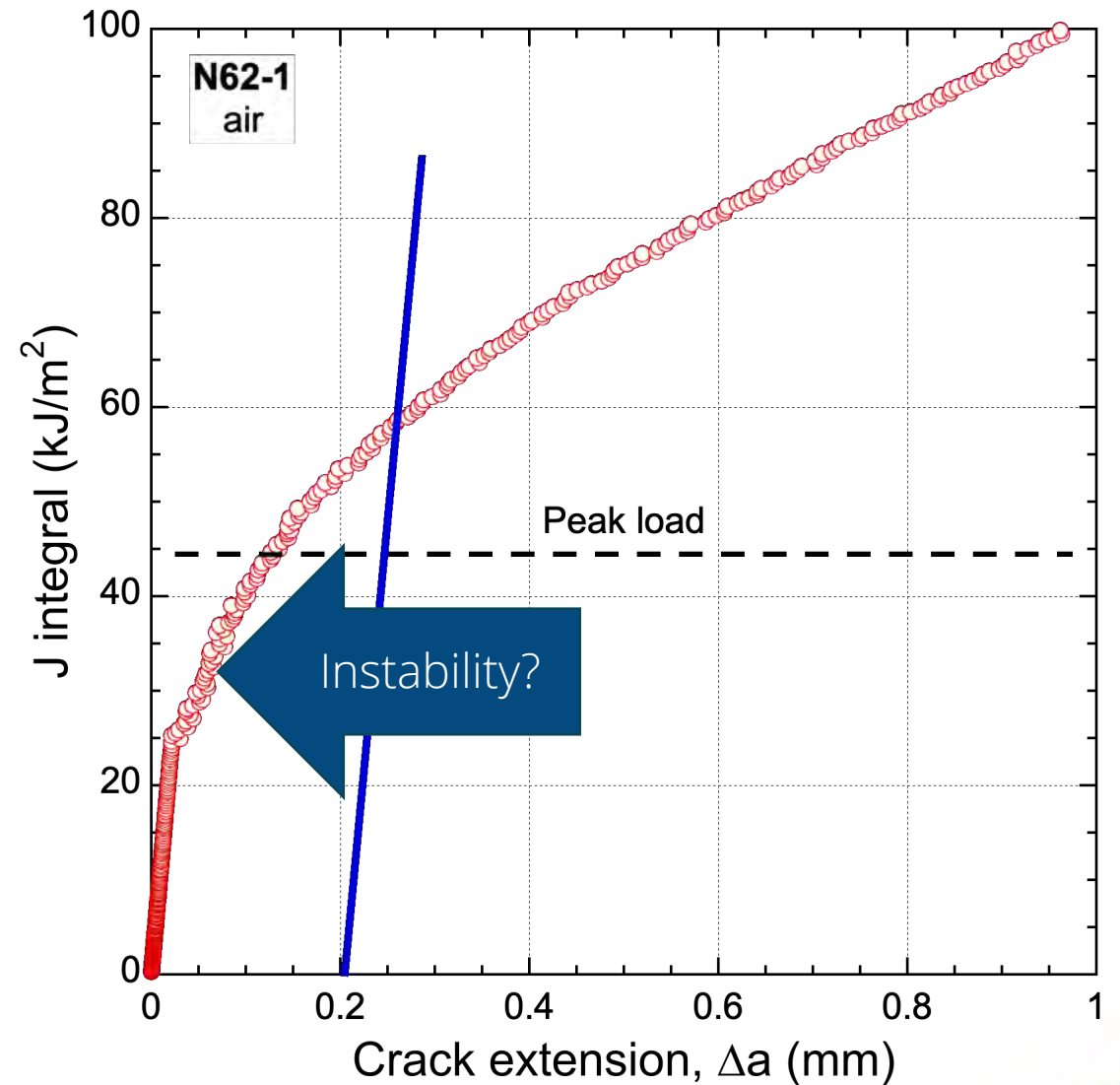
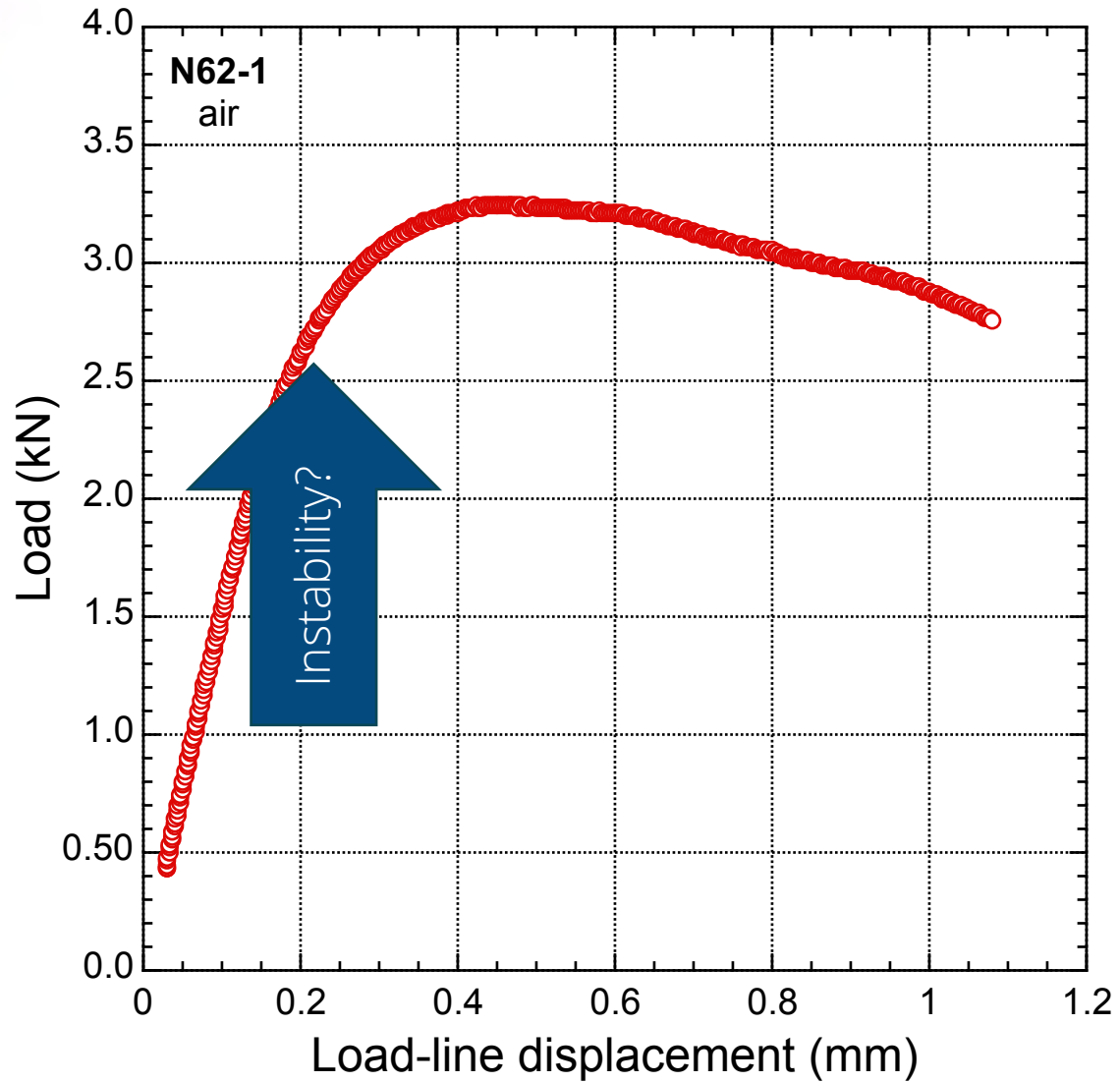


Why does a crack grow under constant load? (when load is less than expected peak load)

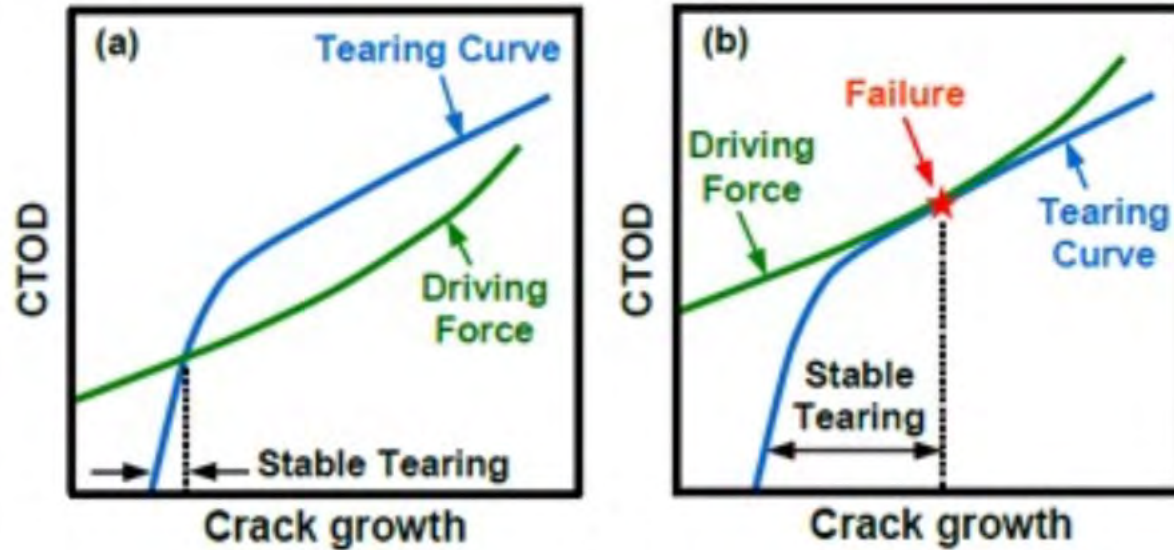
- Consider:
 - Crack extension is very sensitive to the load – *a very small change of load results in a large change of crack length*
 - The crack front is not straight – *the driving force along the crack front varies*
- Therefore,
 - Any perturbation in the system (ie, crack front) will 'trip' the geometric instability



Is the CT specimen intrinsically unstable?



Stability criterion for a crack in a body – tangency method



Driving force

- Mechanics based
- Depends on the geometry and loading

$$\left(\frac{\partial J}{\partial a}\right)_{\Delta} \geq \frac{dJ_R}{da}$$

Material resistance:
Slope of the JR curve



Other considerations

- Creep at the crack tip
- Loading system instability (control feedback that drives crack as system tries to maintain load)

Questions:

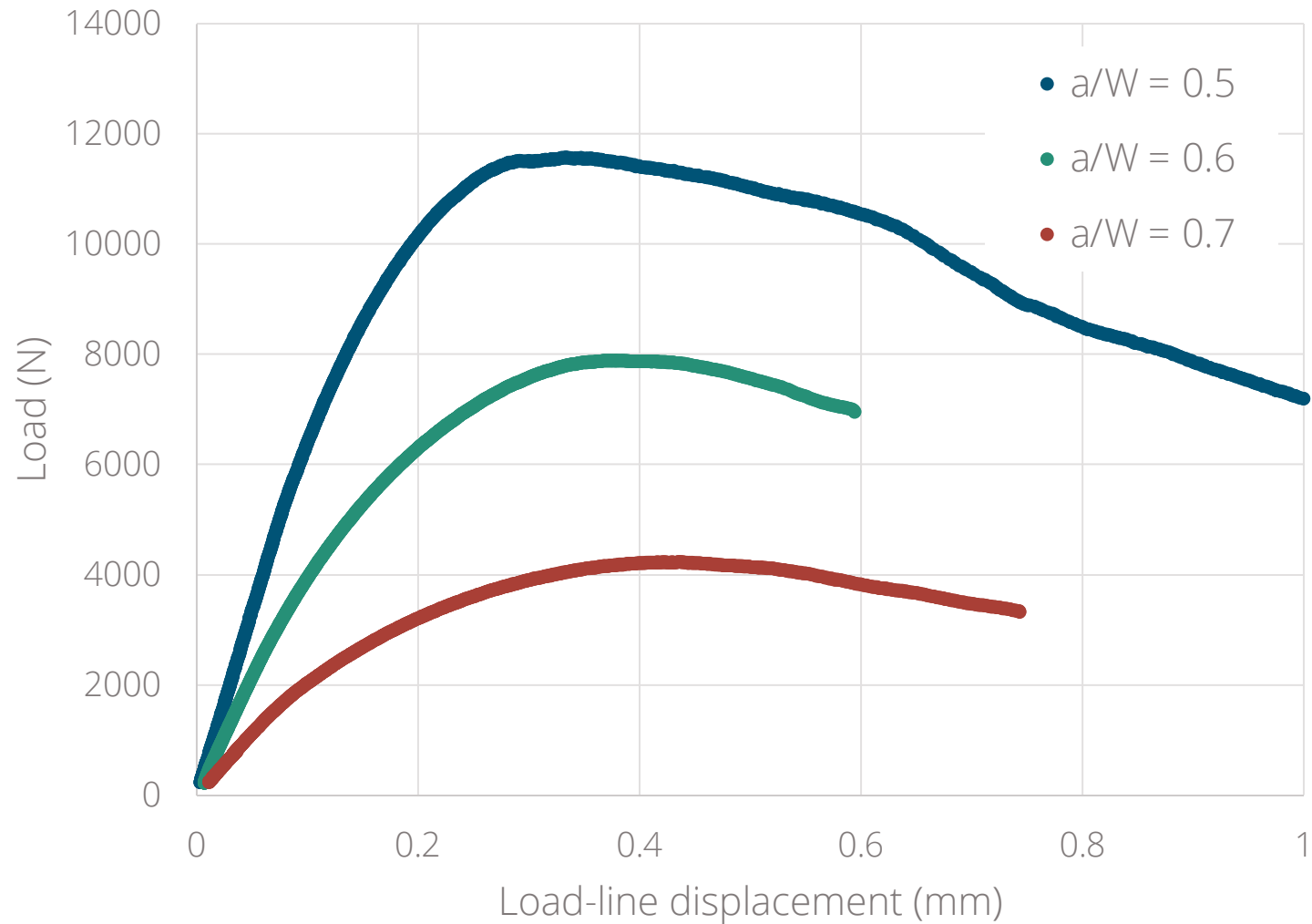
- Why does the crack grow slow if stability criteria are not satisfied?
- Will the crack stop?
 - Is there a criterion for crack arrest or will the crack continue? (or accelerate?)



Summary

- Sustained load cracking is not a materials property
 - Rather, sustained load cracking is a geometric instability
 - Observation of sustained load cracking in a test specimen does not imply crack extension in a structure
 - Therefore, constant load tests are not necessarily informative
- Can a critical J (or K) be defined where cracks will not grow under “sustained load”?
 - Yes, with proper analysis of the structure
 - The critical value depends on the structure and is informed by the J-R curve (ie, materials properties)
 - The critical value cannot be determined from the J-R curve, step loading, or a constant load test

Load capacity of CT specimens for different crack lengths



Update on full scale tests in Hydrogen on pipelines materials in Europe

Sandia Hydrogen Study group

Bostjan Bezensek

25th July 2025

SAFEH2PIPE

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

Bostjan Bezensek
Shell



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 of research is on the mechanical damage & corrosion

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)
- EPRG as external advisor

RINA CSM



CPW



Tenaris Dalmine



OCAS



Rosen



Shell



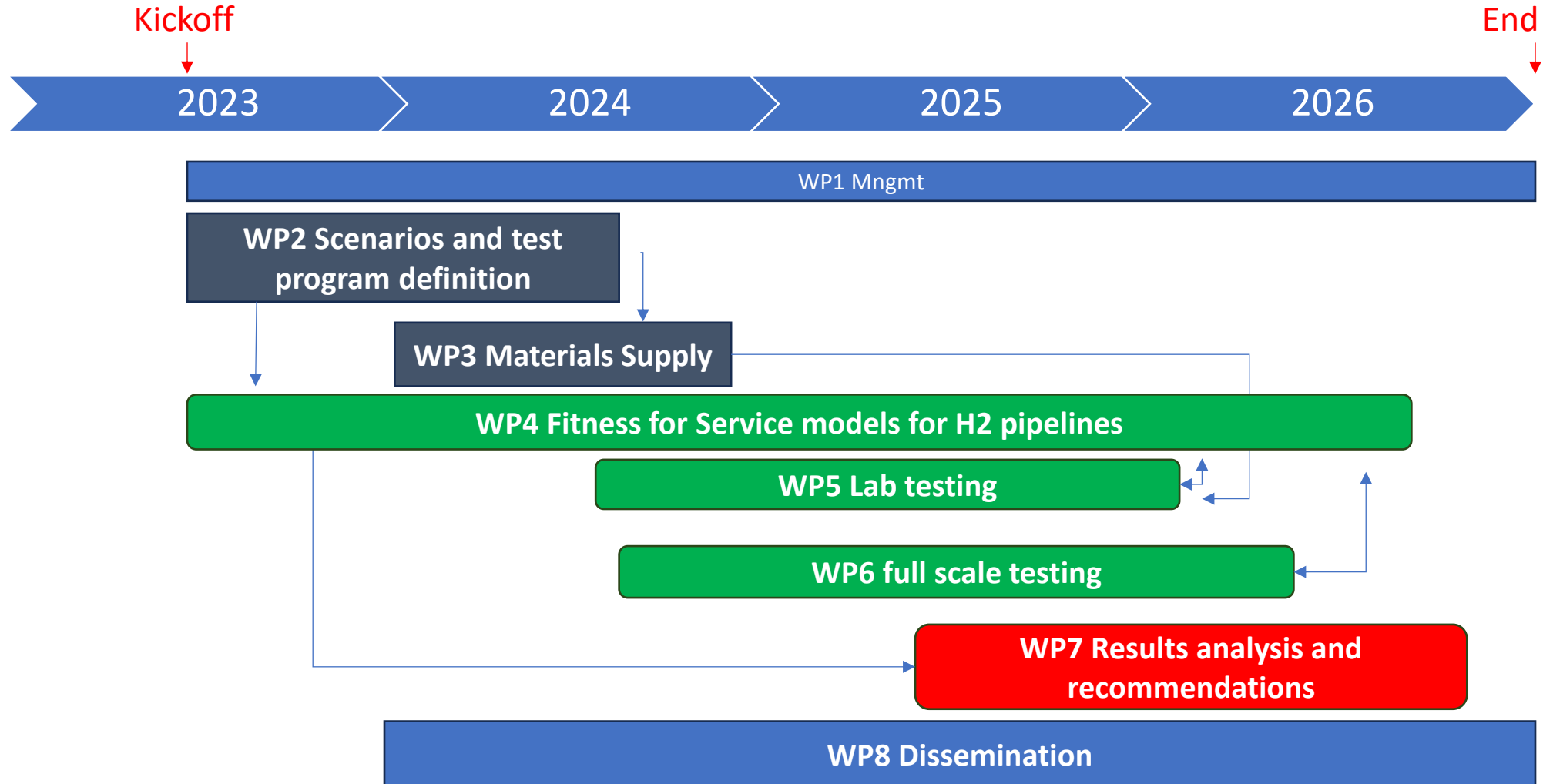
GRTGAZ



EPRG



Project structure and planning



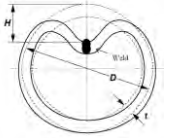
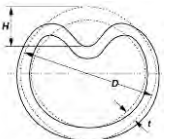
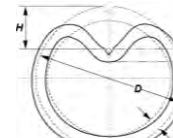
Materials

As a result of the initial activities, the project consortium has identified a set of material and geometries deemed representative of H2 and H2NG transport.

Both modern and vintage material have been considered, and several full-length pipes have already been secured to provide enough material for the experimental activities, both small scale and full scale.

Material type	WP3 ID	OD [in]	OD [mm]	WT [mm]	Pipe Steel Grade
MODERN SEAMLESS	3.1a	12"	323	17.5	API 5L X65QS / X65 QO, SMLS
	3.1b	24"	610	12.7	API 5L X70Q, SMLS
MODERN WELDED	3.2a	24"	610	11.3	API 5L X65MO, HFW
	3.2b	30"	762	14.3	API 5L X65M, LSAW
VINTAGE WELDED	3.3a	36"	914	22.0	API 5L X60MO, LSAW
	3.3b	26"	660	11.1	API 5L X60M, LSAW

Test matrix

Geometry	Damage size	Environment	Vintage LSAW onshore	Modern LSAW	Modern SMLS	Vintage LSAW offshore
Dent on Weld 	Dent Height 2% OD	Water		●		
		H ₂		●		
Plain dent 	Dent Height 6% OD	Water	●	●		
		H ₂	●	●		
Dent-Gouge 	Dent Height 6% OD Gouge: 1.5mm x 300mm	Water			●	
		H ₂			●	
Corrosion	60% WT; 300 mm long	H ₂				●

Strategy for full scale tests

Damage creation

Ref	Test	Material	Defect	Environment	Notes	Step #	Ref
1.10	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	1	1.10
1.11	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	2	1.11
1.12	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	3	1.12
1.13	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	4	1.13
1.14	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	5	1.14
1.15	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	6	1.15
1.16	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	7	1.16
1.17	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	8	1.17
1.18	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	9	1.18
1.19	Hydrogen Damage	Carbon Steel	Hydrogen induced cracking	High pressure water	Hydrogen induced cracking	10	1.19

Rome

Ship to test site (Sardinia)

End caps +
instrumentation

Oxide layer mitigation

Fatigue cycles

Interim Inspection

Burst

Failure Investigation

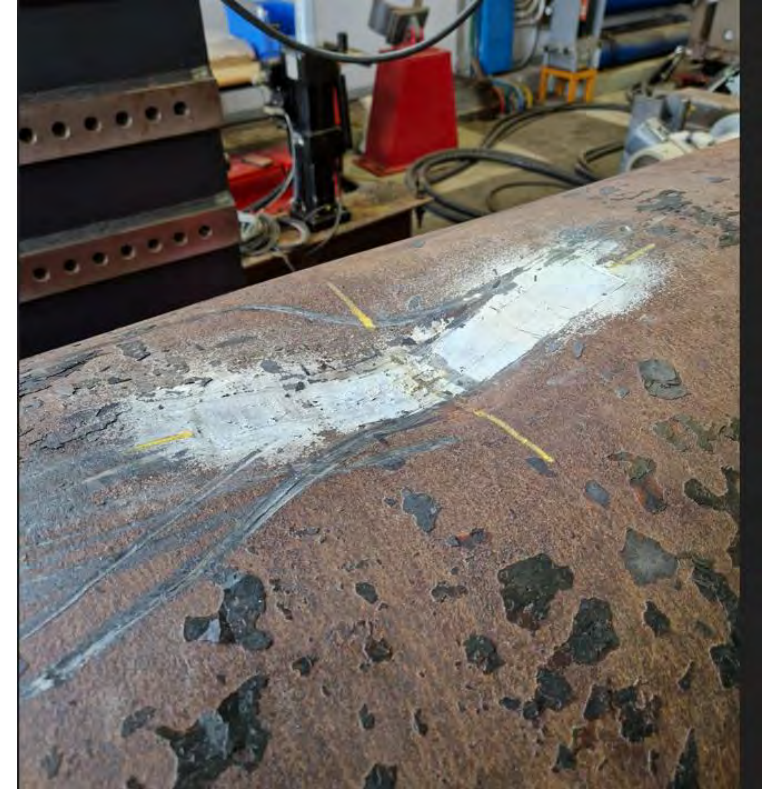
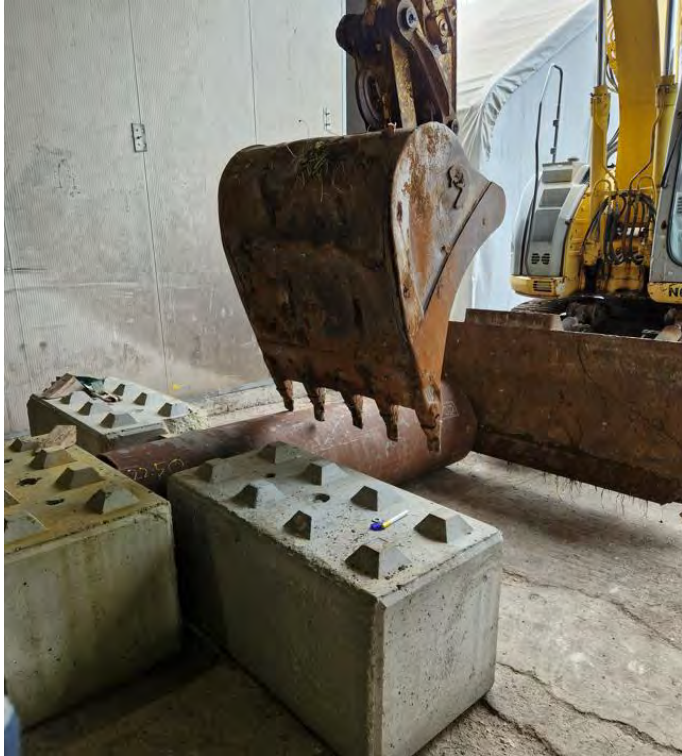


Select pipes for
ILI Inspection
Lingen

Sister sample
Tenaris Dent
Specimen only



— Gouge Damage creation:

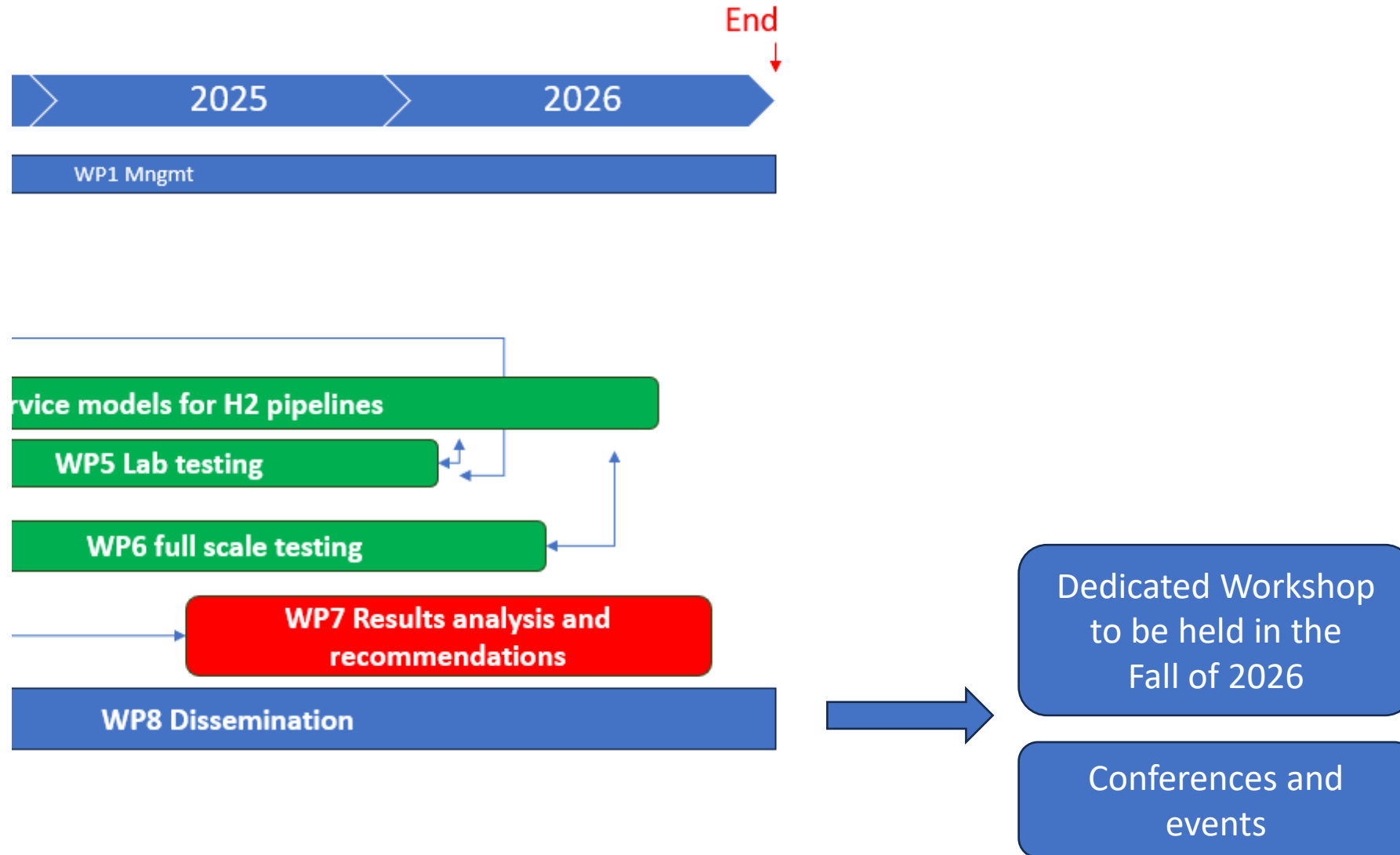


Lab scale testing

- Establish baseline values for the materials in hydrogen
- The test matrix has been defined.
- The tests are being carried out in the hydrogen testing laboratories of 3 project partners (GRTgaz Natrans, OCAS, Rosen)

Test type	Test environment	Material			
		Seamless	Welded (Modern + Vintage)		
			BM	HAZ	WM
K _{IH}	H2 100%	● ●	● ● ● ●	● ● ●	● ● ● ●
	H2 blend	●	● ● ●		
J-R	H2 100%	●	● ●	●	●
	Air	●	●	●	●
S-N	H2 100%	●	● ●		
	Air	●	● ●		
SSRT	H2 100%	●	● ● ●		● ● ●

Next steps



→ Further information

- Webpage: safeh2pipe.eu
- LinkedIn page: <https://www.linkedin.com/company/safeh2pipe/>

Thank you for your attention

Name Surname

Job Title

Contact mail





:

EPRG Full scale fatigue crack growth test on a modern linepipe in gaseous hydrogen

Bostjan Bezensek, Shell ; Otto Jan Huising, Gasunie; Paul Roovers, Fluxys; Luca Bacchi, SNAM,
Carlo Spinelli, ENI, Emanuele Bertelli, CSM RINA

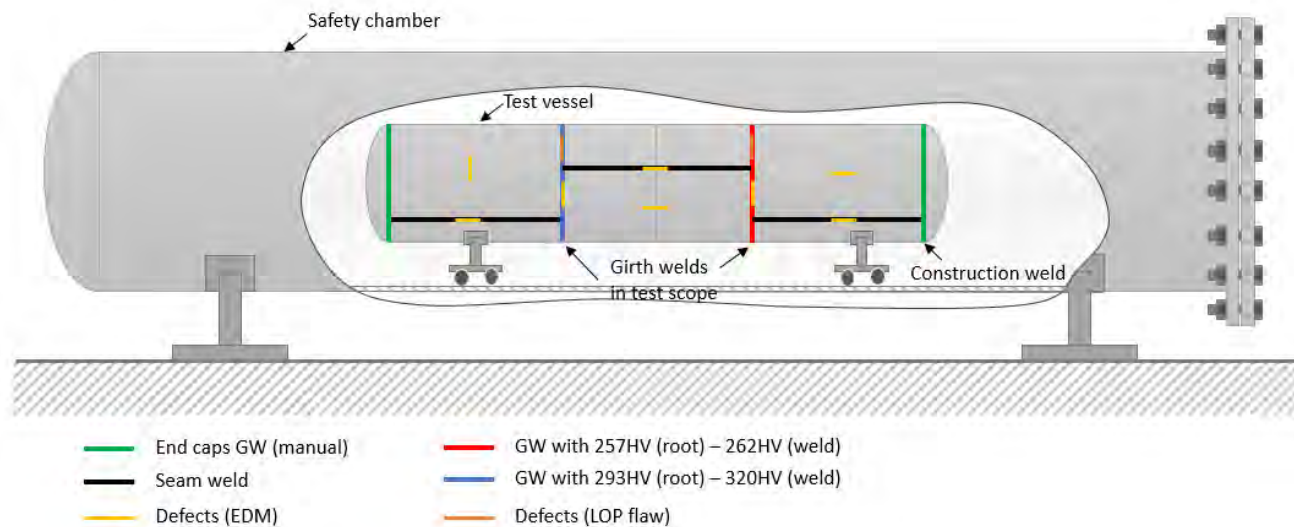
July 25th 2025

Aims of the EPRG Hydrogen programme (2021~2025)

- Challenge the hardness limitations to 235 HV / 248 HV of ASME B31.12
- Compare Material performance of modern vs vintage materials vis-a-vis ASME B 31.12's 1 dig/mile requirements
- Compare material performance w.r.t fatigue crack growth measured on a small scale lab test versus full pipe test
- Provide guidance on small scale fracture toughness testing (which test method) by correlation with the full scale pipe behaviour

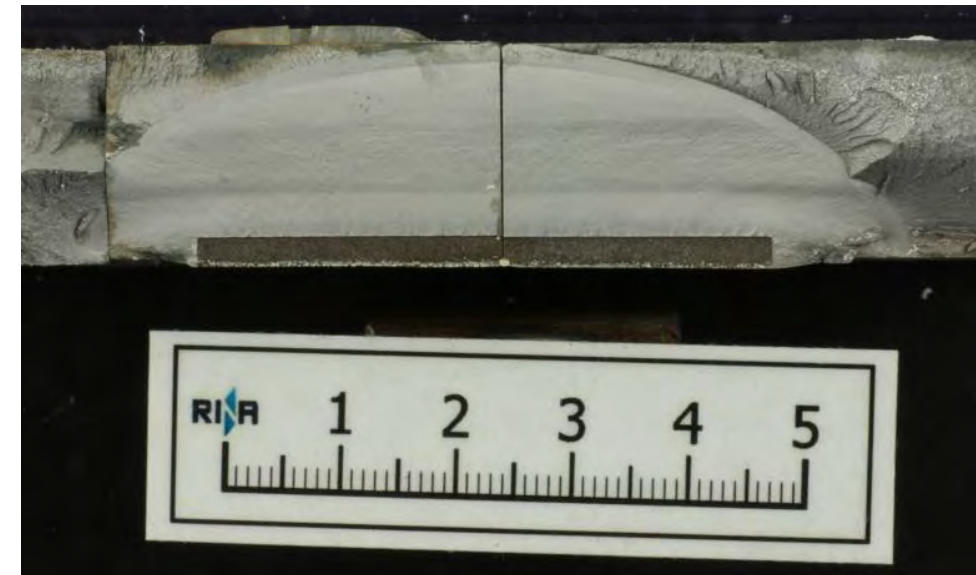
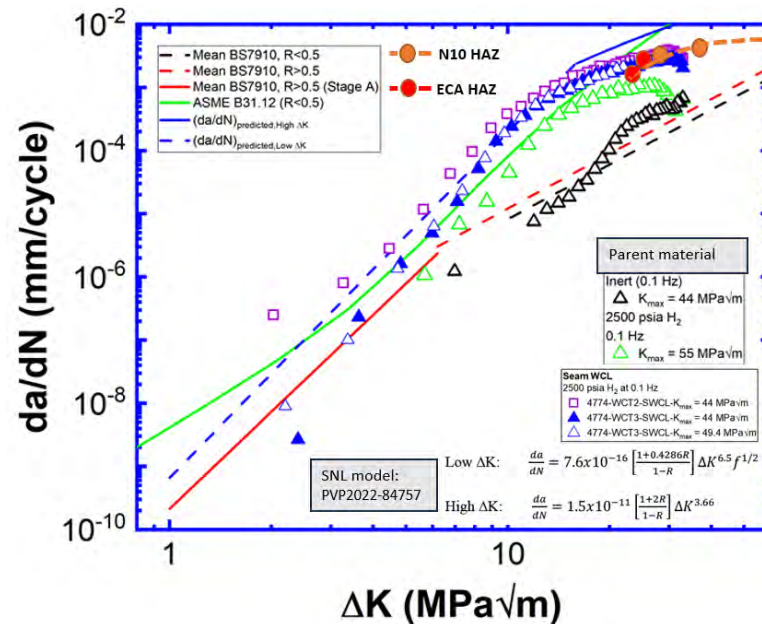
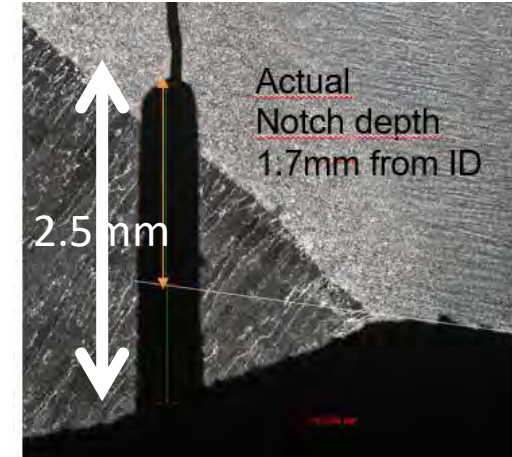
Approach

- Pj 231 – full scale fatigue test of 28” OD modern and 26” vintage linepipes with notches
- Pj 232 – small scale material testing : fatigue and fracture



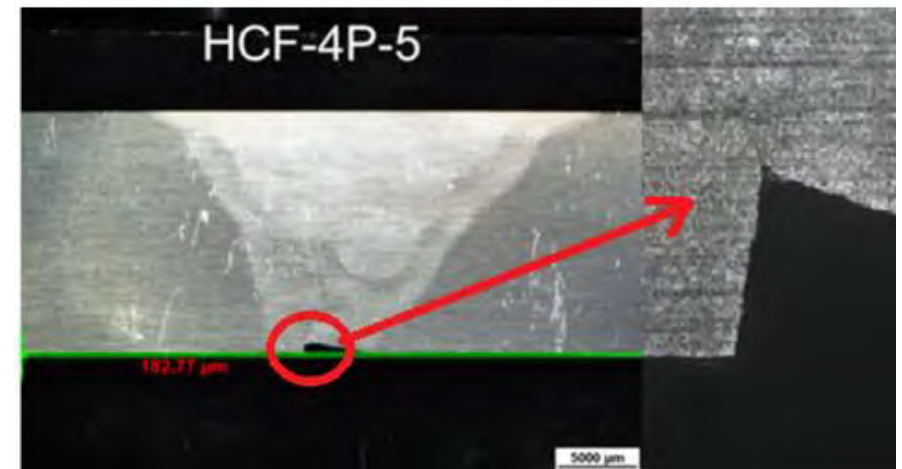
Modern pipe findings (PVP2024-124195)

- Rapid initiation from an EDM notch in the LS HAZ
- Crack growth to leak in ~4000 cycles @ R=0.5
- Accelerated crack growth
- Consistent with the Model predictions



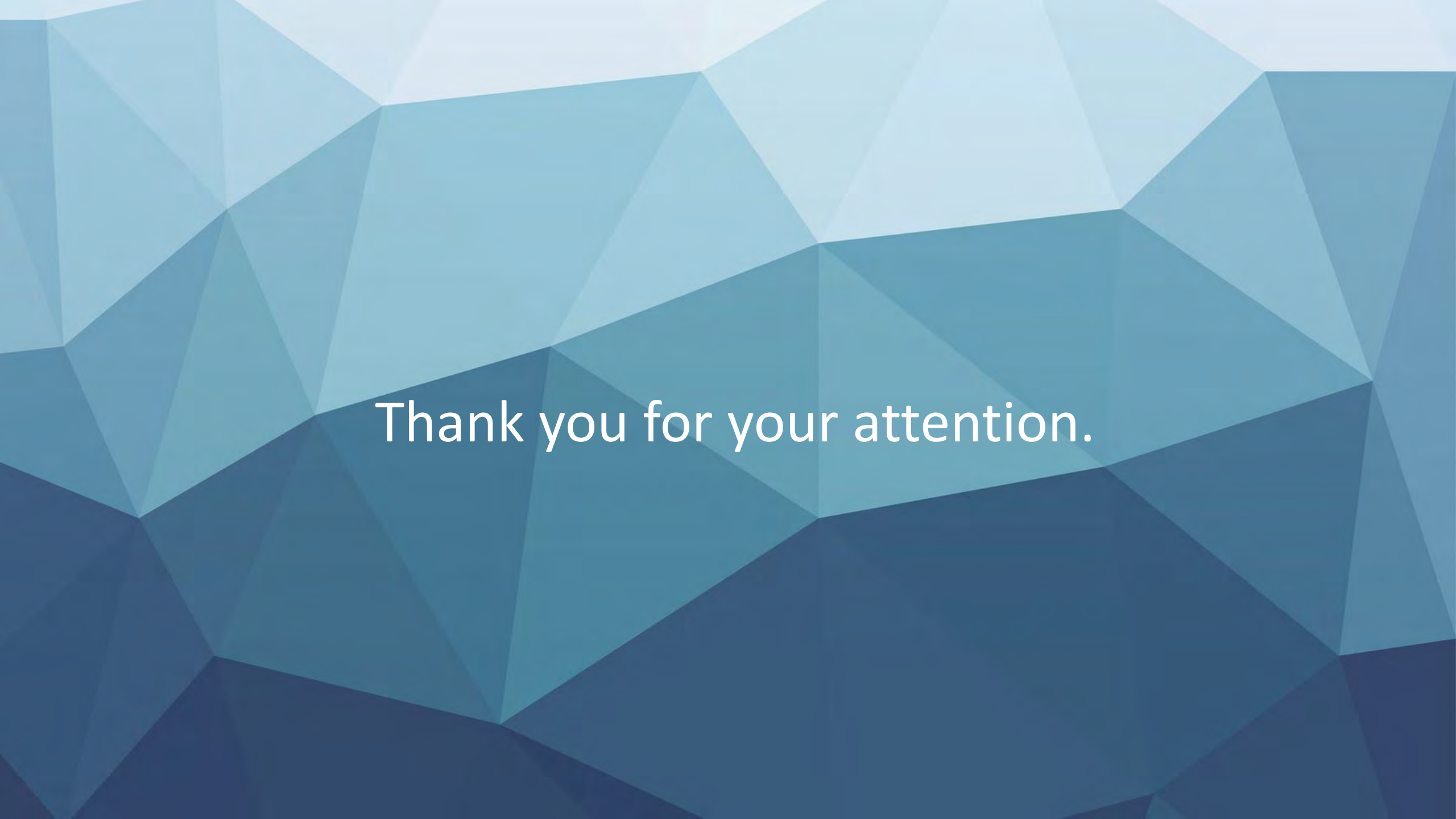
Modern pipe findings (EPIC Cambridge September 2025)

- Field repair made
- Found sensitivity to weld root profile and to the residual stress from the repair
- 2nd leak in ~7000 cycles @R=0.5 from the repair



Vintage pipe findings

- 1950's ERW pipe from North America & 1970's LSAW pipe from Europe
- Same preparations (EDM notch with the k_t of ~ 8) and same test procedure as for the modern pipe.
- Both pipes found to be significantly more resistant to initiation of a fatigue crack from the EDM notch
 - ERW pipe eventually cracked and produced a Paris curve
 - LSAW pipe did not produce a measurable crack growth using the TOFD sensor array at any notch. Test stopped after 6 months and notches are under sectioning now.

The background is an abstract geometric pattern composed of numerous triangles in various shades of blue and teal. The triangles are arranged in a way that creates a sense of depth and movement, with some triangles being larger and more prominent than others. The overall effect is a modern, minimalist design.

Thank you for your attention.



Exceptional service in the national interest

Defect simulation

Chris San Marchi
Joe Ronevich
Sandia National Laboratories, Livermore CA

Not for public release

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.





HyBlend CRADA

Probabilistic Fracture Mechanics software:

- Extend probabilistic tools
- Add new defect configurations (including ML algorithms)



Subscale Pipe Testing

- Develop strategies to quickly and efficiently test surrogate defects
 - Hard spots
 - Dents
 - Wrinkle bends
 - Laminations, etc



PRCI/EFI threats

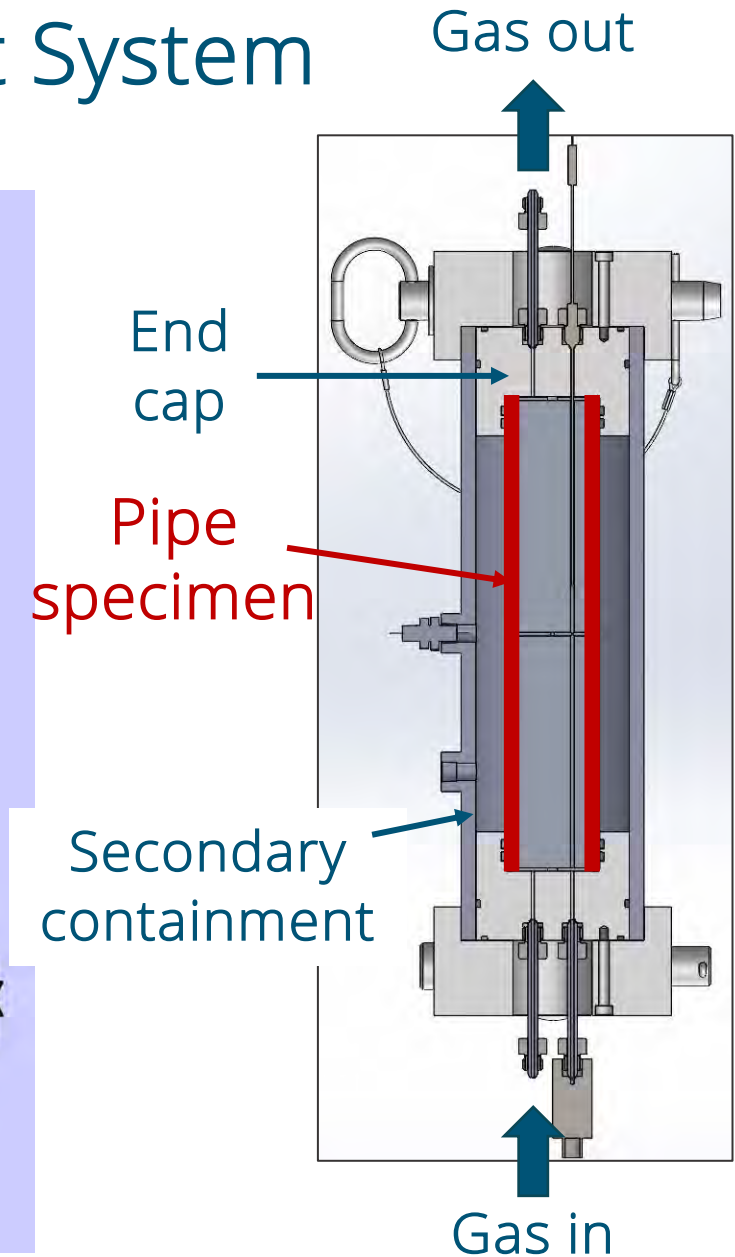
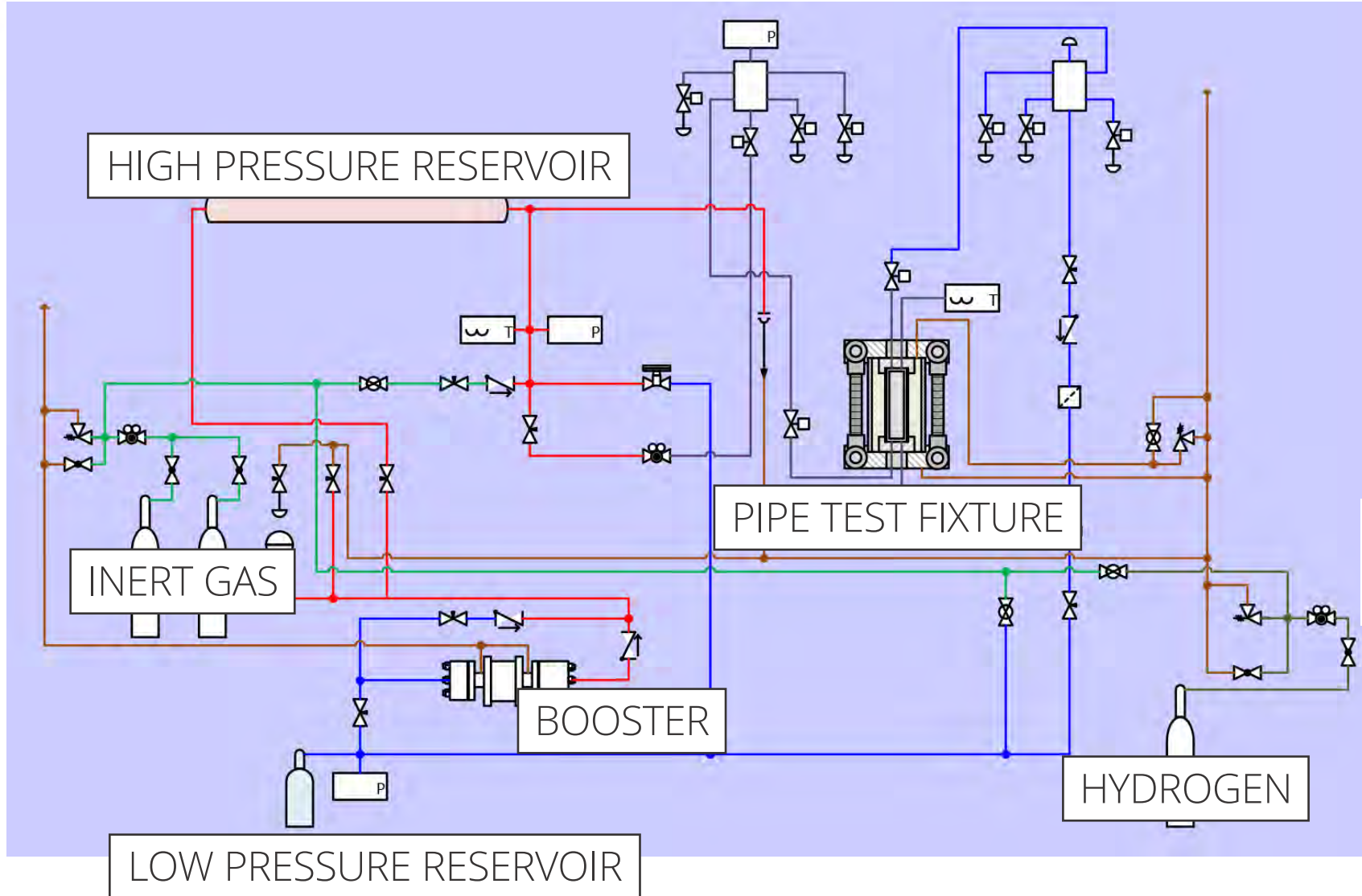


New test geometries and new methods may be needed

Fatigue and Fracture Testing in Gaseous Hydrogen

- HAZ and welds of seam and girth
- Crack nucleation and propagation from PRCI threats
- Assess operational influences: constraint (SENT), overloading, non-uniform stress cycles, etc

Subscale Component Hydrogen Test System





System constructed and operational



Computer control, data acquisition and piping



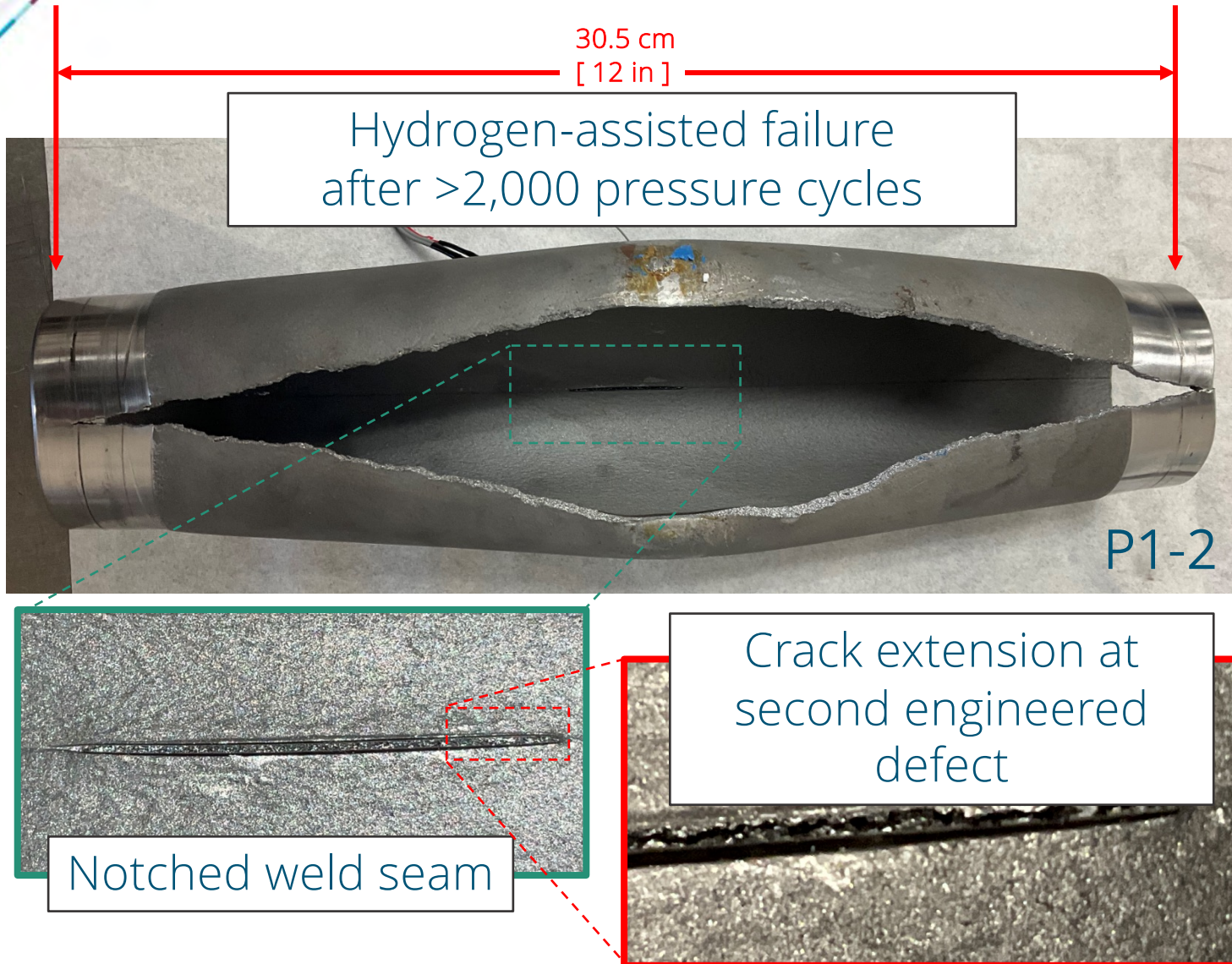
Assembled test fixture

Pipe specimen with end caps





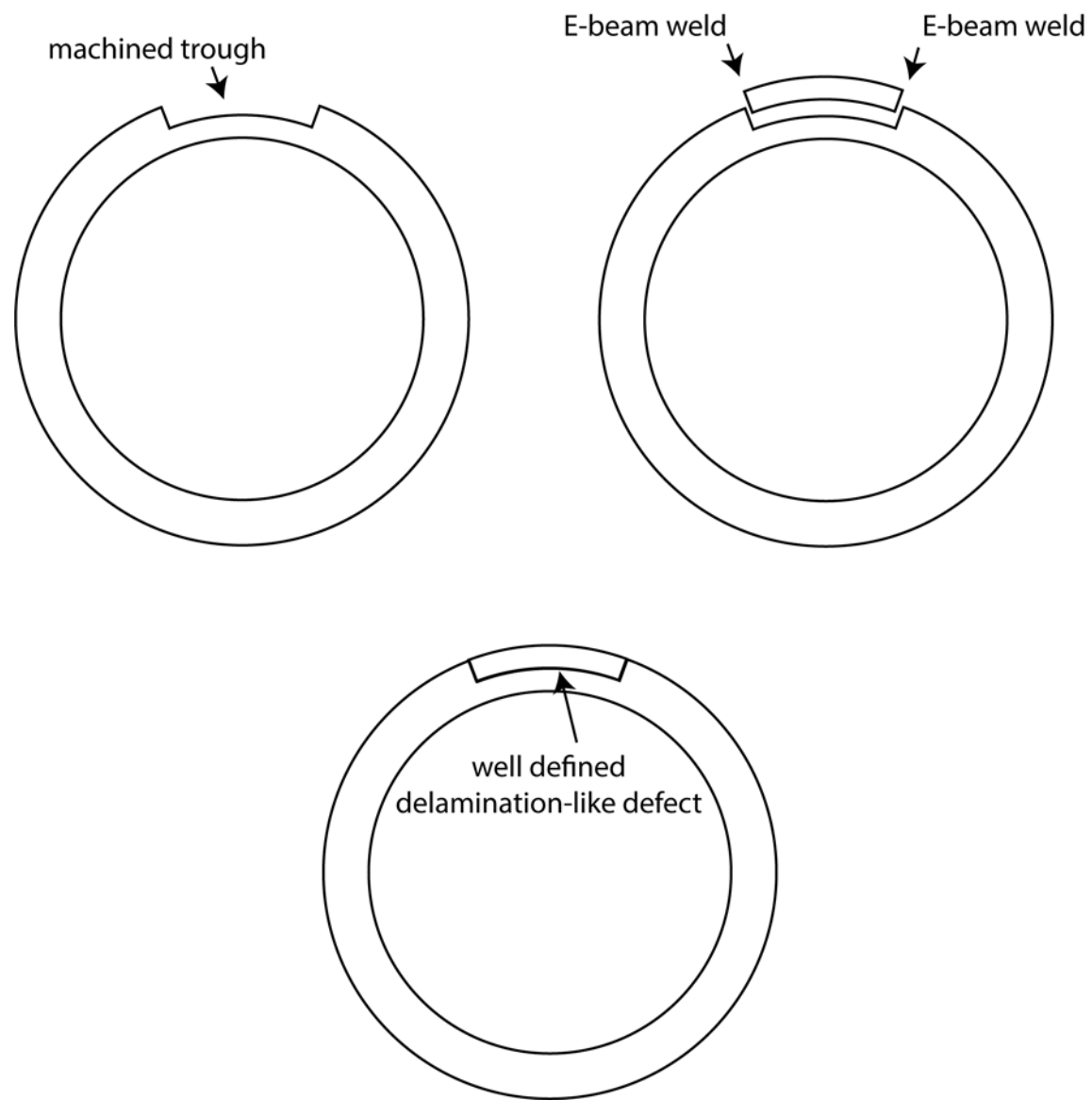
First article: subscale pipe testing



- Specimen consists of pipe (NPS 2, Schedule 40) with two engineered defects
 - Notches machined on inside of pipe:
 1. On seam weld
 2. Opposite seam
- Pressure cycle:
 - $P_{\max} = 280$ bar
 - $P_{\min} = 140$ bar
- Rupture upon over-pressurization

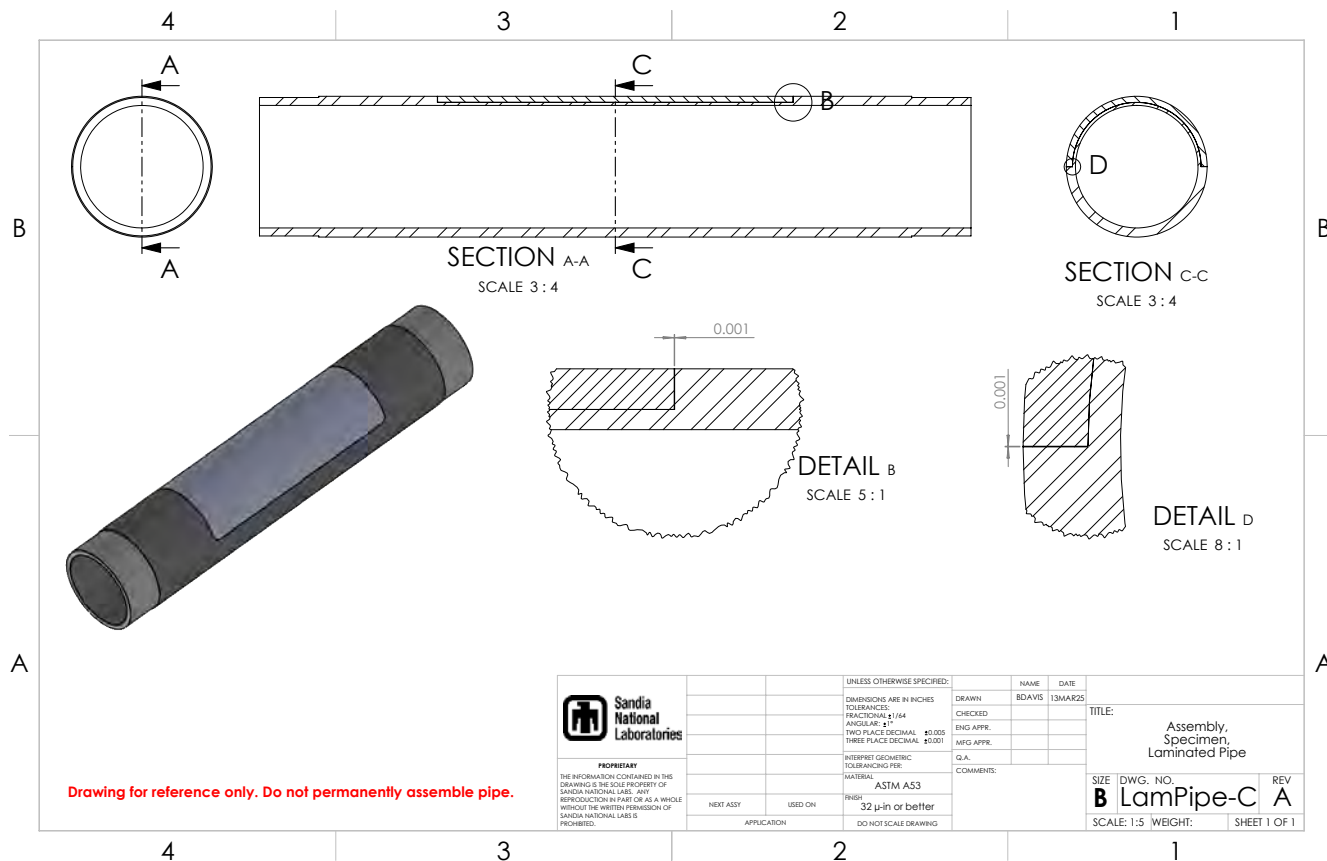


Laminations: base concept

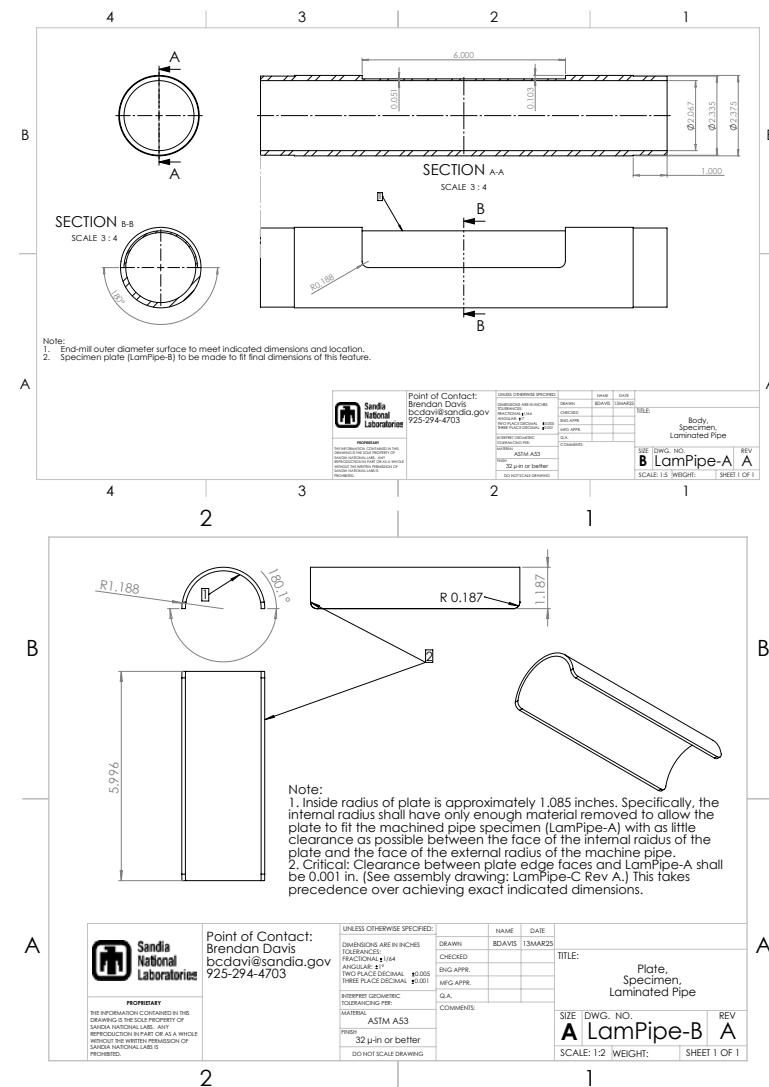




Planned geometry



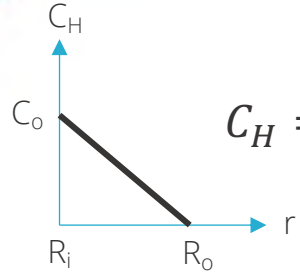
Drawing for reference only. Do not permanently assemble pipe.





Equivalent pressure in a lamination

Assume linear hydrogen concentration across wall (flat plate)



$$C_H = C_0 \frac{(r - R_i)}{(R_o - R_i)}$$

$$C_H = K f^{1/2}$$

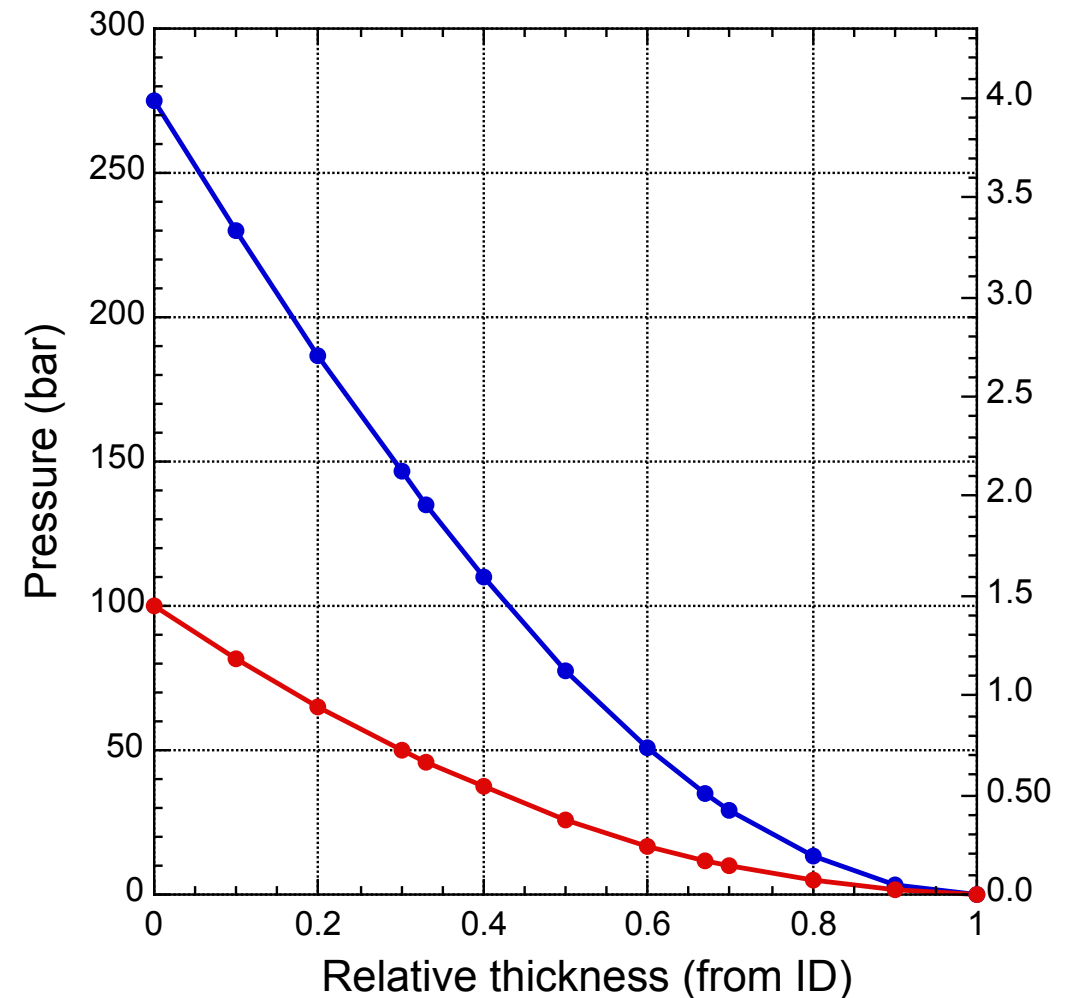
$$C_0 = K (f_i)^{1/2}$$

$$\left(\frac{f}{f_i}\right)^{1/2} = \frac{(r - R_i)}{(R_o - R_i)}$$

$$\text{Fugacity, } f(r) \quad f = f_i \left[\frac{(r - R_i)}{(R_o - R_i)} \right]^2 \quad f = \left[\frac{x}{T} \right]^2 f_i$$

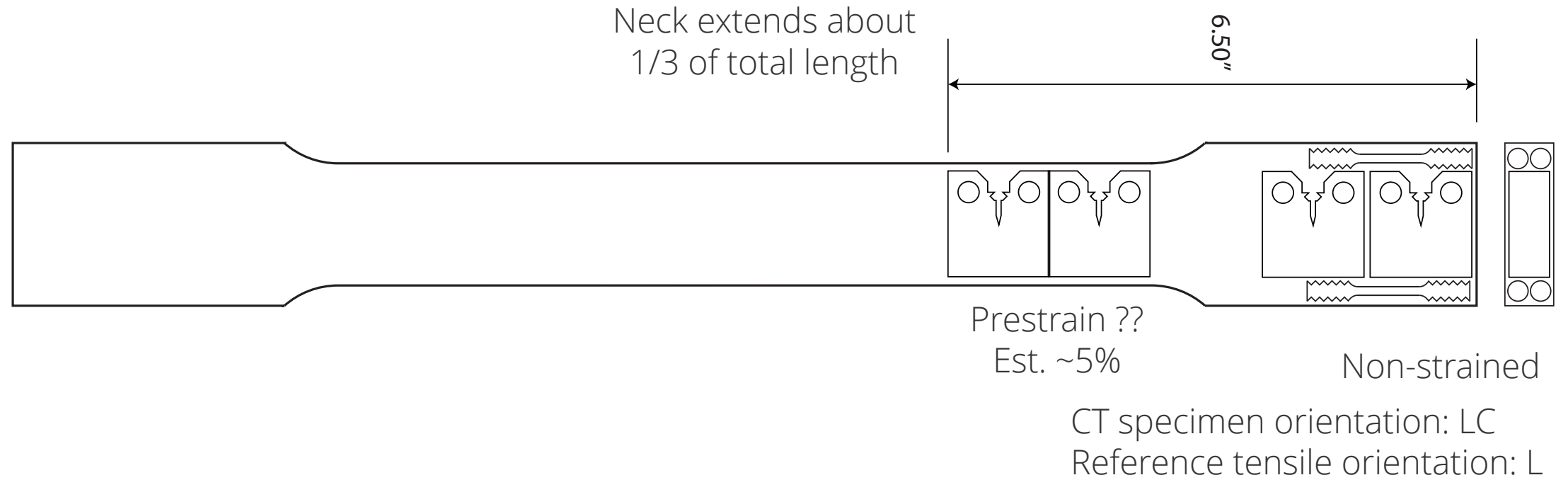
EOS for H₂ $\frac{f}{P} = \exp\left(\frac{Pb}{RT}\right)$

$$P[\text{bar}] = 0.39402 + 0.97727f - 0.0004365f^2$$



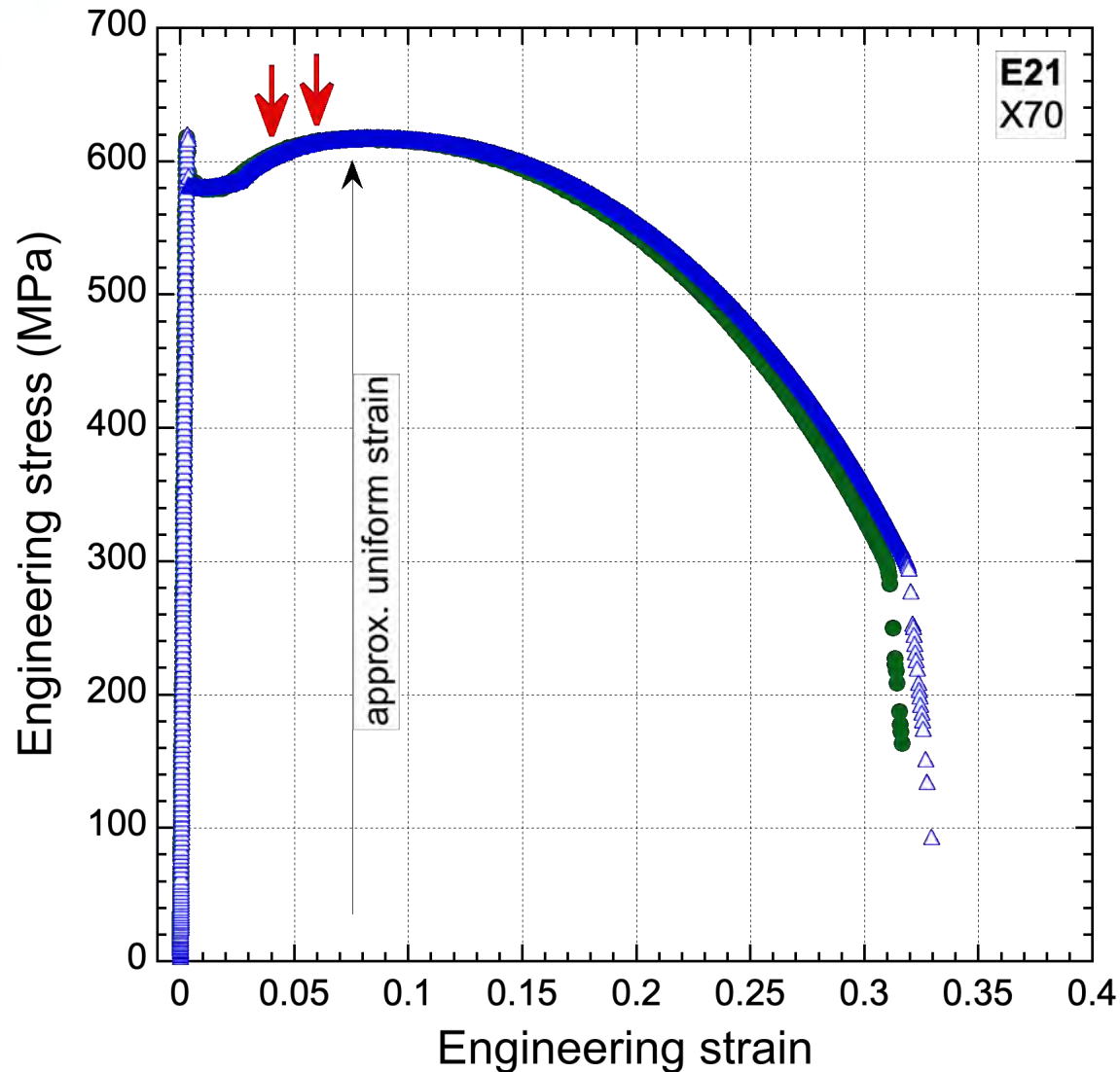


Effect of deformation in pipe: prestraining





Tensile flow curves



4 mm dia round bar

- Yield strength (0.2% offset) = 583 MPa
- Tensile strength = 619 MPa
- Uniform elongation = 7.6%
- Strain rate $\sim 10^{-3} \text{ s}^{-1}$
- Orientation: C (hoop stress direction)

Plan:

- Pre-strain tensile bars (2) to specified average strain
 - E21-BB1 = 4%
 - E21-BB2 = 6%
- Measure strain by any convenient means



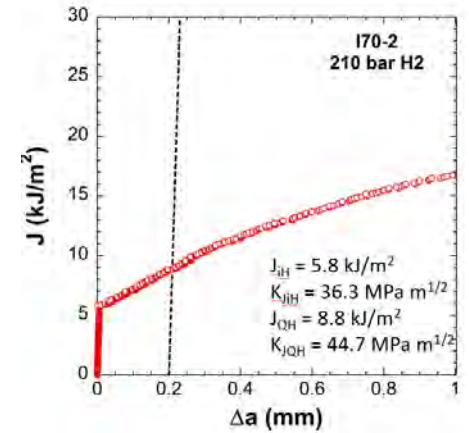
EPRG Round robin benchmark study on the fracture toughness testing in hydrogen – Update for the Sandia Study group @ Montreal

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

July 2025

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 best practice guidelines published in June 2024
 - Mostly incorporated into the revised ANSI/CSA CHMC-1: 2025



- ❑ Multi laboratory study following the EPRG Guidelines based test procedure
- ❑ Generate consistent set of baseline data for closing the knowledge gaps
- ❑ Identify industry baseline performance (ISO 13528 /ASTM E691)
- ❑ Provide improvement & learning opportunity for each participating lab

We are not testing a given material,
We are testing the test procedure !

Task	Aim	Responsible party
Task 0	Material selection& supply	European producer
Task 1	Test sample preparation (machining & notching)	PM's + Machine shop
Task 2	Definition of the test protocol for the project	EPRG + lead lab,
Task 3	Baseline test results in H2	Lead lab (Sandia)
Task 4	In-kind test results from the participating labs	Participating labs
Task 5	Results analysis and reporting	PM's

Reminder - List of participating labs for the RR

EPRG	Europe non EPRG	Americas	Asia	Australia
Corinth Pipe Works	CETIM France	C-FER Edmonton	DNV Singapore	Uni Wollongong / Rosen Australia
CSM RINA	CEA LITEN	DNV Columbus	KRISS (SKorea)	
Element	Fraunhofer IWM	EWI Columbus	HydroGENIUS/ IC2NER (Japan)	
GRTGaz / Natrans	French Institute of corrosion	EMC ²	PipeChina	
OCAS	H2 IIS SIDERLab Italy	HyPerformance (Kevin Nibur)		
Rosen	MPA Stuttgart	INT Brasil	28 participants	
	Tecnalia Spain	NIST Boulder		
	TWI	Sandia Livermore (lead lab)		
		SWRI		

Labs in the parallel track

- These labs are to be given some material for their own testing . Their results will not be part of the RR statistical study.
 - Blade Energy
 - BMT fleet
 - Canadian Nuclear Laboratory
 - Nippon Steel
 - SINTEF
 - SZMF
 - University of Burgos (UBU)
 - Materials Institute Leoben
 - P-Prime Institute France

Sample extraction plan

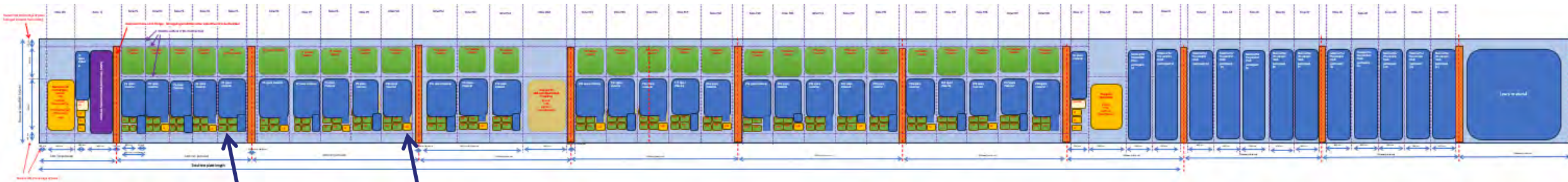
Baseline &
Reference tests

RR participants material
& lead lab in-between

Baseline &
Reference tests

Parallel track
participants

Balance of
material

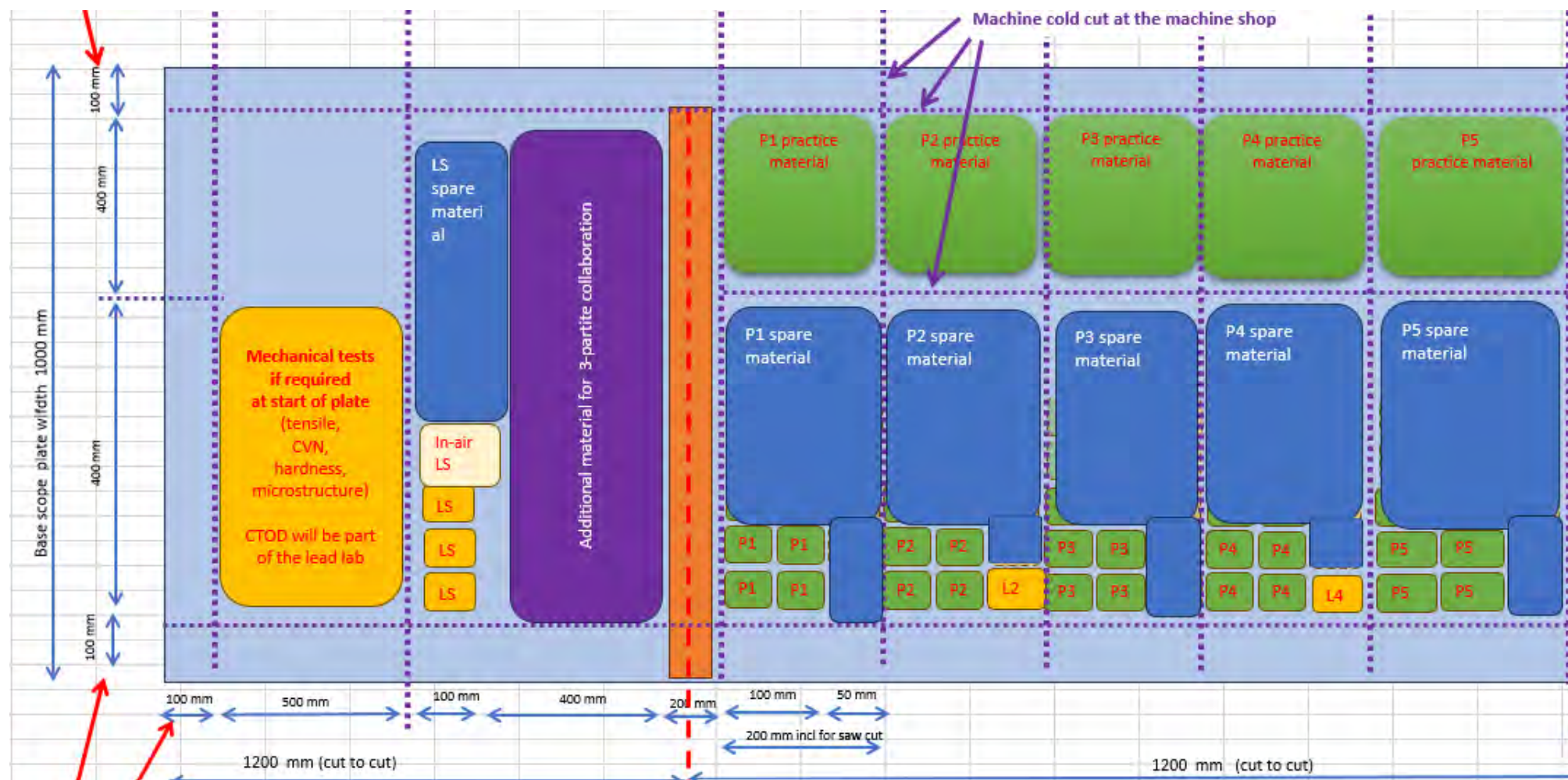


14m long mother plate

3+1 spare
samples to be
made for each
participant

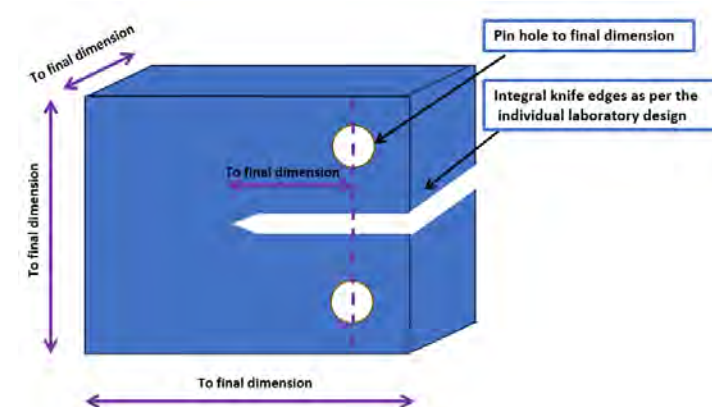
Lead lab sample
on either side of
each participant

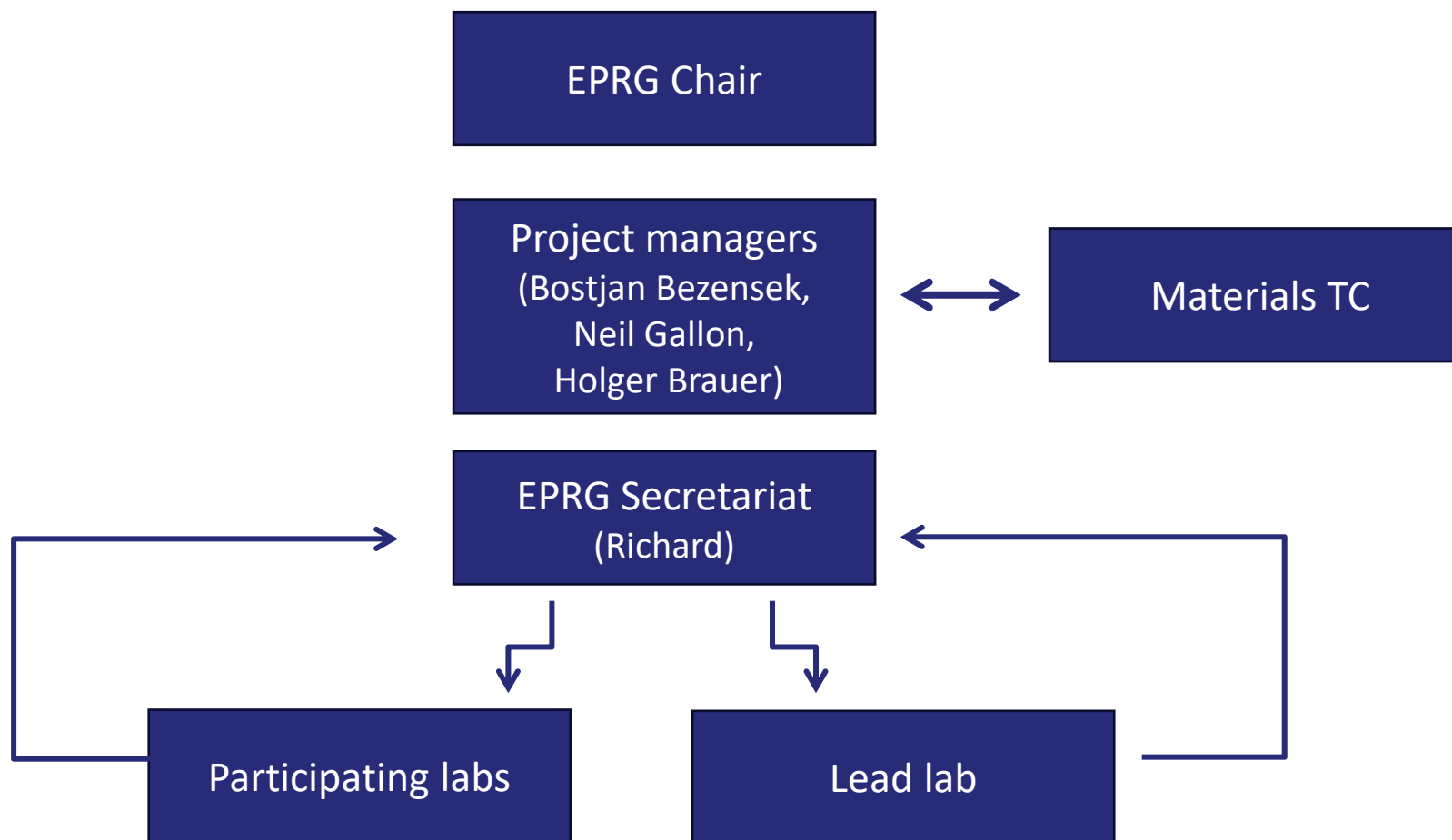
Sample extraction plan



Test material & samples & procedure

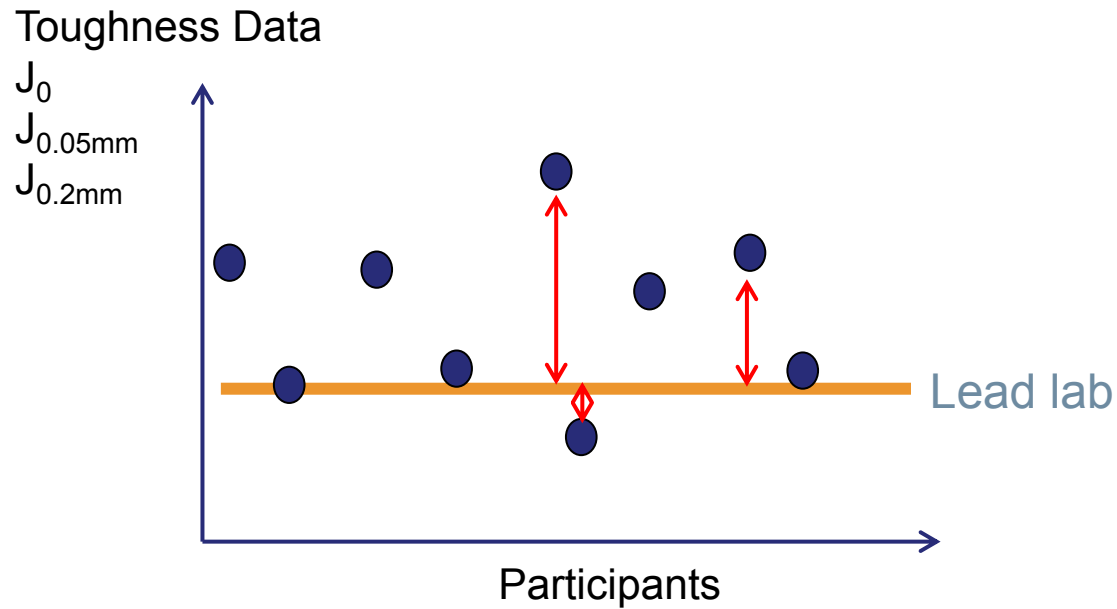
- Task 0: Sourced the material
 - Thermomechanically (TMCP) rolled plate of grade L450 (~X65)
- Task 1: CT test samples defined and machined
 - $B = \frac{1}{2}$ "
 - $W/B = 2$ (except for 2 labs)
- Task 2: Defined the test protocol
 - Control on impurities
 - Test execution
 - Results postprocessing
 - Reporting



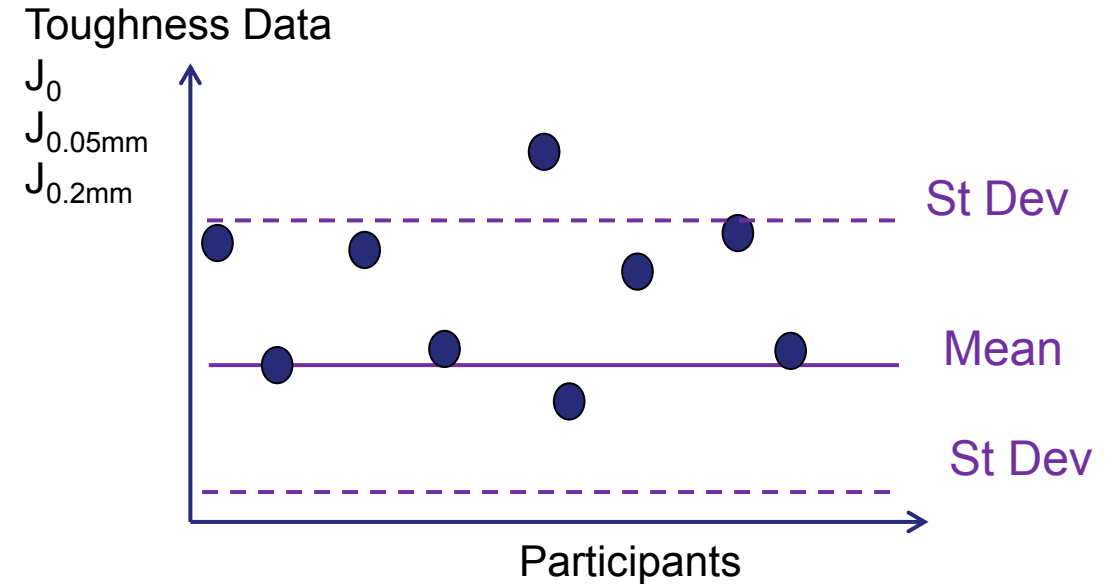


Data analysis & expectations

- Follow ASTM E691 and ISO 13528



Compare with lead lab



Industry average performance

Expected main sources of deviations & scatter

- Ability to measure O_2
 - Ability to measure Moisture
- } **Test environment**
- Ability to measure crack initiation (J_{0mm}) and $J_{0.05mm}$
 - Those who don't have EPD
 - But also those who do have EPD as we still lack the exact protocol
- } **Result post-processing**
- (Loading rate DK/dt)
- } **Test execution**

Timeline

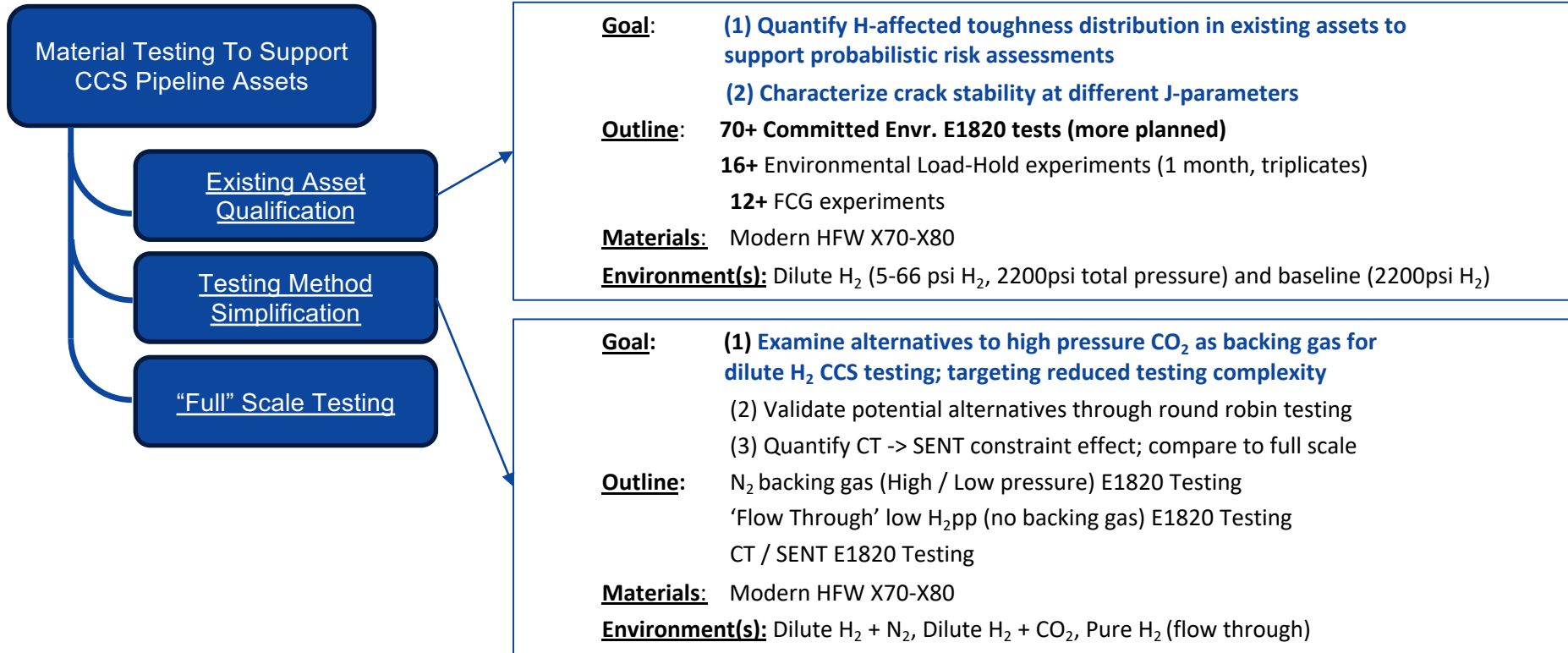
	2025							2026	
Task	June	July	August	September	October	November	December	January	February
Sample Machining									
Sample delivery (EU)									
Sample correction (worldwide)									
Testing									
Reporting									
Data analysis									
Reporting									



July 2025

ExxonMobil CO₂-H₂ Fracture Testing Efforts to Support CCS Pipelines

CO₂-H₂ Fracture Testing Programs



CO₂-H₂ Fracture Testing Programs

Material Testing To Support
CCS Pipeline Assets

Existing Asset
Qualification

Testing Method
Simplification

“Full” Scale Testing

Goal: (1) Quantify conservatism of coupon-scale CO₂-H₂ testing to support use of higher FT from CCS asset qualification studies

(2) Assess impact of subcritical crack growth on pup scale defect pipeline materials

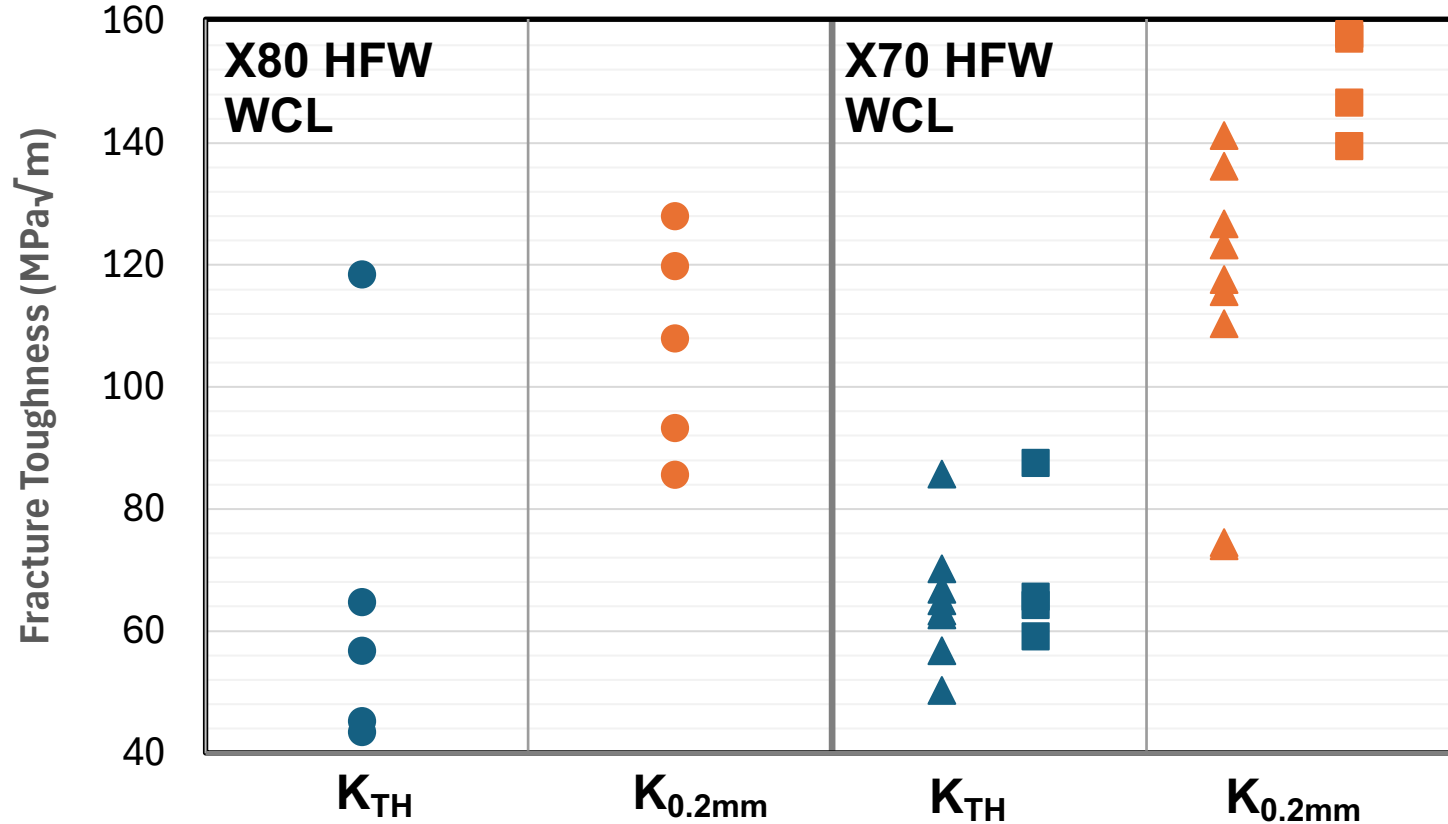
Outline: 18 Pup-scale H₂ pressure ramp experiments
6 Pup-scale H₂ load hold experiments (1,2, 3 month duration)
ID/OD Flaw comparison in H₂ load ramp experiments
Coupon H₂ scale testing (E1820 / Load-Hold) in parallel for comparison
In-Air tests for reference and comparison

Materials: Modern X65 Seamless, 10” OD

Environment(s): Pure HP H₂; considering (~1% / 23psi) in HP CO₂ / N₂ backing gas.

Initial stage program; full results expected EOY 2026

Dilute Hydrogen E1820 Testing (5-67psi H₂ + HP CO₂)



Findings and Questions about SENB Fracture Toughness Tests in Hydrogen

Lu Sun, Mark Cuglietta, Yu Chen, Sissi Zhang

C-FER Technologies

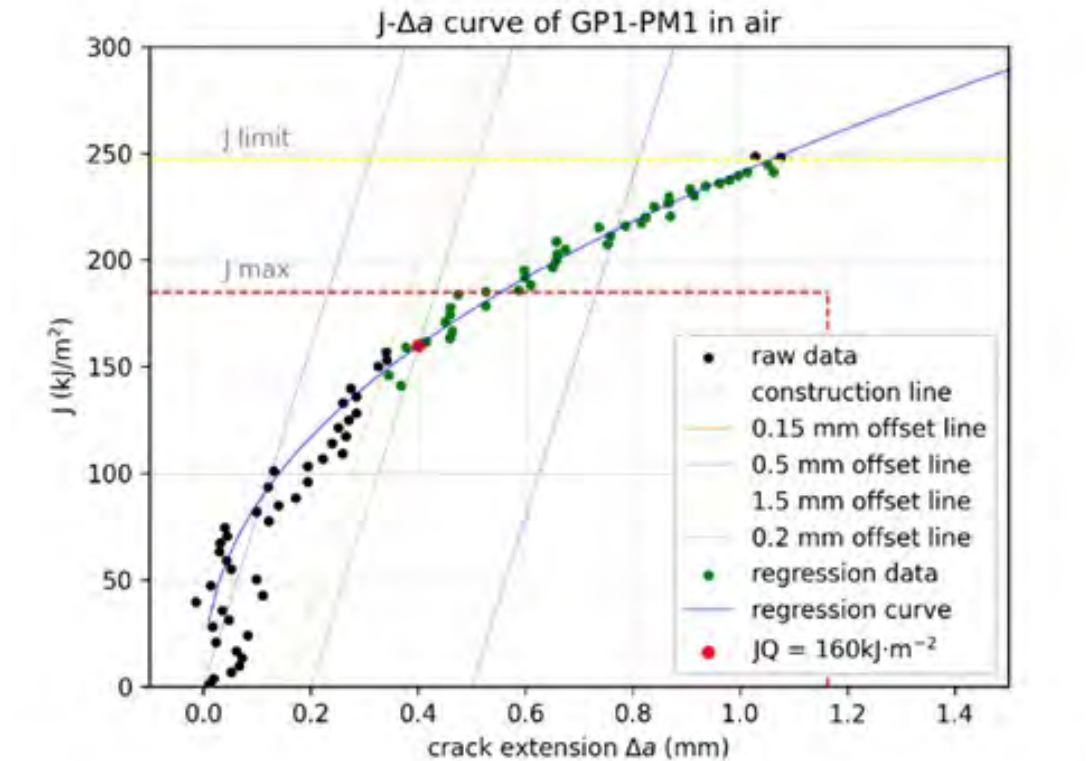
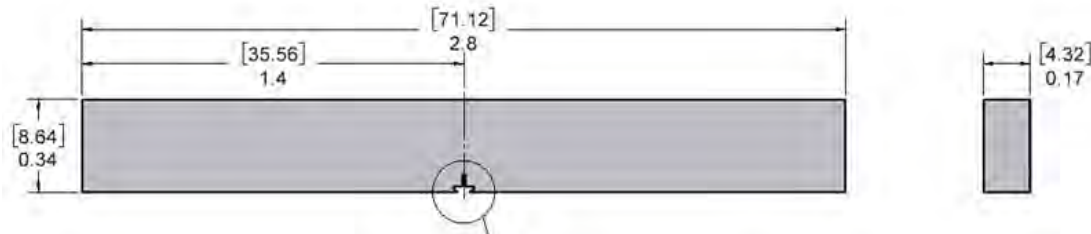
July 25, 2025

Topic 1: Accuracy of testing on small SENB specimens

- Challenge 1

Get accurate a_{0q} (ASTM E1820 A9.3.3)

$$a = a_{0q} + \frac{J}{2\sigma_Y} + BJ^2 + CJ^3 \quad \underline{R^2 > 0.96}$$

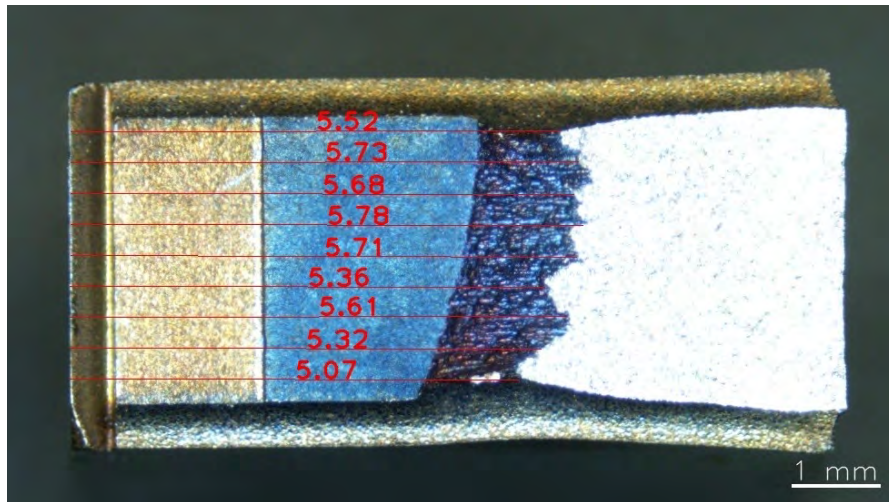


Topic 1: Accuracy of testing on small SENB specimens

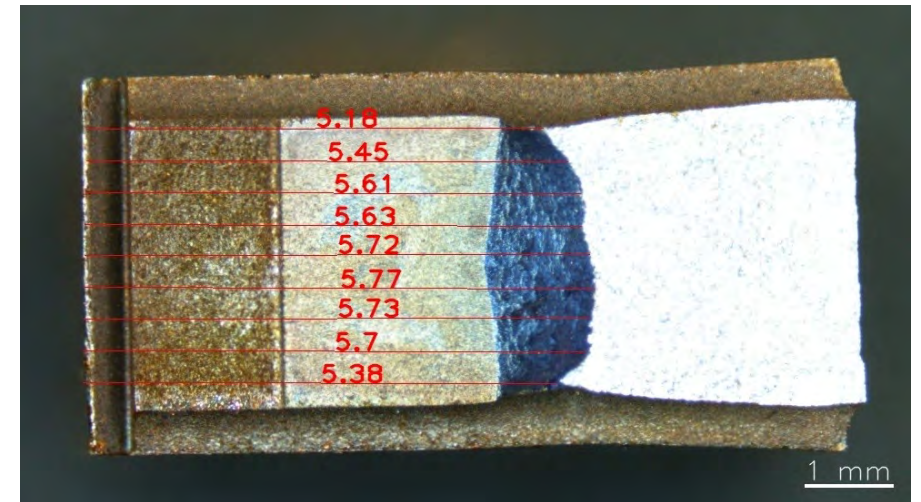
- Challenge 2

Tunnelling effect (ASTM E1820 A9.1.4)

$$|a_i - a_{p,average}| < 0.1(b_0 B_N)^{1/2} \approx 0.38 \text{ mm}$$



Parent Metal in air (GP1-PM-000-PM2)



Weld Metal in hydrogen (G5-WM-60-WM7)

Topic 1: Accuracy of testing on small SENB specimens

- Challenge 3

Get accurate crack extension prediction (ASTM E1820 A9.1.5.2)

$$|\Delta a_{prediction} - \Delta a_p| \leq 0.03 b_0 \approx 0.129 \text{ mm}$$

Topic 2: Effect of loading rate on fracture toughness testing results

- ANSI/CSA CHMC 1-2014 5.5.4.4

"Displacement rate shall be selected such that the crack tip stress intensity factor, K , increases at a rate between $0.1 \text{ MPa} \sqrt{\text{m/minute}}$ and $1 \text{ MPa} \sqrt{\text{m/minute}}$ during the nominally elastic region of specimen loading."

K rate used: $\sim 14 \text{ MPa} \sqrt{\text{m/minute}}$

-> Use $J_{0.05\text{mm}} / J_0$ instead of $J_{0.2\text{mm}}$ to "estimate" J_Q under low K rate using data obtained under high K rate?

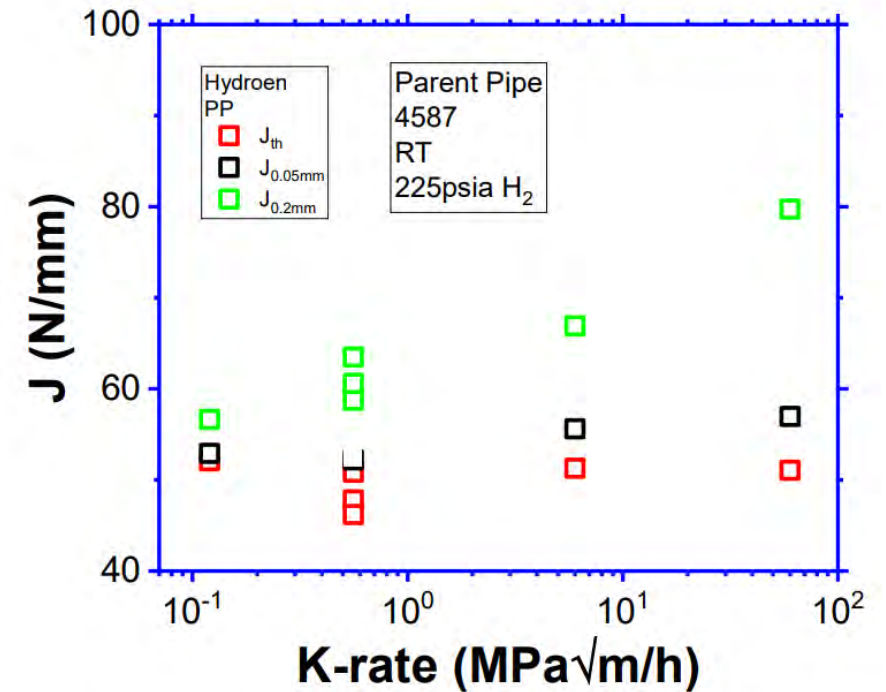
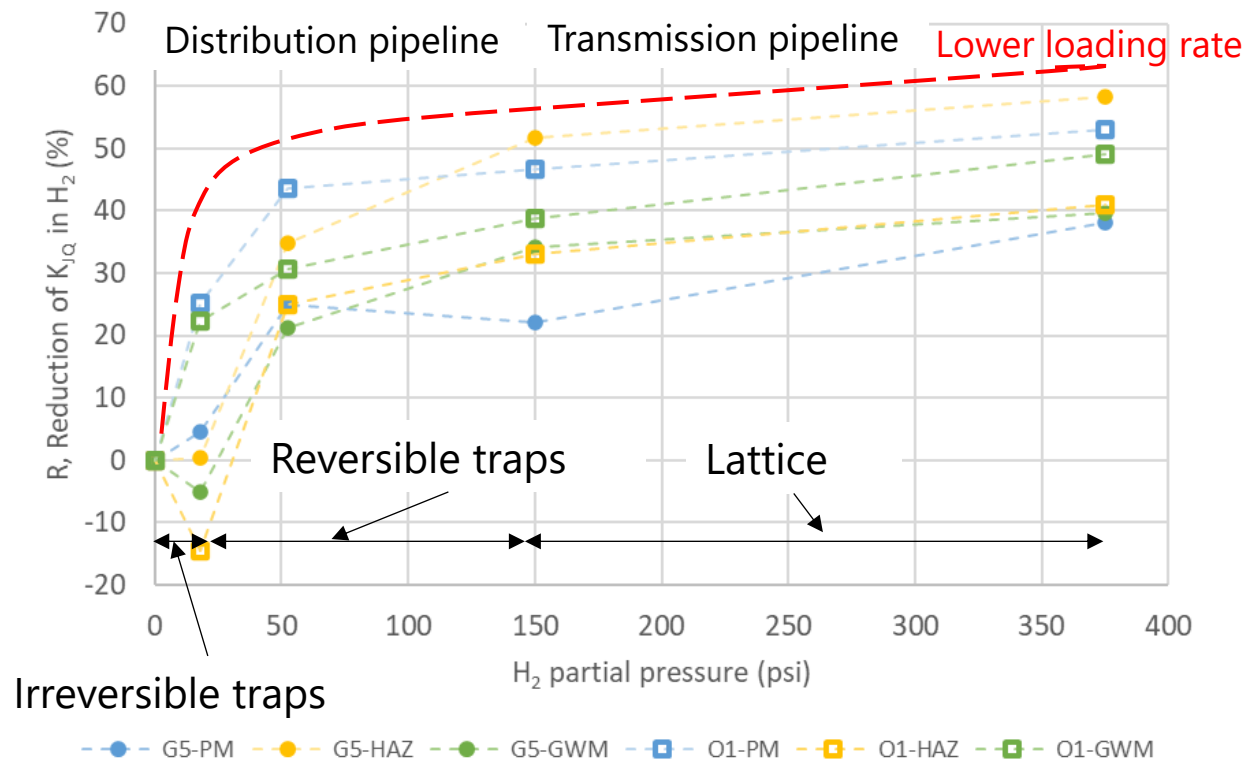


FIGURE 4: SENSITIVITY OF THE INITIATION FRACTURE TOUGHNESS TO THE LOADING RATE
(Bezensek, 2023)

Topic 2: Effect of loading rate on fracture toughness testing results

- Effect of loading rate on R-pH₂ curve ?

$$\text{Reduction rate of } K_{JQ}: R = \frac{(K_{JQ,air} - K_{JQ,H_2})}{K_{JQ,air}} \times 100$$



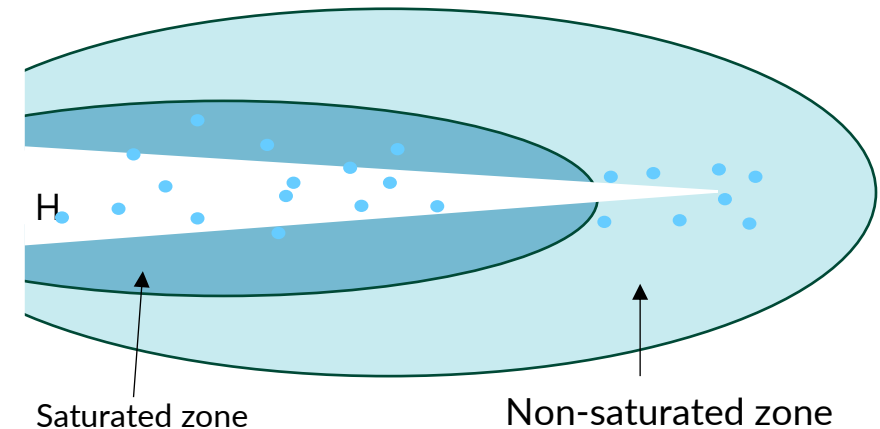
Processes involved:

- Crack growth:** loading rate (ϵ), $K_{JQ,air}$
- H diffusion:** temperature (T), H partial pressure (pH₂)
- H trapping:** temperature (T), trap density ($N_{ir,t}$, $N_{r,t}$)

-> Distribution pipeline: pH_{2, critical} is important

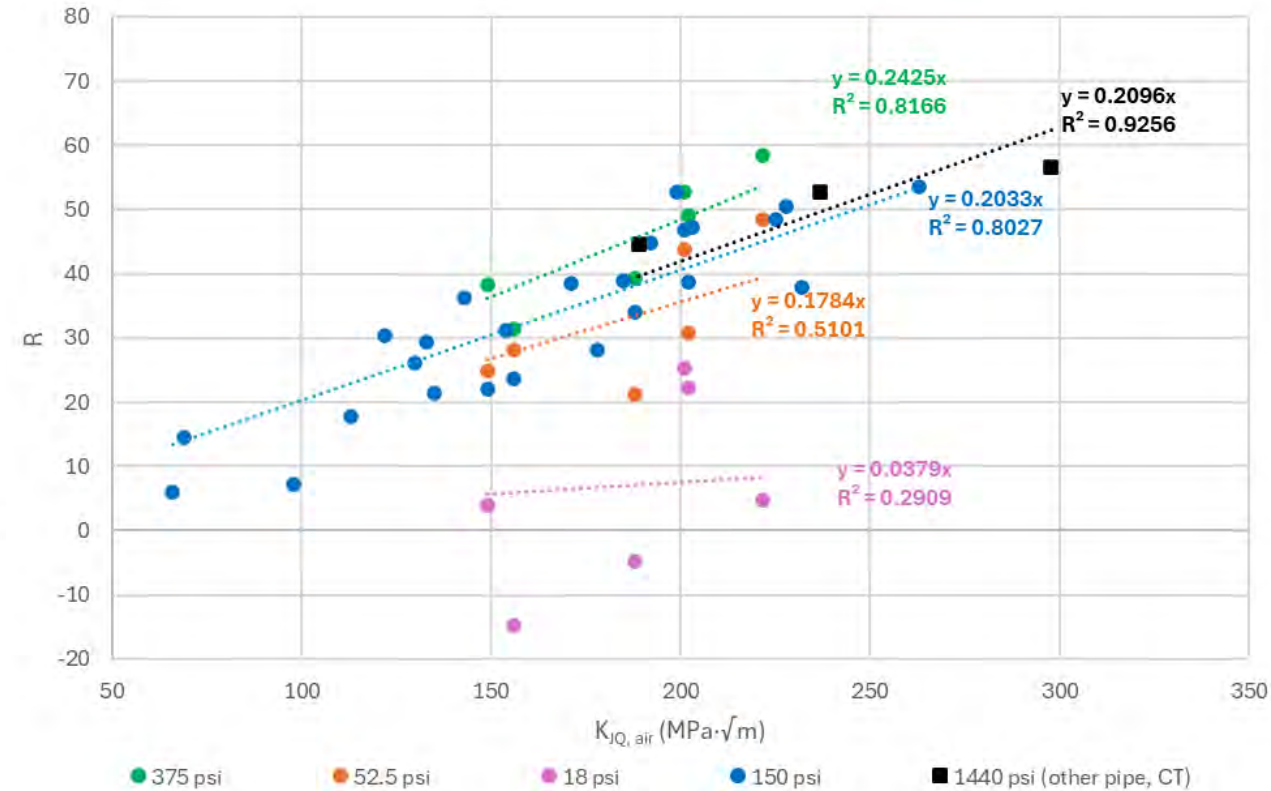
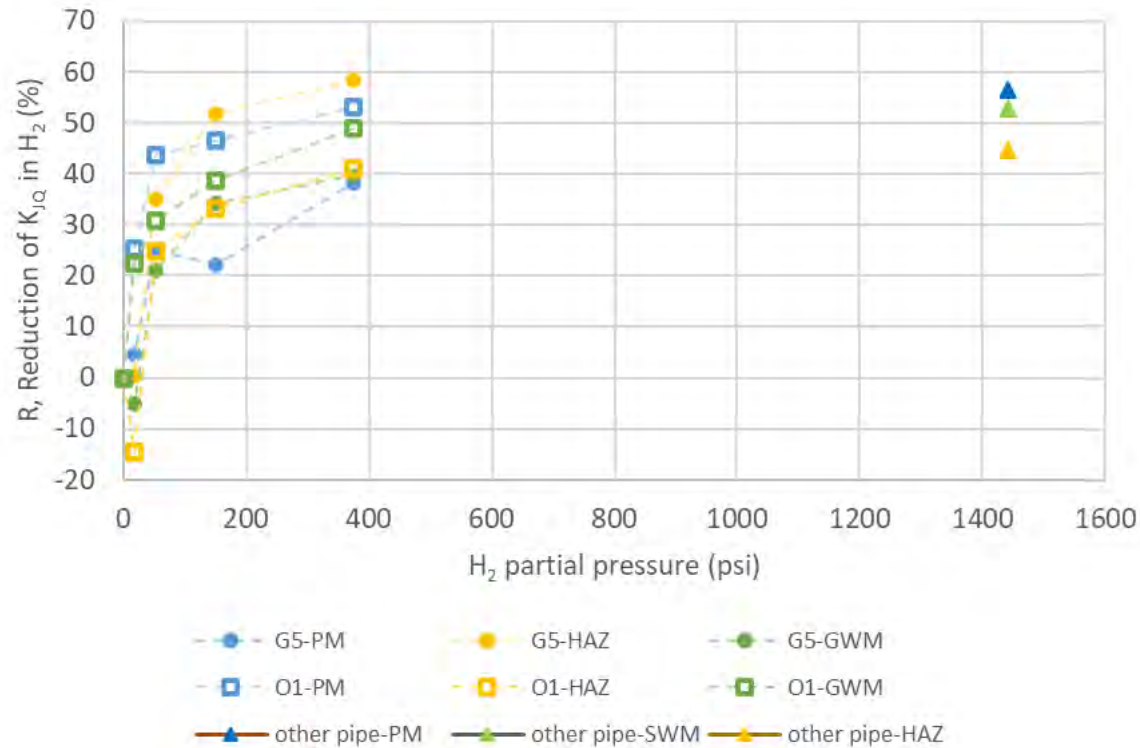
-> Transmission pipeline: H in lattice, mechanisms, models

(R- $K_{JQ,air}$ linear relationship)



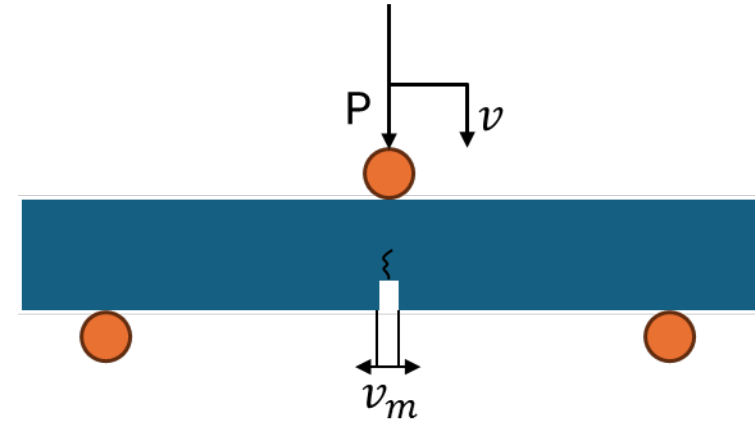
Topic 2: Effect of loading rate on fracture toughness testing results

- Validation data from other material (CT specimens)



Topic 3: Load-line displacement method to calculate crack size

- In ASTM E1820 tests, with SEN(B) geometry two displacement of the specimen were measured:
 - Crack mouth opening displacement (CMOD)
 - Load-line displacement
- Compliance method of crack size measurement:
 - Specimen compliance is related to crack size, larger the crack size, larger the specimen compliance
 - Using load-line displacement and CMOD can both calculate specimen compliance during unloading-reloading segments
 - According to Note A1.3 of ASTM E1820-24, crack size can be determined from load-line compliance if the correct calibration is available.



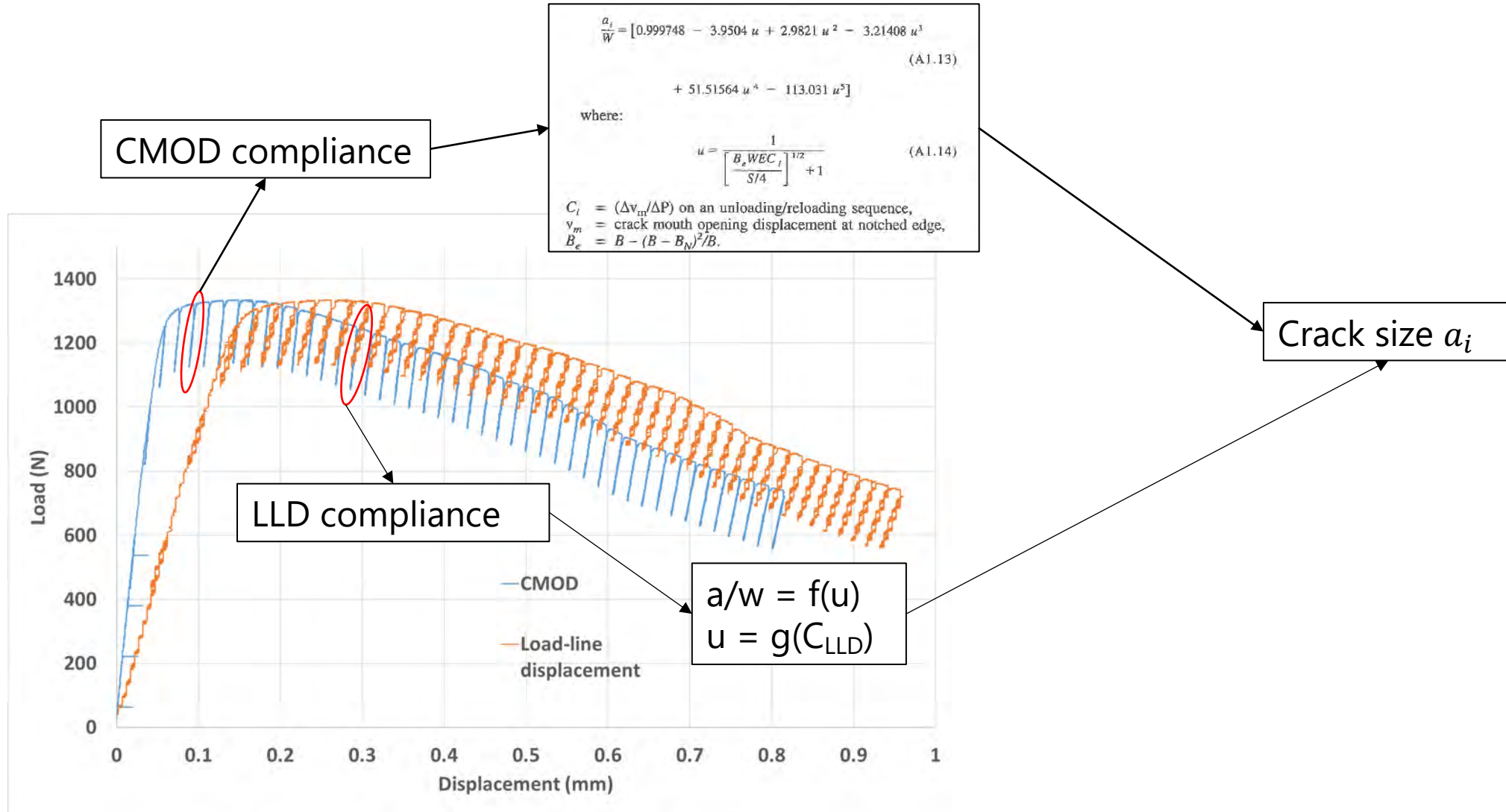
$$\frac{a_l}{W} = [0.999748 - 3.9504 u + 2.9821 u^2 - 3.21408 u^3 + 51.51564 u^4 - 113.031 u^5] \quad (\text{A1.13})$$

where:

$$u = \frac{1}{\left[\frac{B_e W E C_l}{S/4} \right]^{1/2} + 1} \quad (\text{A1.14})$$

C_l = $(\Delta v_m / \Delta P)$ on an unloading/reloading sequence,
 v_m = crack mouth opening displacement at notched edge,
 B_e = $B - (B - B_N)^2 / B$,

Topic 3: Load-line compliance method to calculate crack size



Topic 3: Load-line compliance method to calculate crack size

1. Perform a test (specimen 1) with clip gauge and load-line displacement
2. Use CMOD compliance to estimate crack size (truth data)
3. Calculate the corresponding load-line compliance
4. Take the same form of compliance equation (load-line compliance equation):

$$\frac{a_i}{W} = [a_0 + a_1u + a_2u^2 + a_3u^3 + a_4u^4 + a_5u^5]$$

where

$$u = \frac{1}{\left[\frac{B_e W E C_{LL-i}}{S/4} \right]^{\frac{1}{2}} + 1}$$

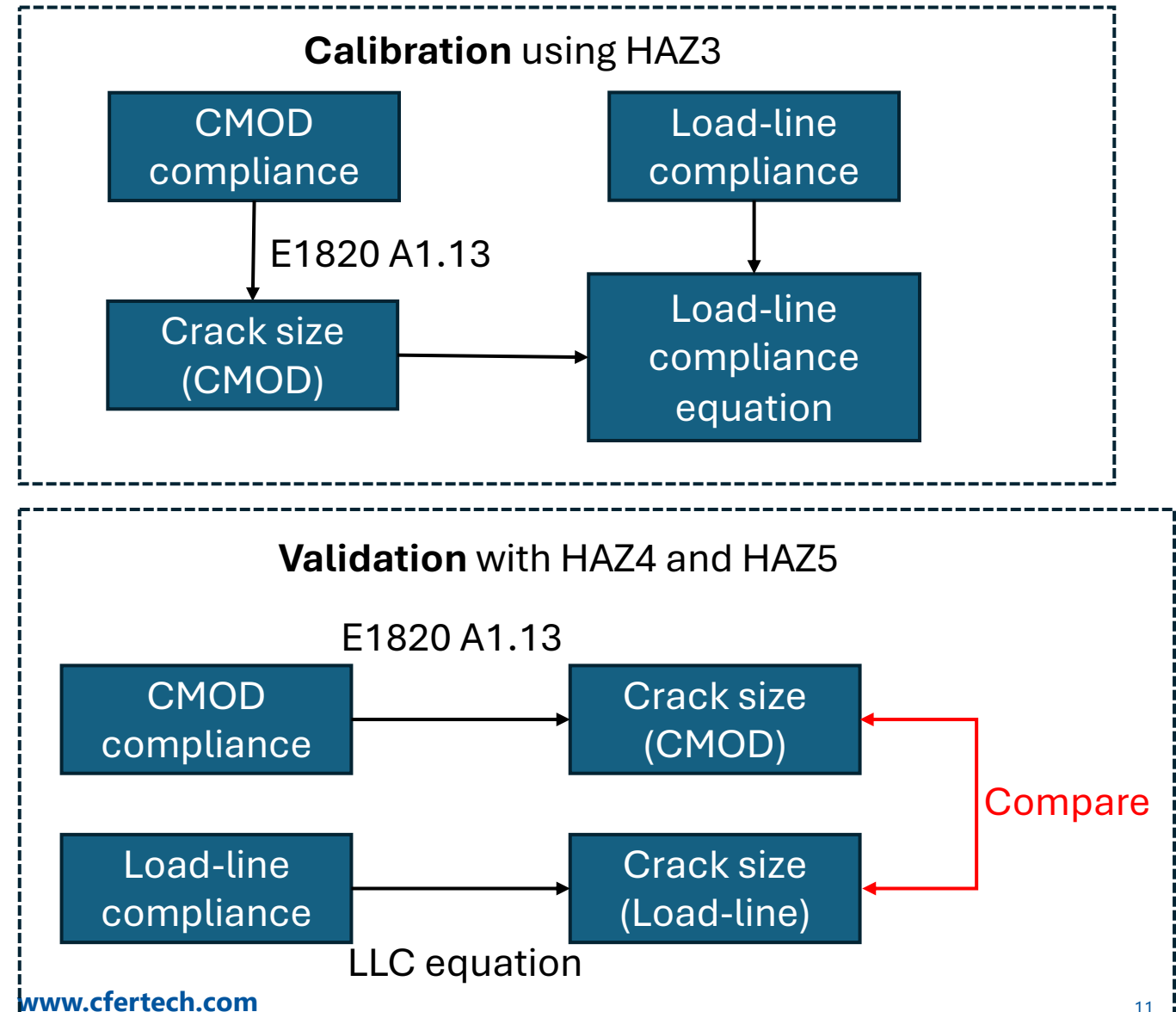
Avoid over-fitting

5. The signs (and relative orders of magnitude) of a_0 to a_5 will be preserved in accordance with Equation A(1.13).
6. Perform another test (specimen 2) with clip gauge and load-line displacement for validation purpose
7. Perform in-environment test with load-line displacement only

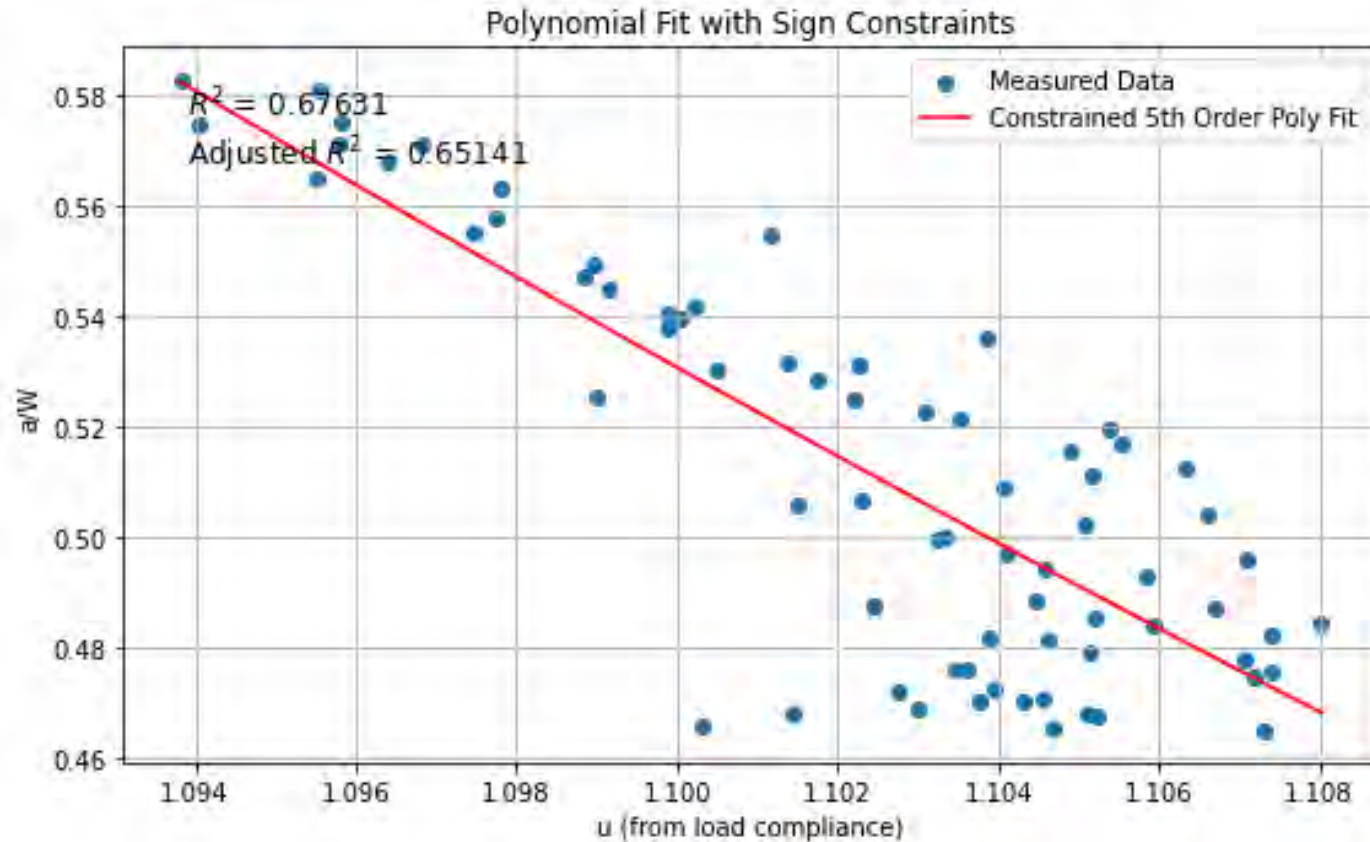
Topic 3: Load-line compliance method to calculate crack size

HAZ3 (60 psi), HAZ4 (175 psi) and HAZ5 (1250 psi) have the same geometry and material. They are tested under different gas pressure.

- ✓ HAZ3 was used to calibrate the load-line compliance equation
- ✓ The calibrated load-line equation was used to generate crack size data of HAZ4 and HAZ5. And further to construct the J-R curve
- ✓ Compare the J-R curve from crack size estimated from CMOD compliance and load-line compliance



Calibration using HAZ3



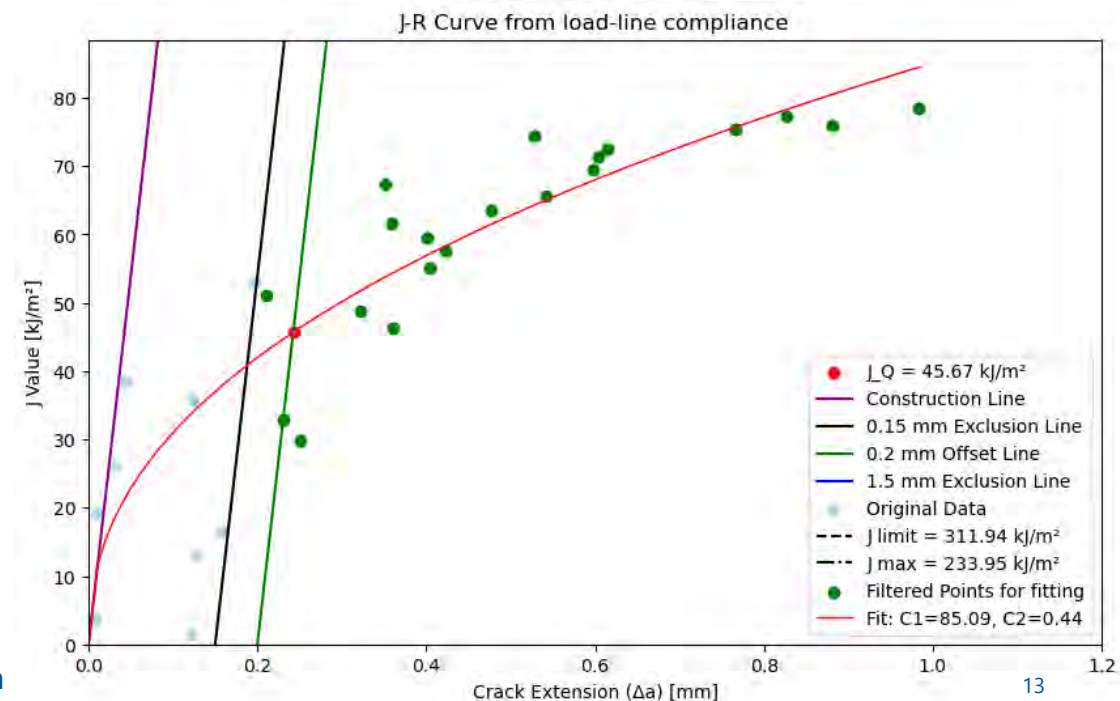
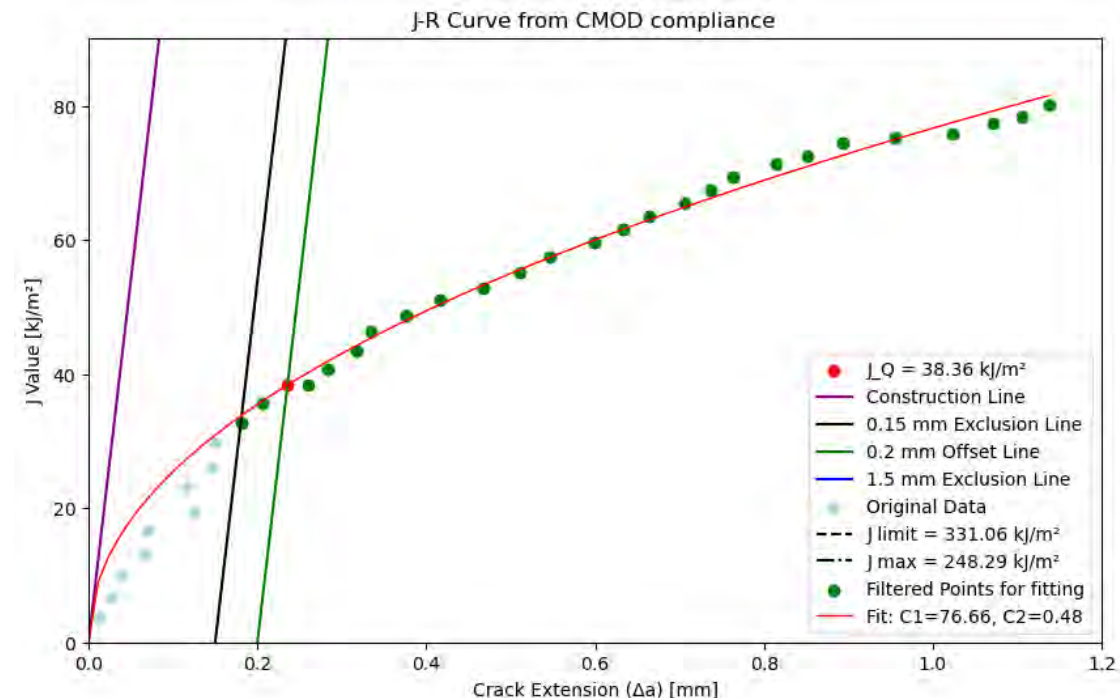
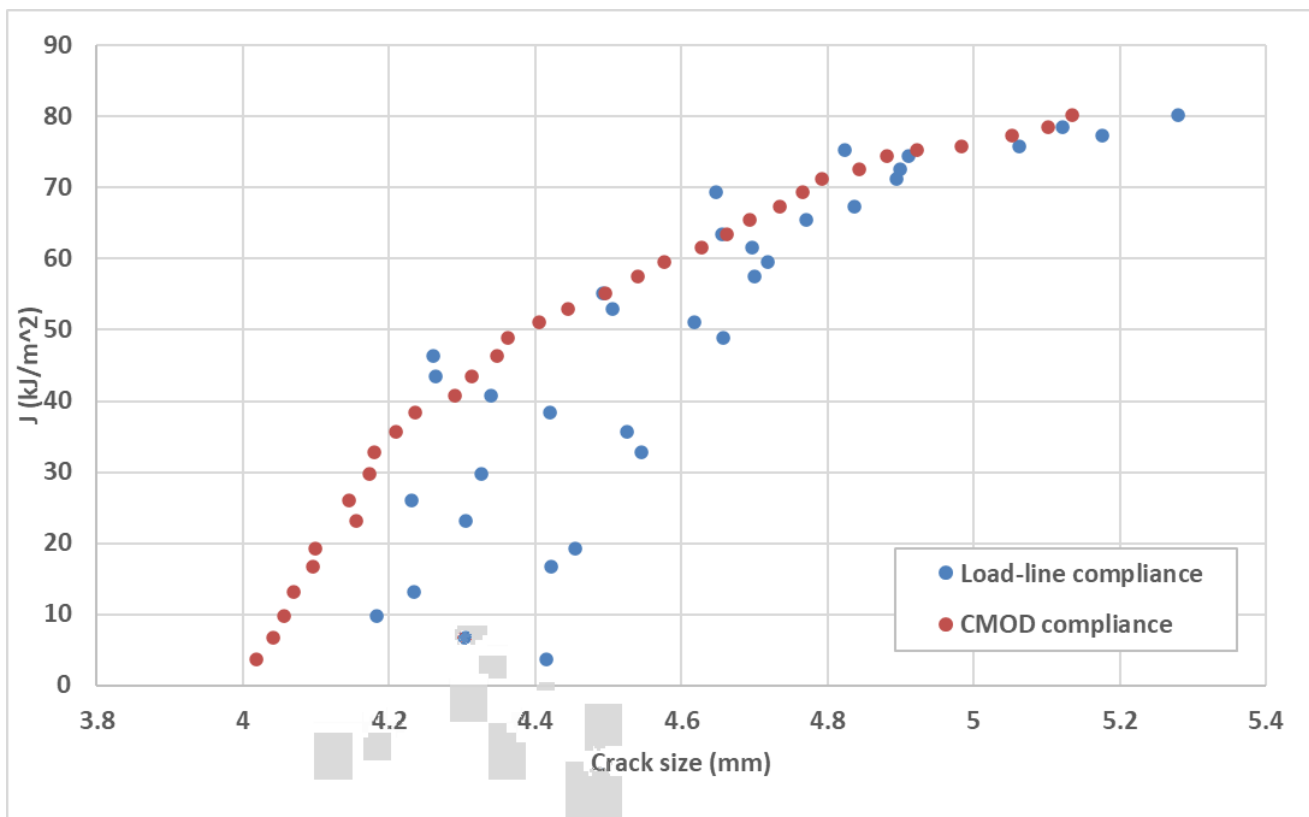
$$\frac{a_i}{W} = [a_0 + a_1u + a_2u^2 + a_3u^3 + a_4u^4 + a_5u^5]$$

where

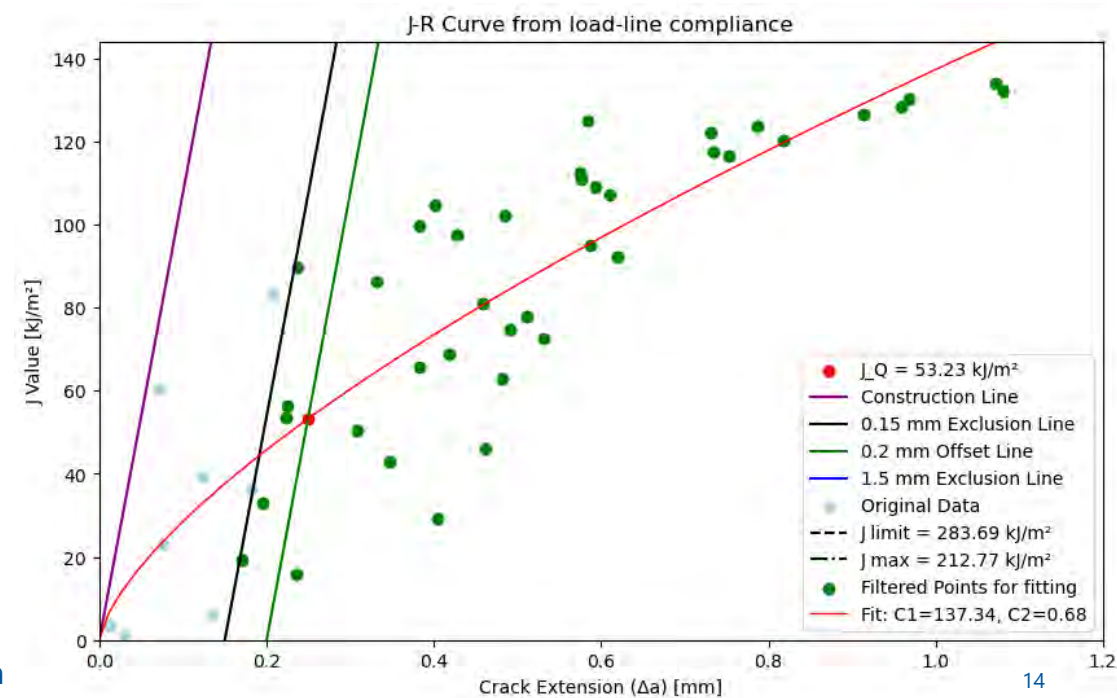
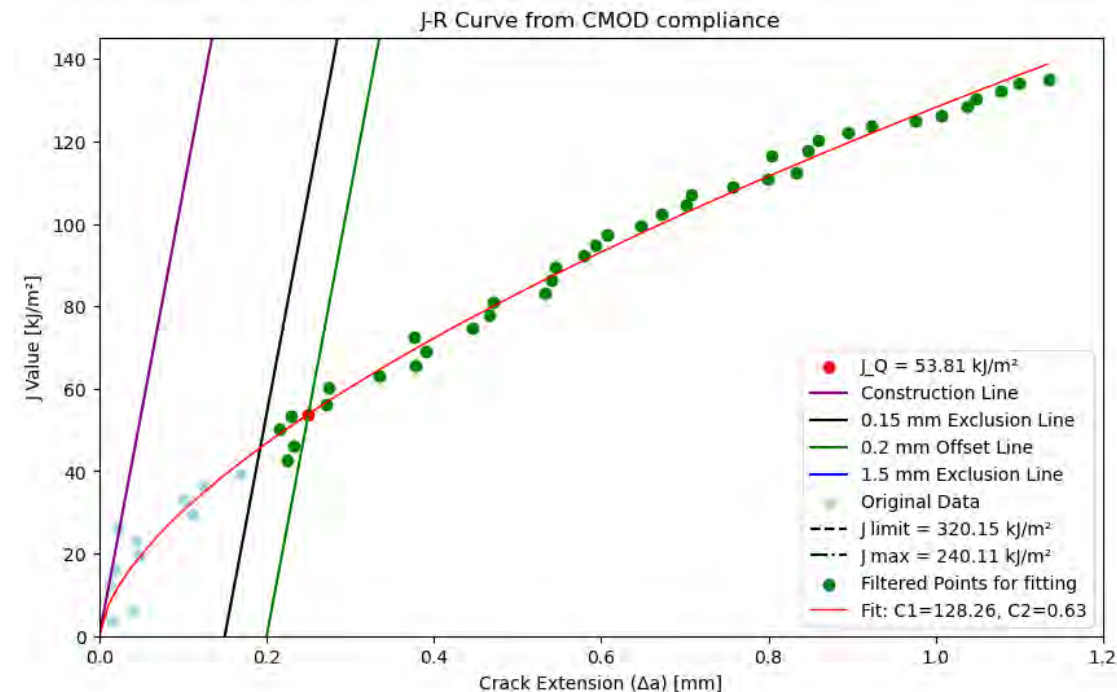
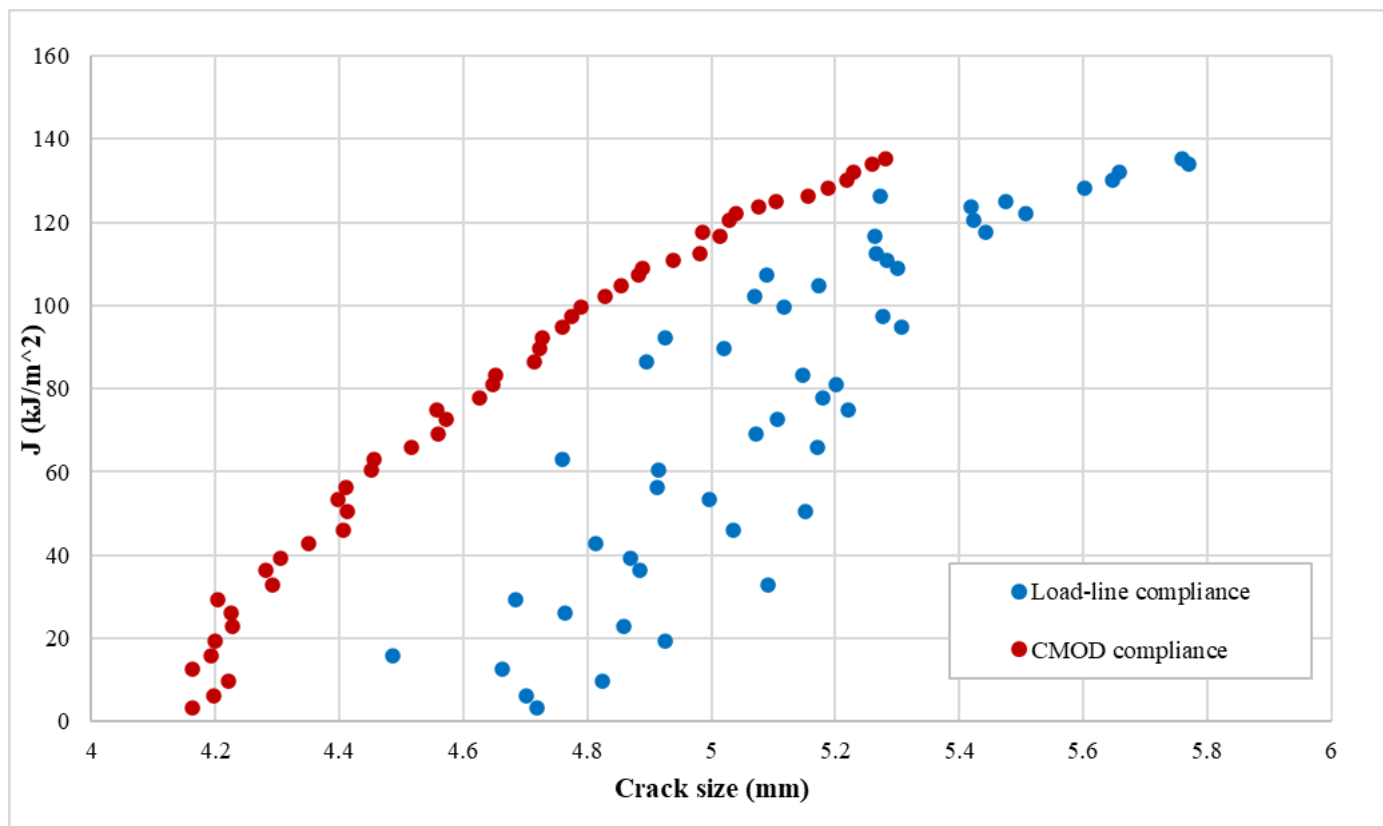
$$u_{LL} = \frac{1}{\left[\frac{B_e W E C_{LL-i}}{S/4} \right]^{\frac{1}{2}} + 1}$$

$$\frac{a}{W} = 20.00000 - 12.8365 \cdot u + 1.46222 \times 10^{-7} \cdot u^2 - 19.9836 \cdot u^3 + 14.5134 \cdot u^4 - 2.00937 \times 10^{-13} \cdot u^5$$

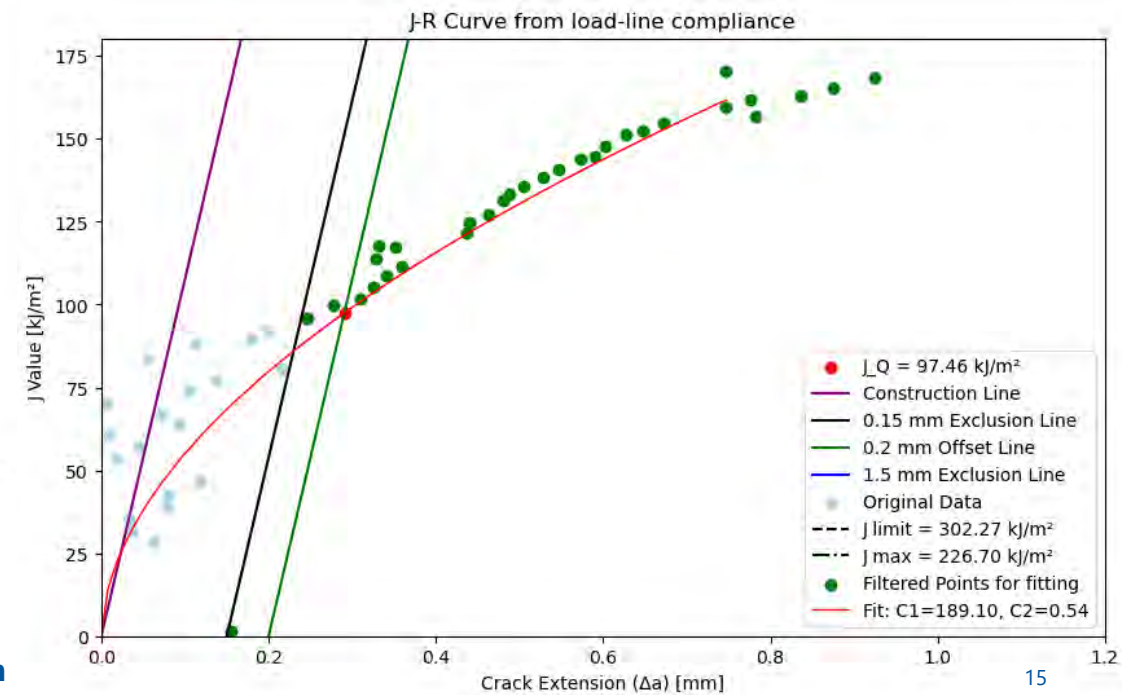
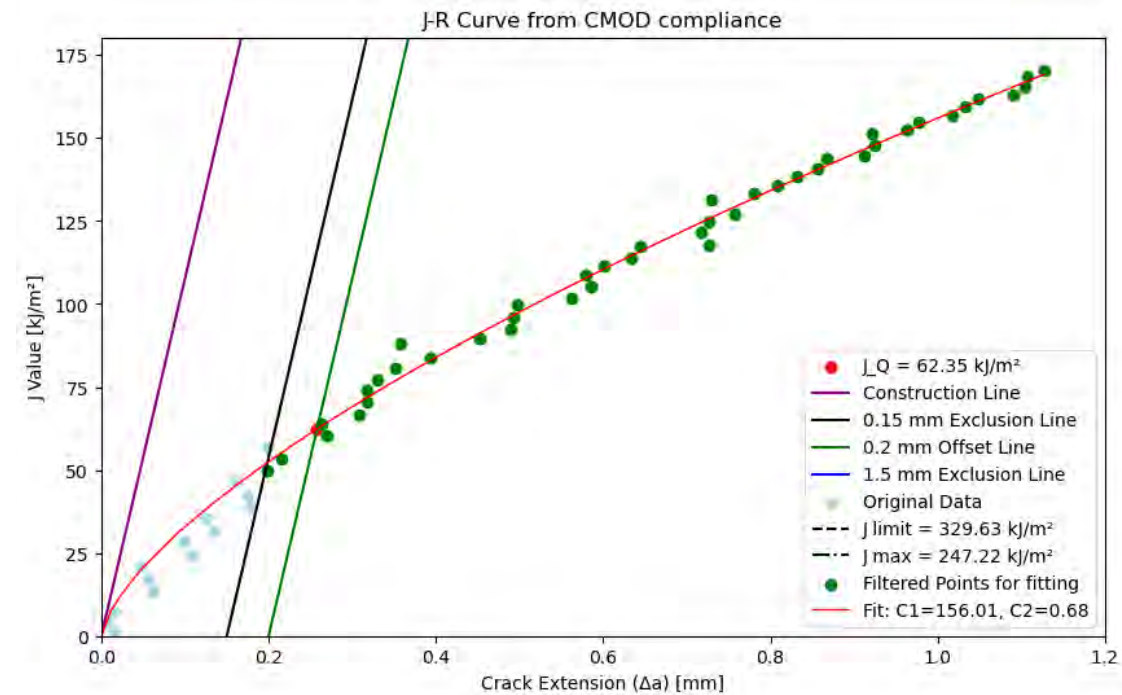
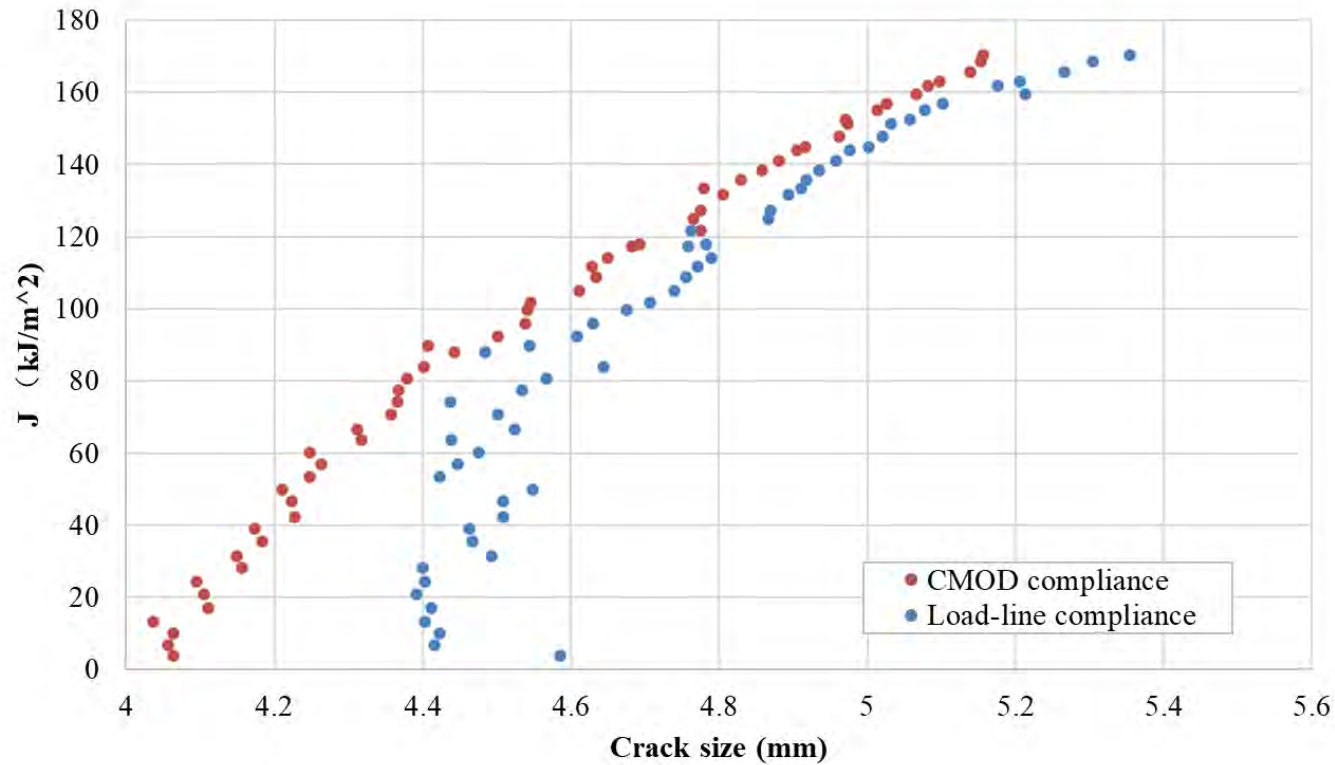
Validation with HAZ4 (175 psi)



Validation with HAZ5 (1250 psi)



Validation with HAZ11 (500 psi)



Thank you !



Exceptional service in the national interest

Best Practices

Chris San Marchi and Joe Ronevich

Study Group on Materials Testing and Qualification for Hydrogen Service

Montreal, Canada 25 July 2025

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Framework for hydrogen gas physics based on thermodynamics

- Classic equilibrium relationship: Sieverts' Law



- Sieverts' Law assumes *ideal gas behavior*, however for high-pressure (greater than ~100 bar), one must consider *non-ideal gas behavior*
- *Non-ideal gas behavior* is accounted for by replacing the pressure with the hydrogen fugacity, f





Determination of fugacity for pure hydrogen and mixed gases

- Abel-Noble equation-of-state (EOS) has been shown to capture hydrogen gas behavior well over wide range of temperature and pressure

*Abel-Noble EOS
for pure gas*

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

f : hydrogen fugacity
 P_H : hydrogen partial pressure
 b : constant = 15.84 cm³/mol

- For mixed gases, a simple formulation can be established by assuming the gas species do not interact – the Regular solution model

*Regular solution model
Mixed gas*

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

P_t : total pressure

References of EOS and mixed gas:

- (1) San Marchi et al, IJHE 32 (2007)
- (2) ASME PVP2021-62045



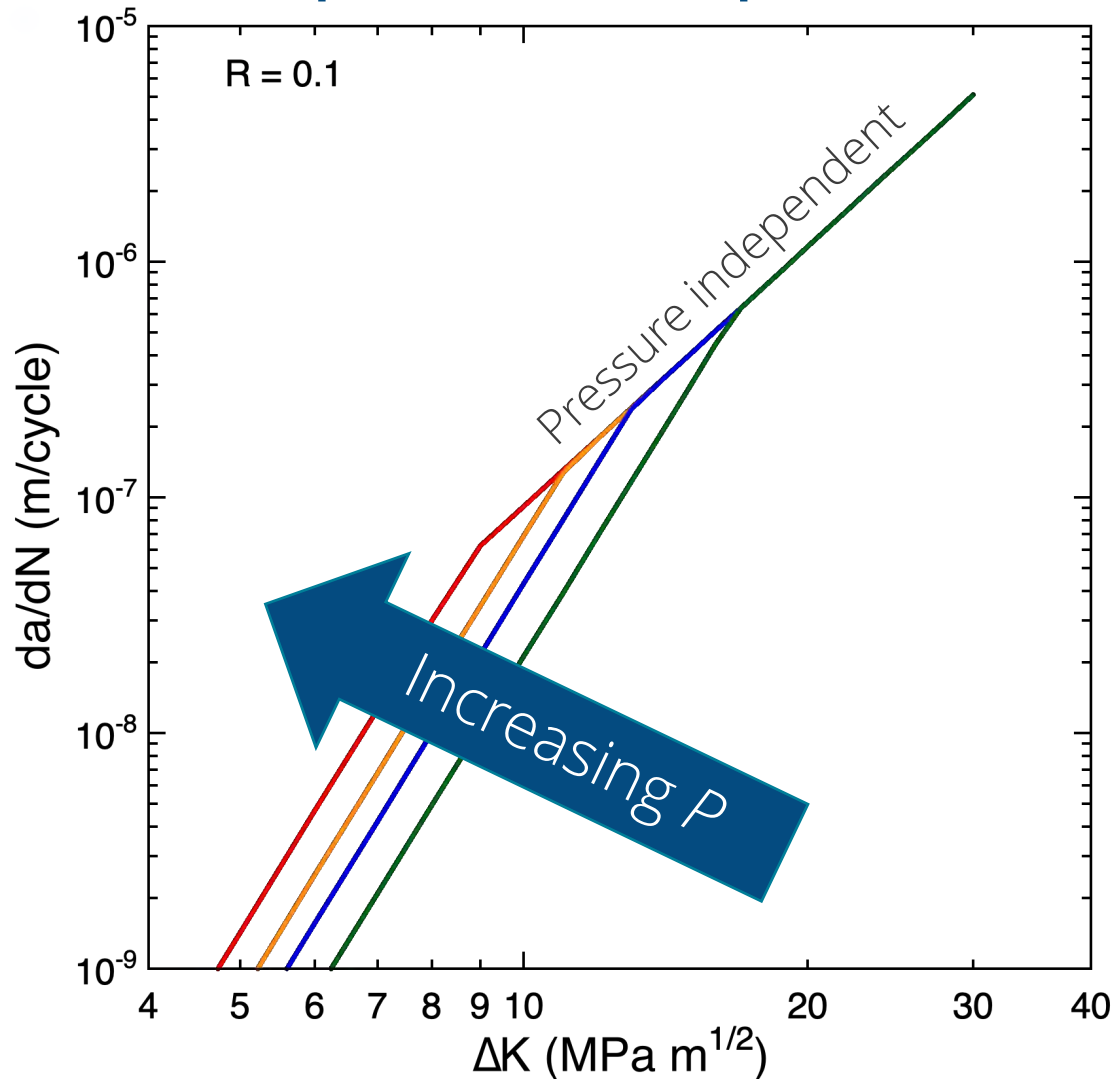
Form of fatigue design curves (FDC) for gaseous hydrogen environments from ASME B31.12 CC220

$$\frac{da}{dN} = C \underbrace{f(R_k)}_{\text{Load ratio dependence}} \underbrace{\Delta K^m}_{\text{Basic ASME power law form}} \underbrace{g(P)}_{\text{Pressure term}}$$

The diagram illustrates the form of the fatigue design curve (FDC) for gaseous hydrogen environments, based on ASME B31.12 CC220. The equation is presented as $\frac{da}{dN} = C f(R_k) \Delta K^m g(P)$. Annotations highlight the components:

- Basic ASME power law form**: A bracket above the equation spans from the constant C to the term ΔK^m .
- Load ratio dependence**: A bracket below the equation is positioned under the load ratio function $f(R_k)$.
- Pressure term**: A purple circle encloses the term $g(P)$, with a purple arrow pointing to it from the label "Pressure term".

Experimental evidence shows two regions of fatigue crack growth:
(1) pressure dependent fatigue crack growth at low ΔK
(2) pressure independent fatigue crack growth at high ΔK



Low ΔK

- pressure dependent

$$\frac{da}{dN} = C \left[\frac{1+C_H R}{1-R} \right] \Delta K^m g(P)$$

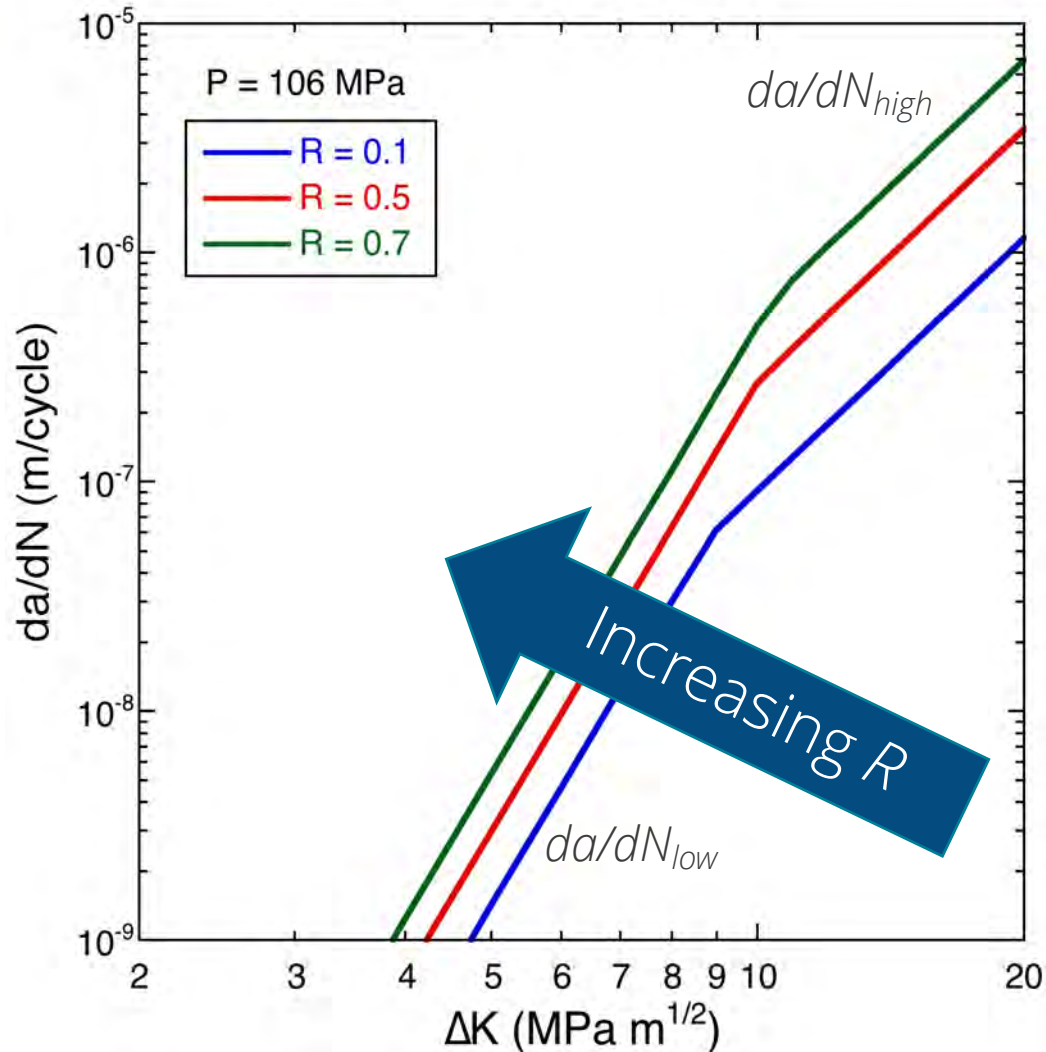
At high ΔK

- pressure independent

$$\frac{da}{dN} = C \left[\frac{1+C_H R}{1-R} \right] \Delta K^m$$



Empirical curve fitting to literature data for testing in high-pressure hydrogen provides constants for FDCs



$$\frac{da}{dN} = C \underbrace{\left[\frac{1 + C_H R}{1 - R} \right]}_{f(R_k)} \Delta K^m$$

	da/dN_{low}	da/dN_{high}
C (m/cycle)	3.5×10^{-14}	1.5×10^{-11}
m	6.5	3.66
C_H	0.4286	2.00

References:

- (1) SAND2018-1098 PE
- (2) SAND2019-8892C
- (3) PVP2019-93907



Pressure dependence is assumed to correlate with hydrogen concentration in the material

$$[H] = K f^{1/2}$$

Dependence on concentration implies dependence on square root of fugacity

$$g(P) = \left(\frac{f}{f_{ref}} \right)^{1/2}$$

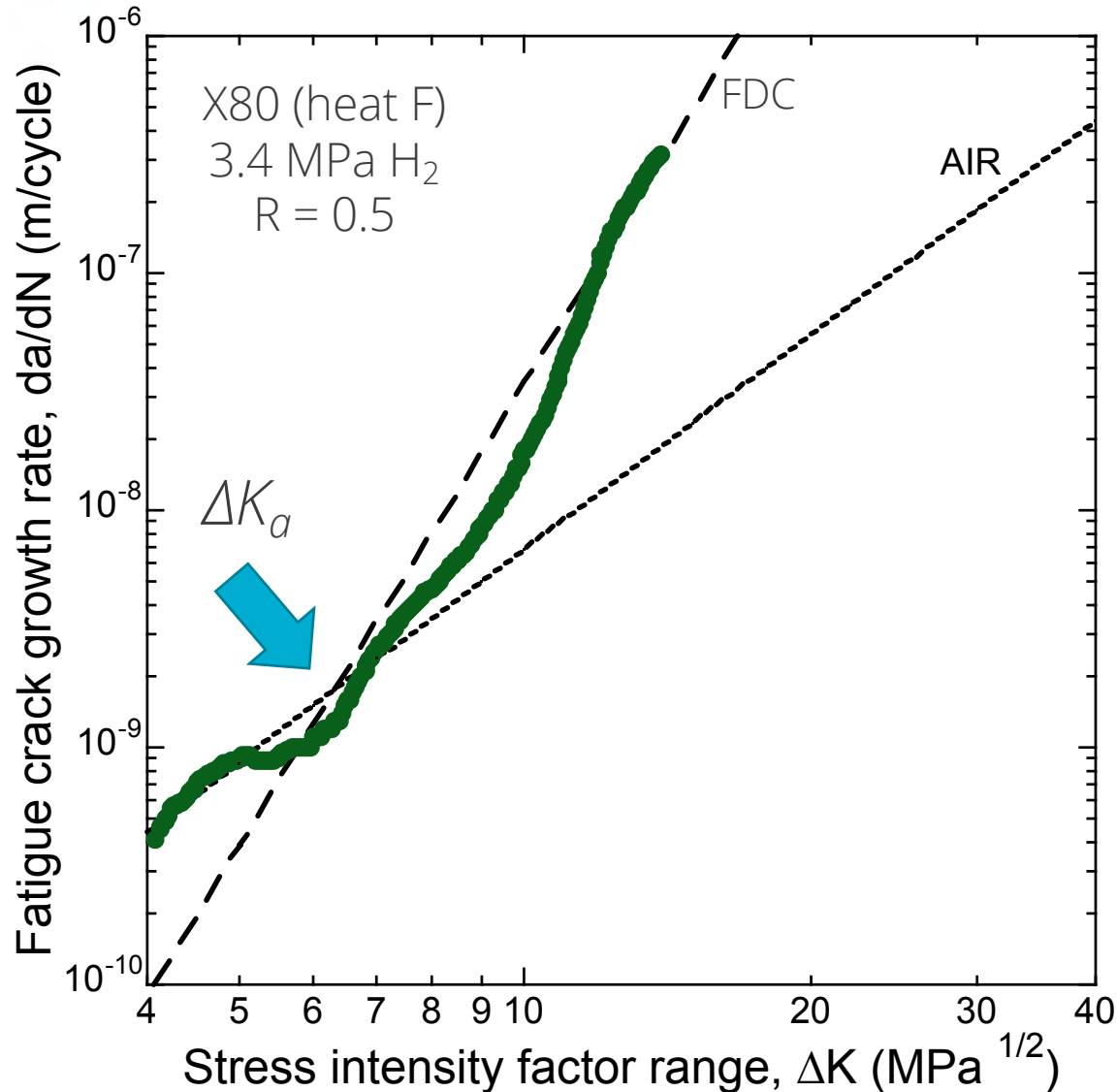
Pressure
dependence
term

Pressure term is established by proportionality to reference condition[†]

$$f_{ref} = P^* \exp\left(\frac{P^* b}{RT}\right) = 211 \text{ MPa}$$

[†]reference condition is pressure at which power law constants are determined

One more thing...



- At low stress intensity (and low pressure) fatigue design curves extrapolate to crack growth rates less than air
- However, experimental observations show that material response can transition to the behavior in air

Fatigue design curves should not be extrapolated below the air curve



Three regimes of fatigue crack growth must be considered for H₂ service

UNITS:	ΔK	(MPa m ^{1/2})
	da/dN	(m/cycle)
	P	(MPa)

Response in air:

$$\Delta K < \Delta K_a$$

$$da/dN = da/dN_{air}$$

$$da/dN_{air} = 3.8 \times 10^{-12} \left(\frac{2.88}{2.88 - R_k} \right)^{3.07} \Delta K^{3.07}$$

Pressure dependent region:

$$\Delta K_a < \Delta K < \Delta K_c$$

$$da/dN = da/dN_{low}$$

$$da/dN_{low} = 3.5 \times 10^{-14} \left(\frac{1 + 0.43R_k}{1 - R_k} \right) \Delta K^{6.5} \left(\frac{f}{f_{ref}} \right)^{1/2}$$

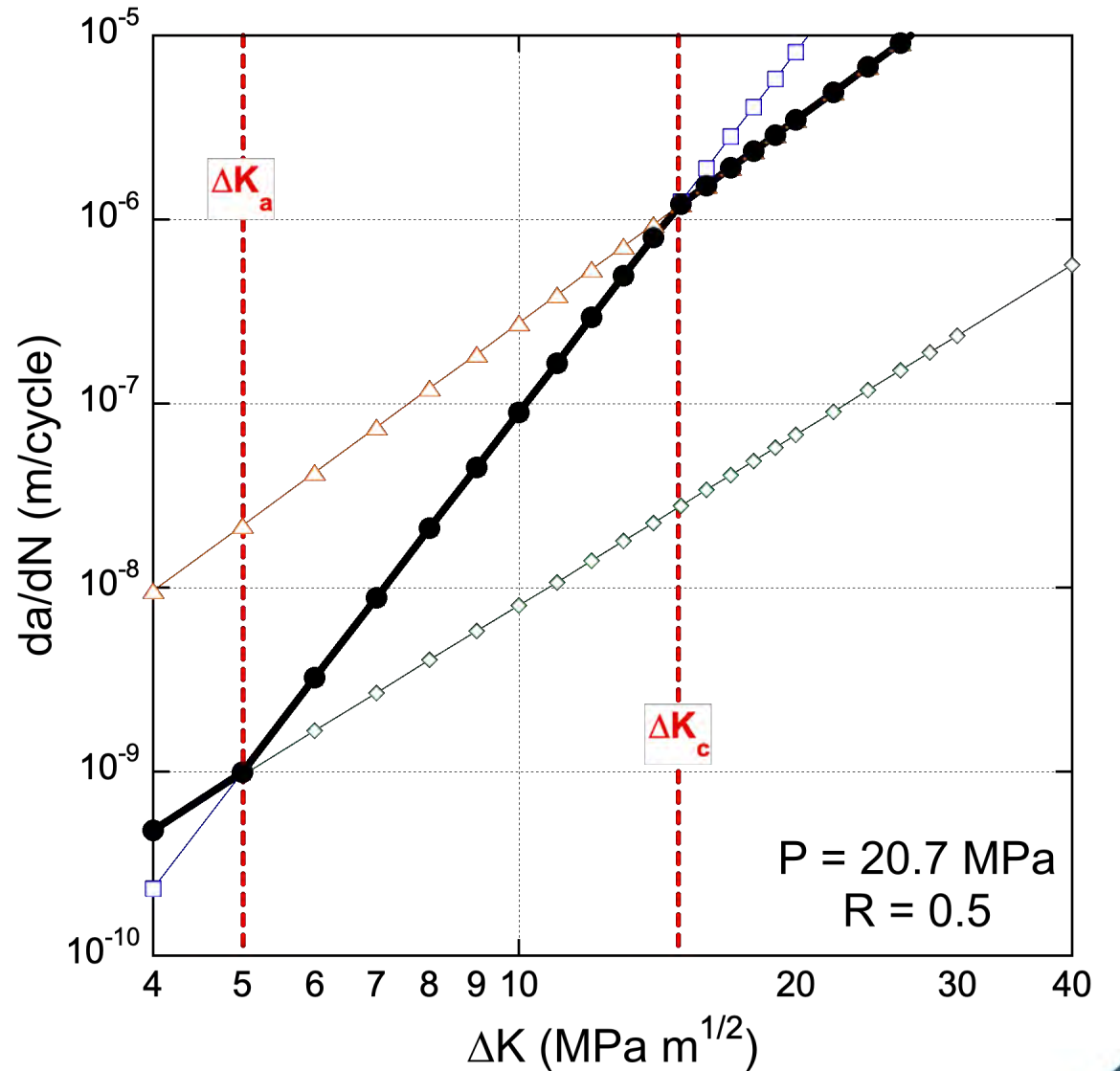
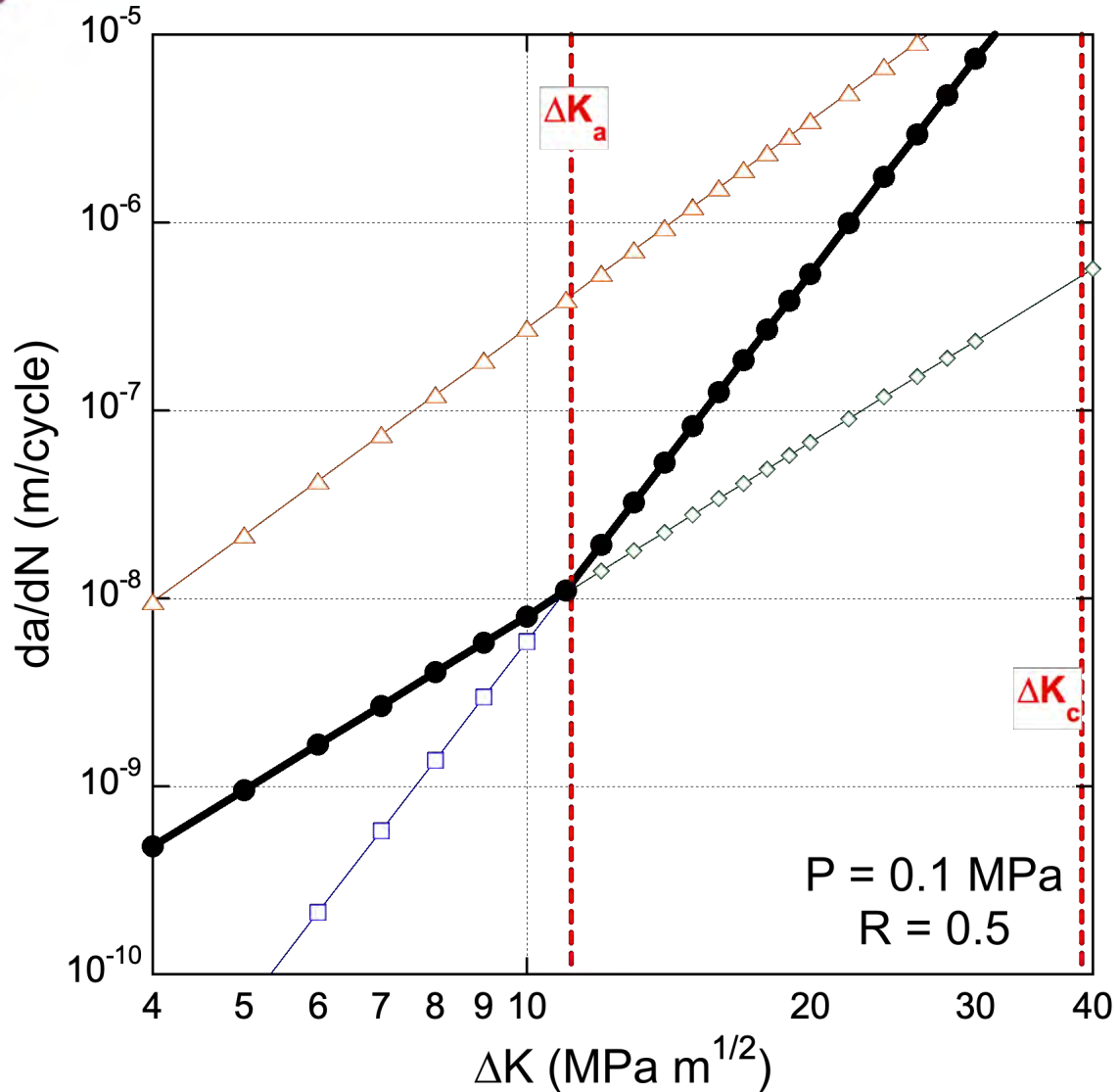
Pressure independent region:

$$\Delta K > \Delta K_c$$

$$da/dN = da/dN_{high}$$

$$da/dN_{high} = 1.5 \times 10^{-11} \left(\frac{1 + 2R_k}{1 - R_k} \right) \Delta K^{3.66}$$

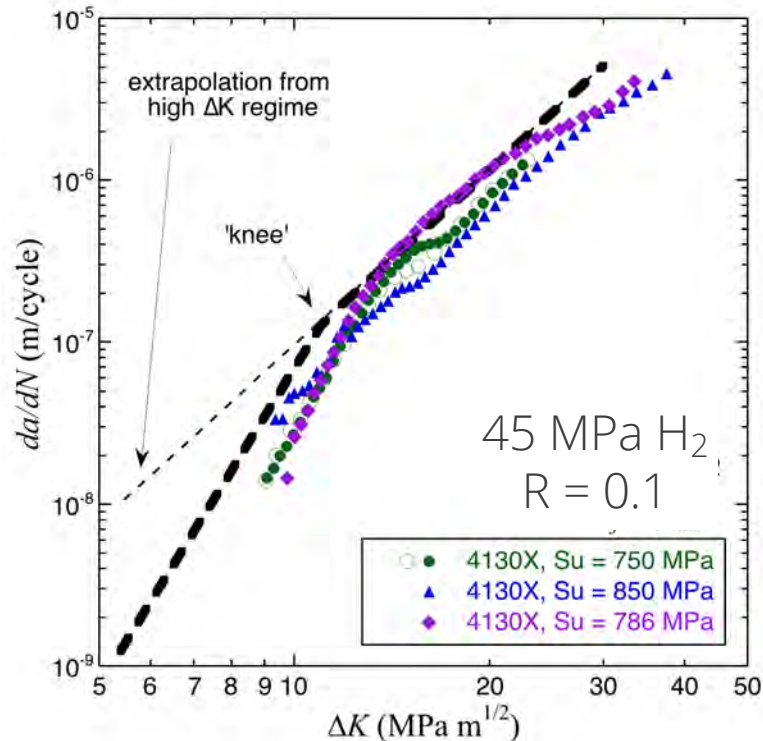
Demonstration of FDCs as $f(P, R_k)$



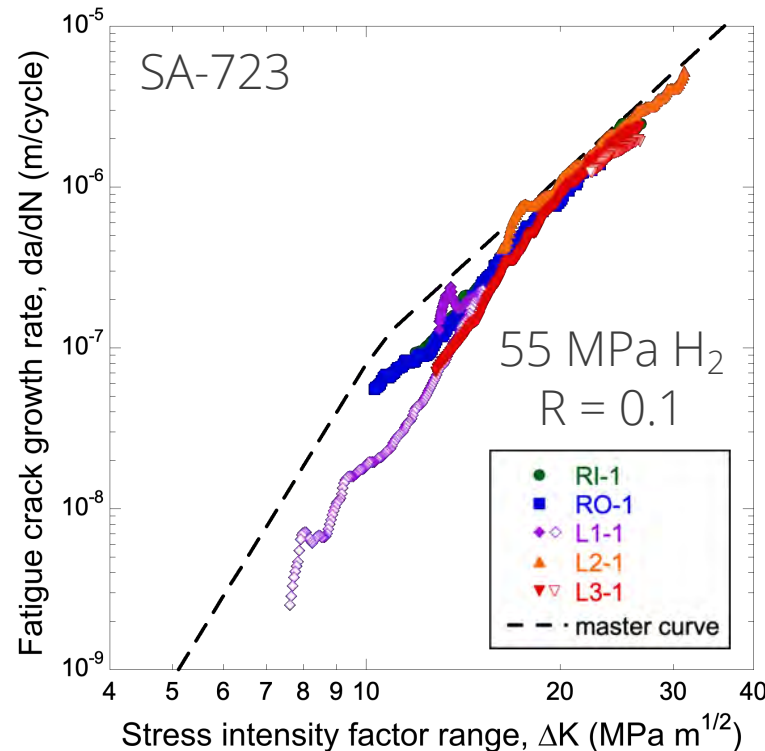


Fatigue crack growth is similar for a variety of low-alloy steels and for different conditions

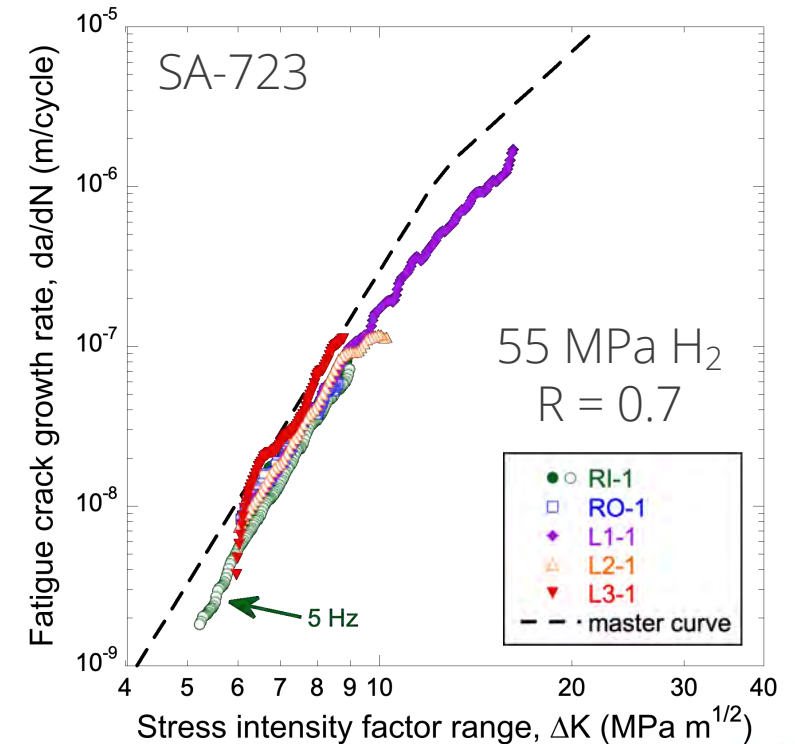
- Note capturing the transition region (*i.e.*, 'below' the knee) is important for design in the low ΔK regime
- Dashed lines are adjusted for test pressure
- SA-723 designations (RI, RO, L) represent different positions and orientations



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

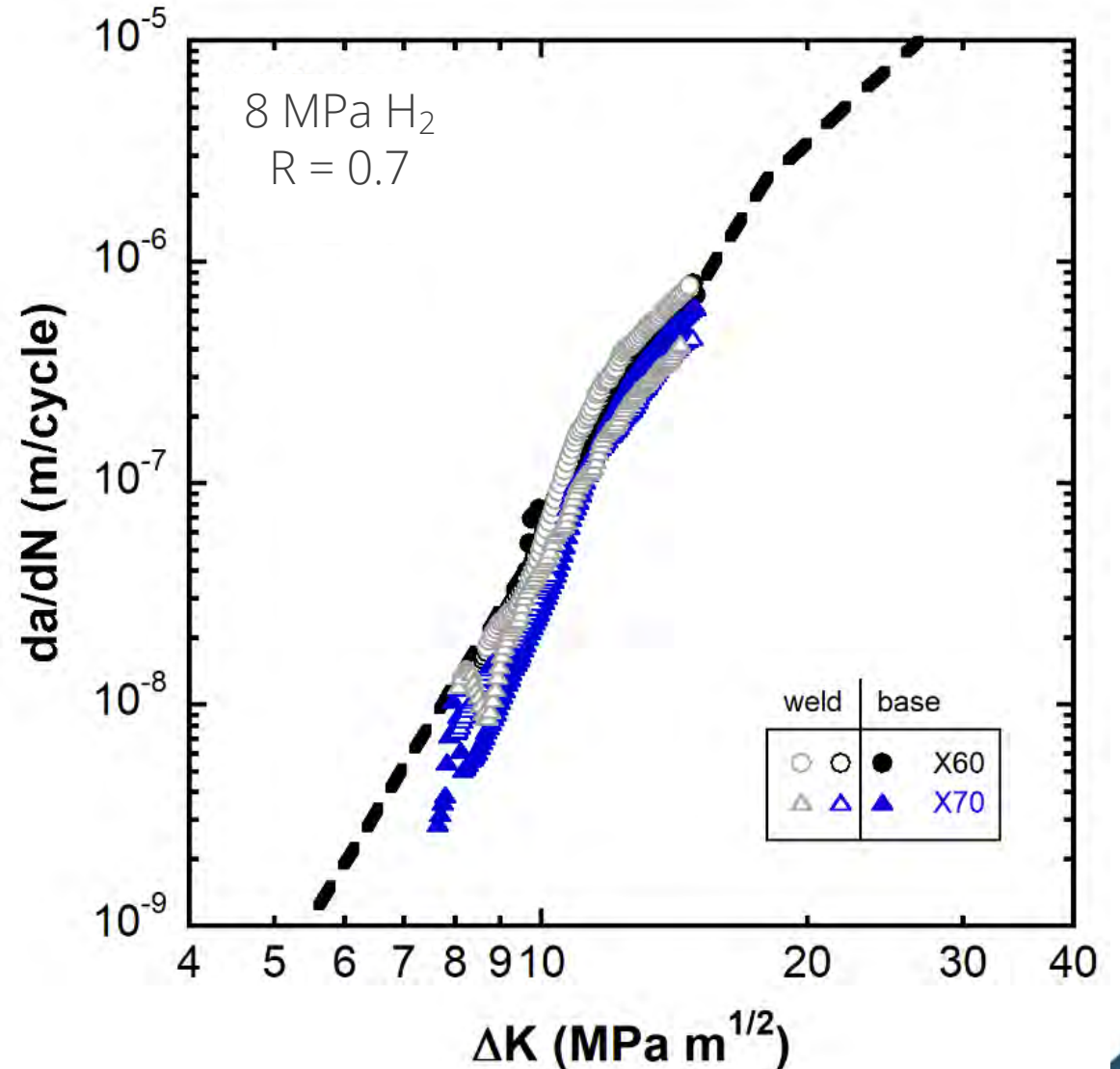
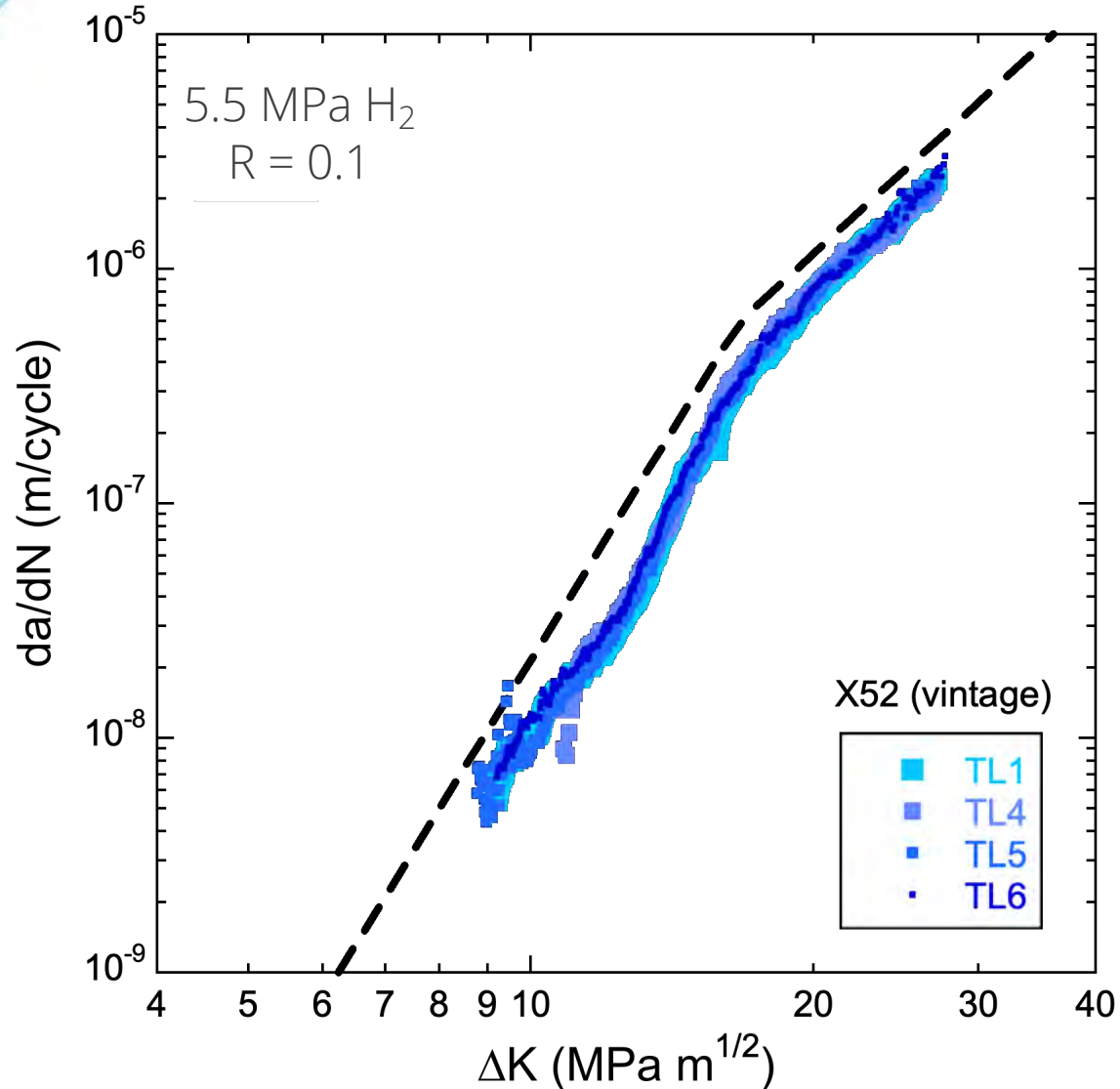


Ref.: Bortot et al., ASME PVP2023-106417



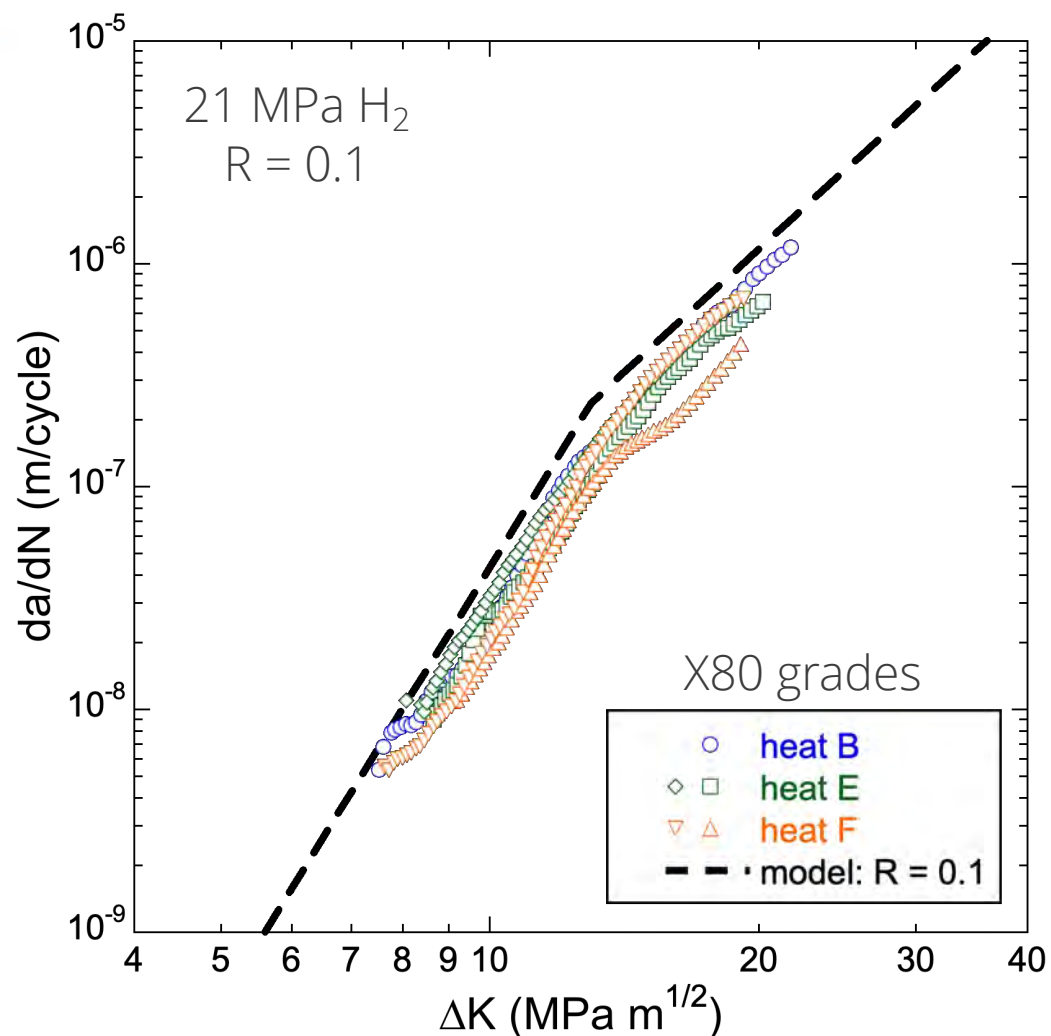


Pressure dependence of fatigue crack growth of line pipe is bounded by MDCs

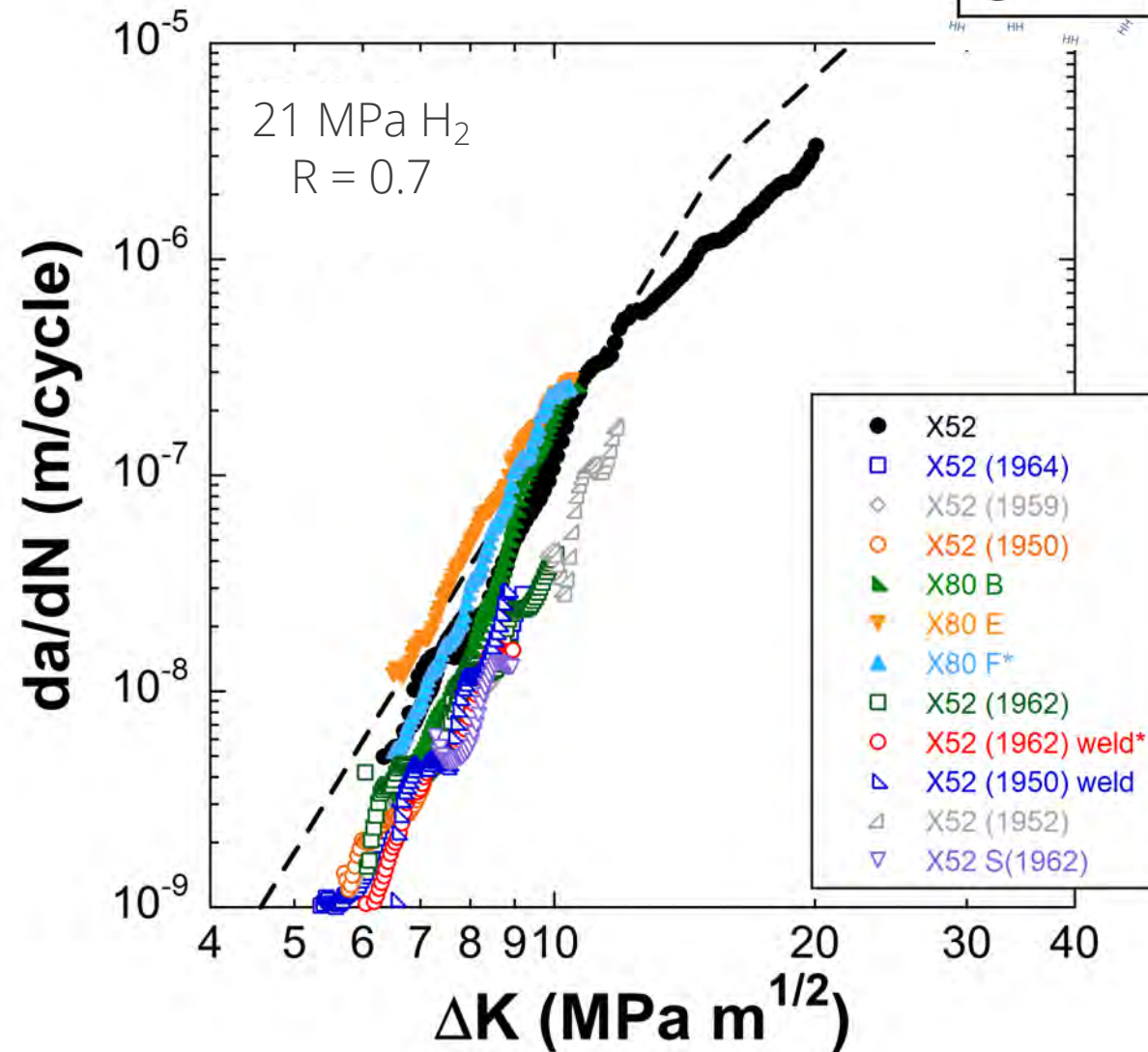




Load ratio dependence of fatigue crack growth of line pipe is bounded by FDCs



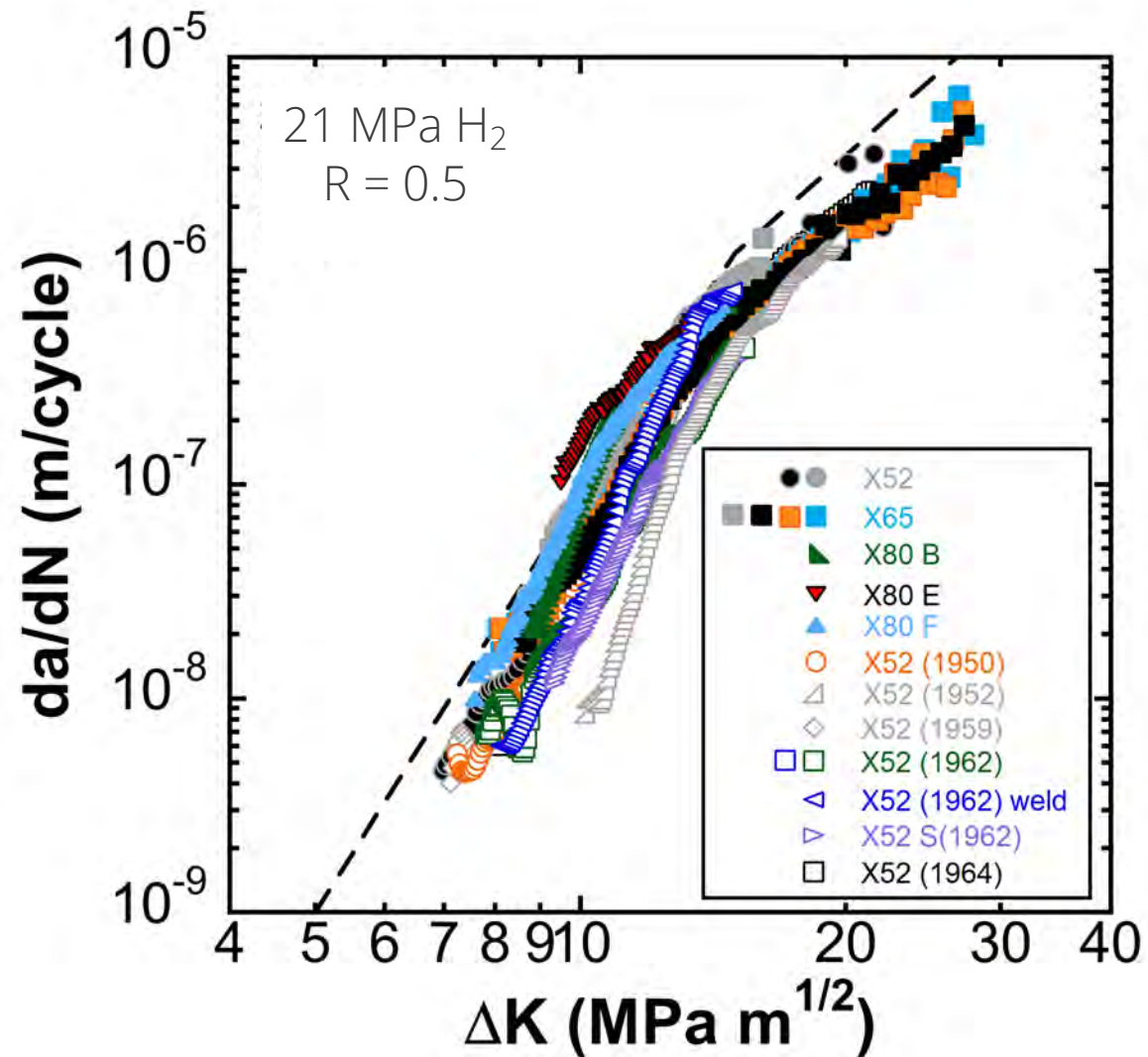
Ref.: San Marchi et al., ASME PVP2022-84757



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



API grade pipeline steels show similar fatigue crack growth rates in gaseous hydrogen



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

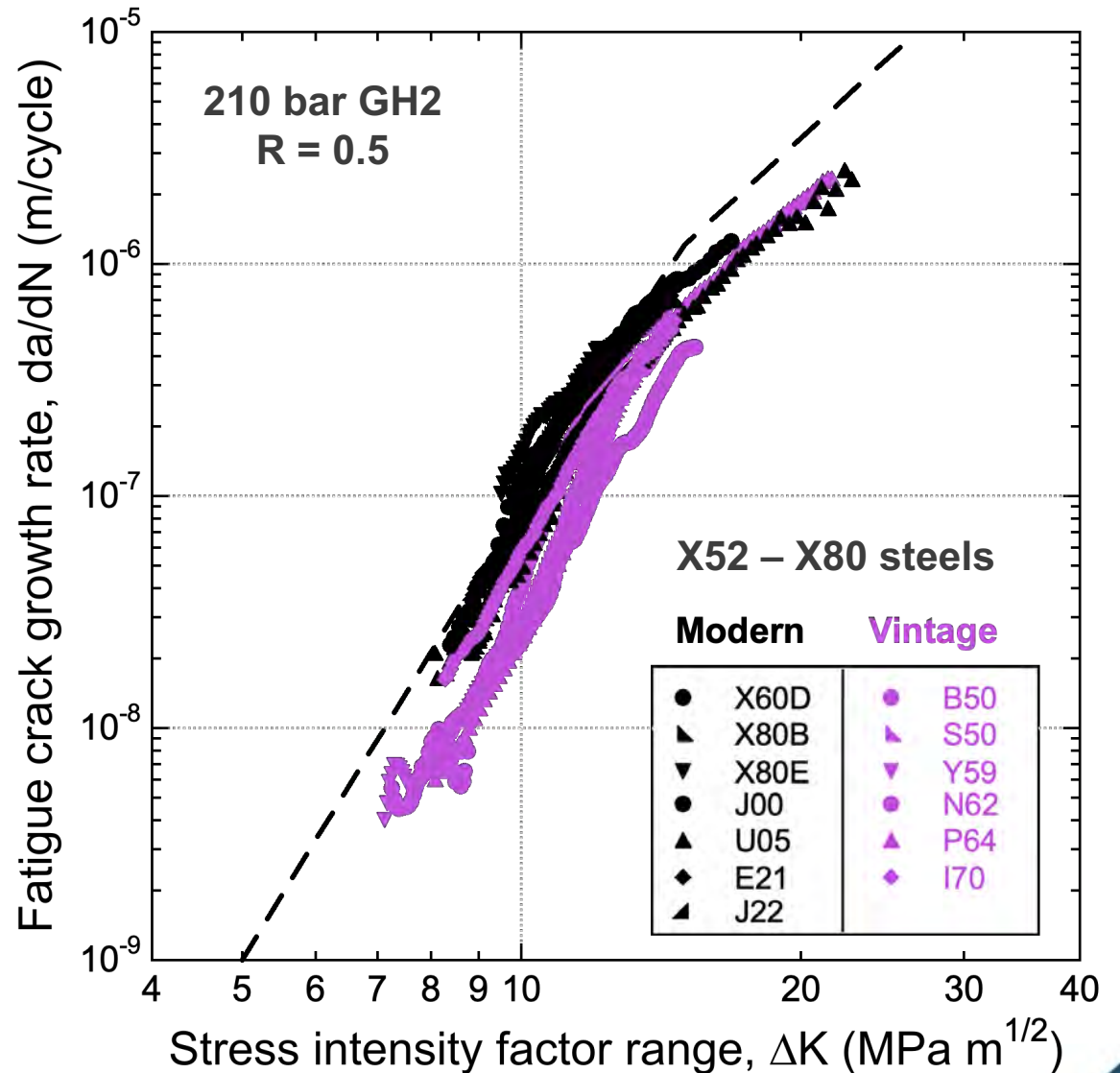
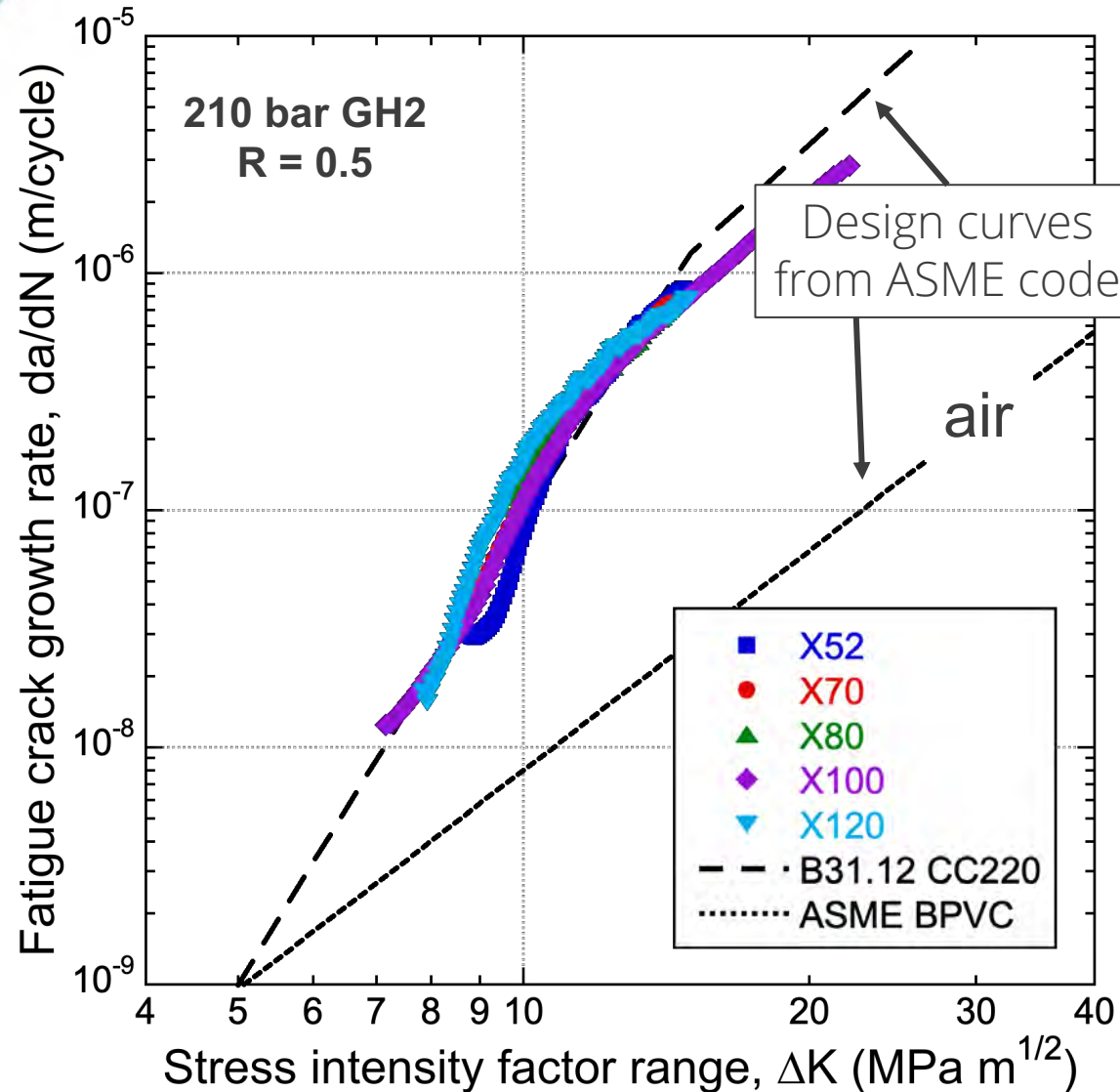
Material	Microstructure	Vickers Hardness
X52	Ferrite / pearlite	164
X65	Banded ferrite / pearlite	188
X80 (B)	90% PF + 10% AF (coarse)	187*
X80 (E)	AF (fine)	222*
X80 (F)	70% AF + 30% PF	217*
X52 (1950)	Ferrite / pearlite	170
X52 (1952)	Ferrite / pearlite	187
X52 (1959)	Ferrite / pearlite	180
X52 (1962)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

Modern

Vintage

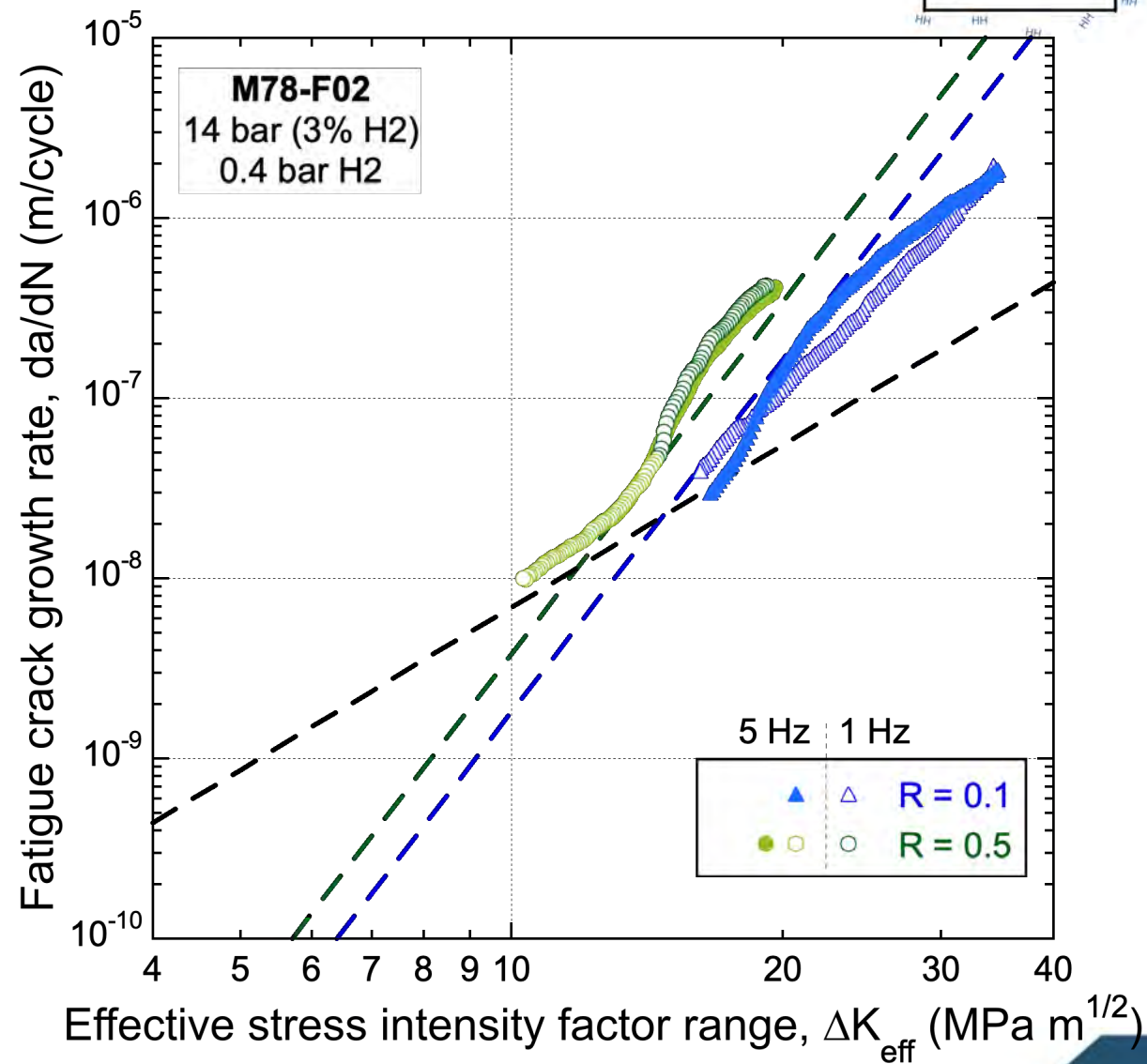
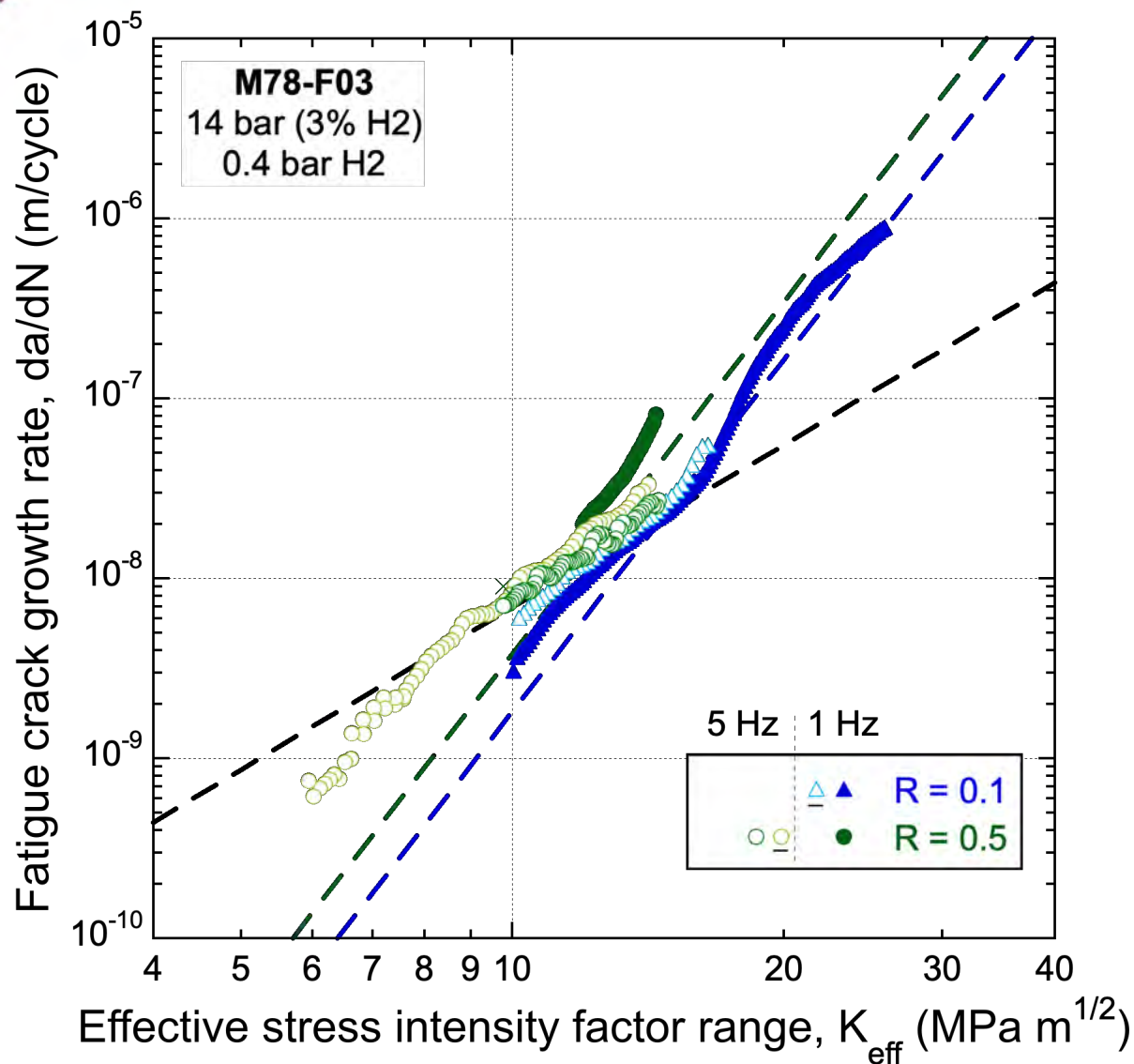
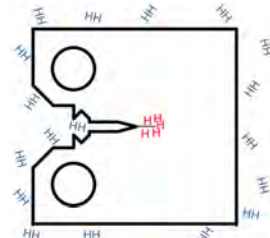


Conservative performance metrics of steels in hydrogen service are often known *and codified*





Fatigue crack growth at pressure as low as 0.4 bara has been measured





Background: ASTM E1820

- Principle requirements for specimen geometry:

- Crack length

$$0.45 \leq a/W \leq 0.70$$

- Specimen thickness[†]

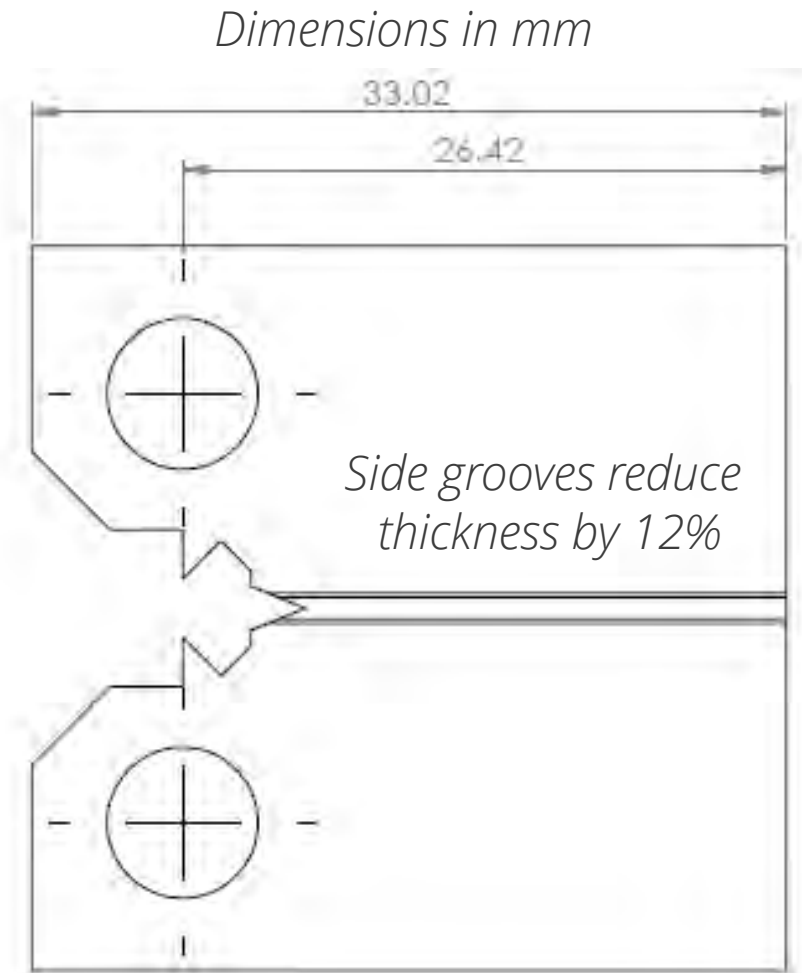
$$2 \leq W/B \leq 4$$

[†]specimen thickness is often considered less important as long as fracture surface remains planar (ie, no slant fracture)

This study:

$$W/B \sim 2, 4$$

$$a/W \sim 0.5, 0.6, 0.7$$



All fracture specimens
extracted in CL orientation



Interrupted fracture tests ensure crack initiation is correctly identified

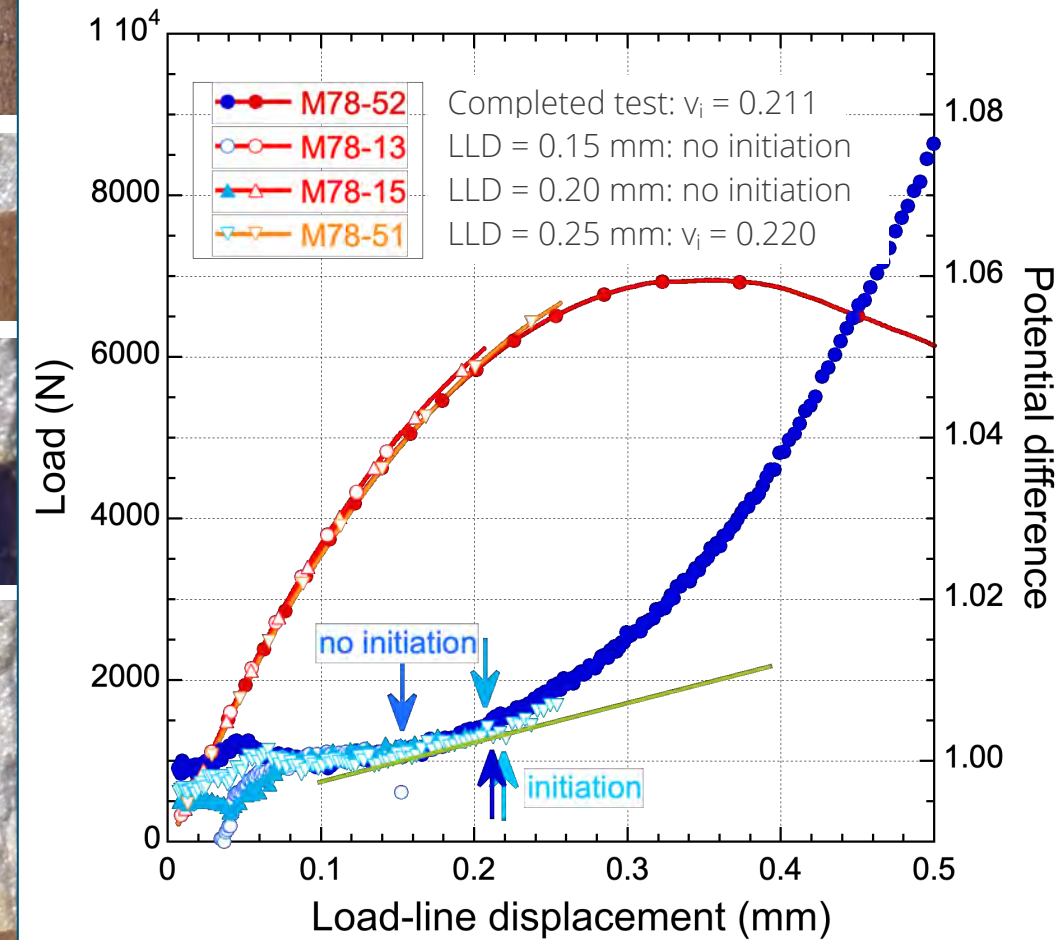
Several interrupted tests at pre-determined LLD demonstrated that cracks typically initiate at LLD between 0.20 & 0.25 mm

LLD = 0.15 mm: no initiation

LLD = 0.20 mm: no initiation

LLD = 0.25 mm: $v_i = 0.220$

Completed test: $v_i = 0.211$



Frequency dependence in fatigue testing

Pressure Vessels & Piping Conference, July 25, 2025, Montreal

Fabien Ebling

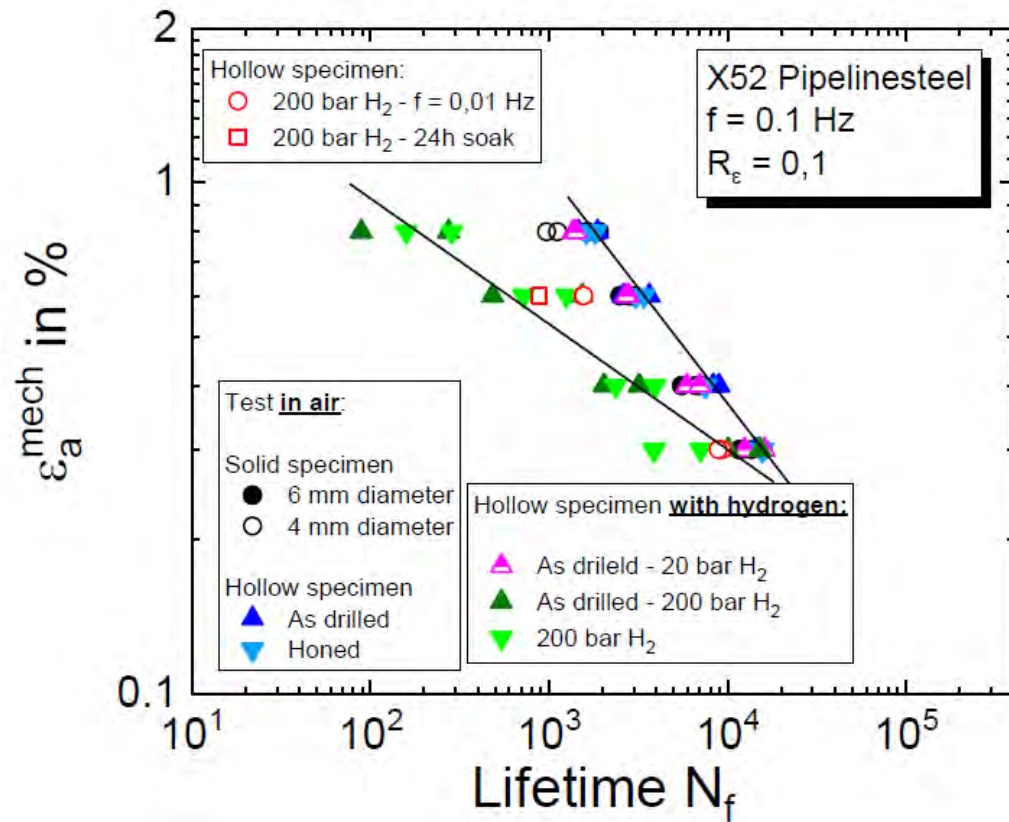
Fraunhofer Institute for Mechanics of Materials IWM, Freiburg, Germany

Motivation

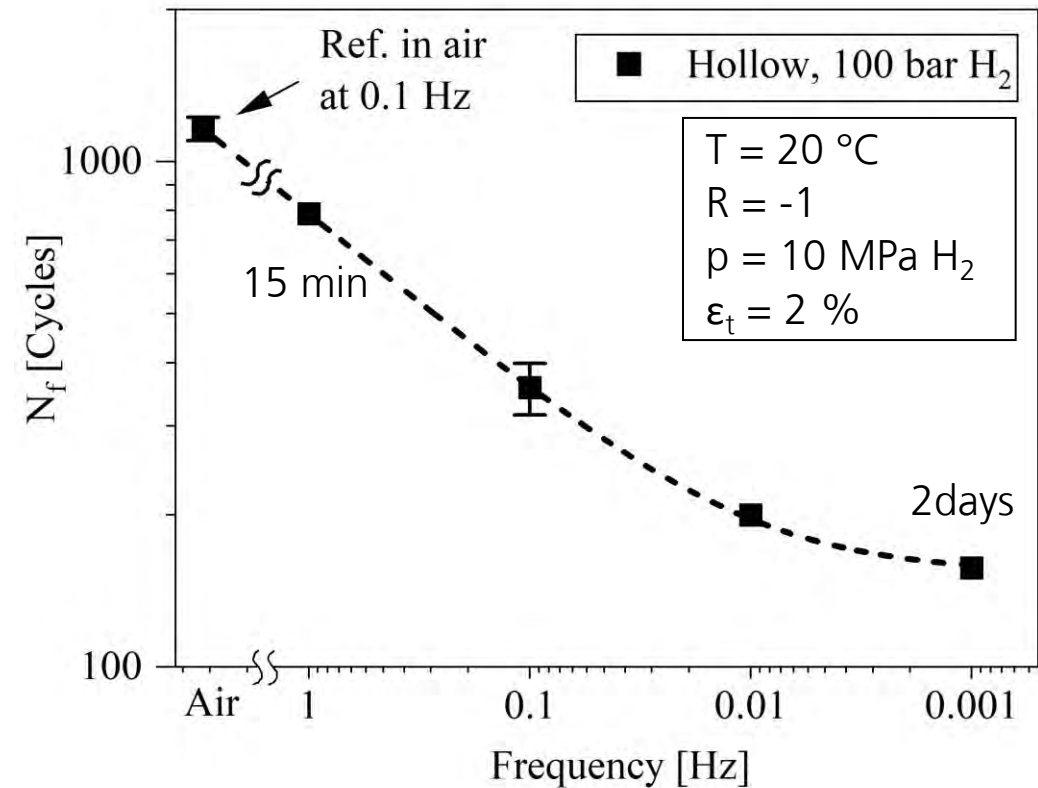
- In literature fatigue tests are performed over a wide frequency range
 - Fatigue crack growth (FCG) and low cycle fatigue (LCF): 0.001 Hz – 1 Hz
 - High cycle fatigue (HCF): Up to 20.000 Hz
- Results can strongly depend on the test frequency as hydrogen needs time to penetrate the material
- **How to ensure conservative results when operating cycles last days or weeks?**

Strain controlled low cycle fatigue tests (hollow specimens)

X52

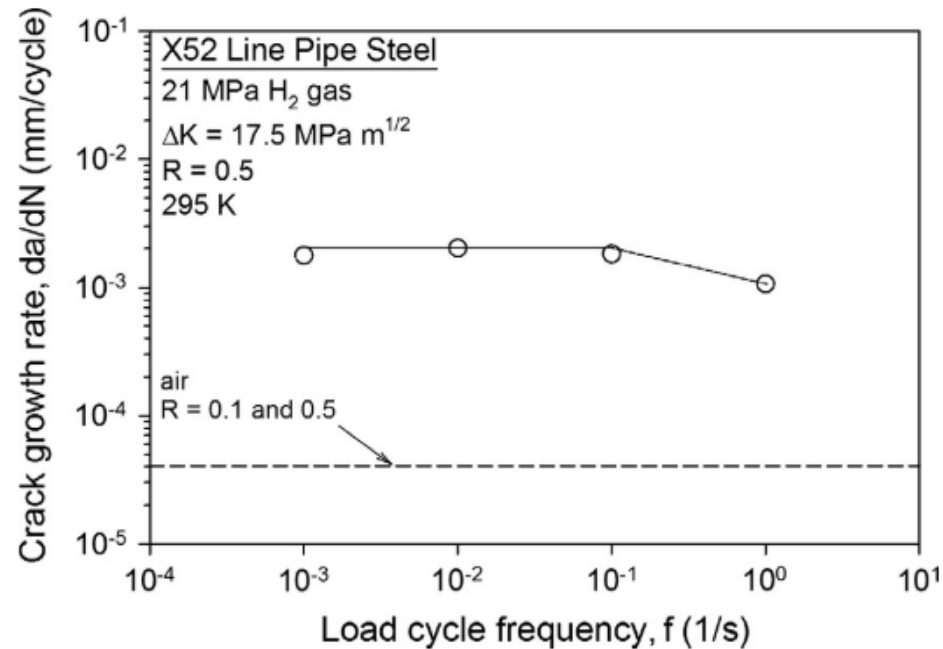


Alloy 718



Fatigue crack growth

X52 (BCC)



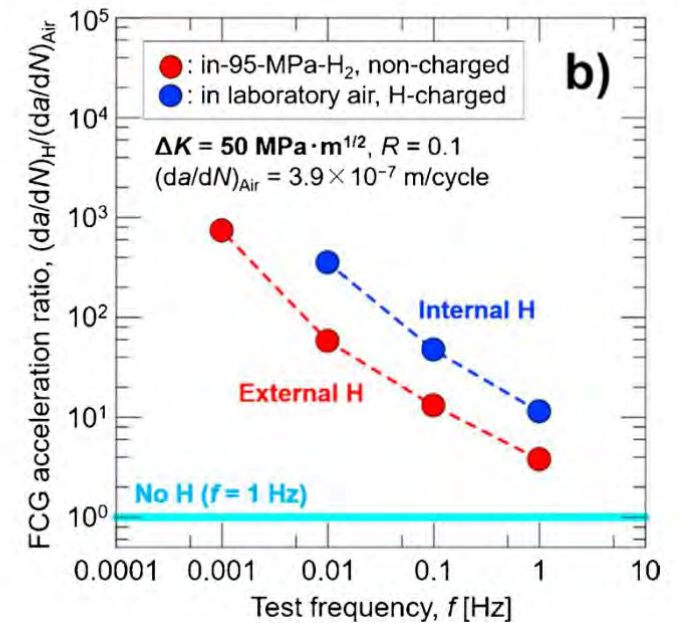
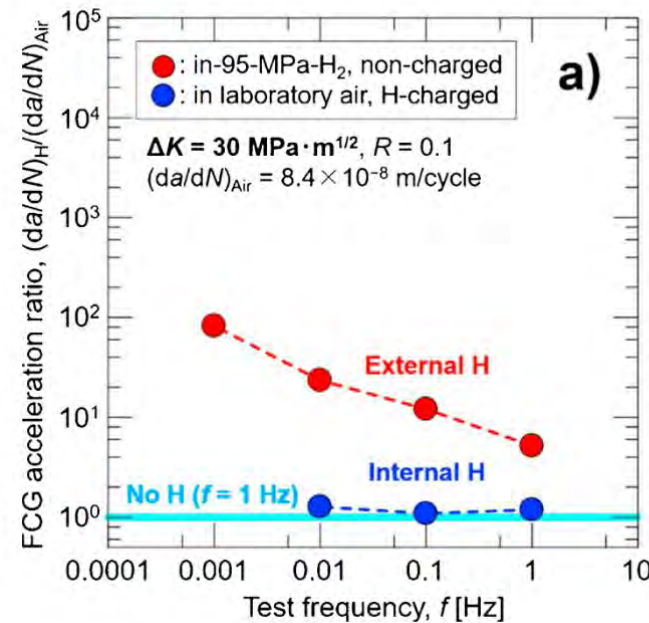
B. Somerday et al. (2013)

$$D_{X52, RT} = 1.1 \cdot 10^{-10} \text{ m}^2/\text{s}$$

Xiusai Xu et al. (2024)

$$D_{X52, -50^\circ\text{C}} = 6.7 \cdot 10^{-13} \text{ m}^2/\text{s}$$

Alloy 718 (FCC)



Y. Ogawa et al. (2020)

$$D_{718, RT} = 1.2 \cdot 10^{-15} \text{ m}^2/\text{s}$$

Ebling and Michler. (2025)

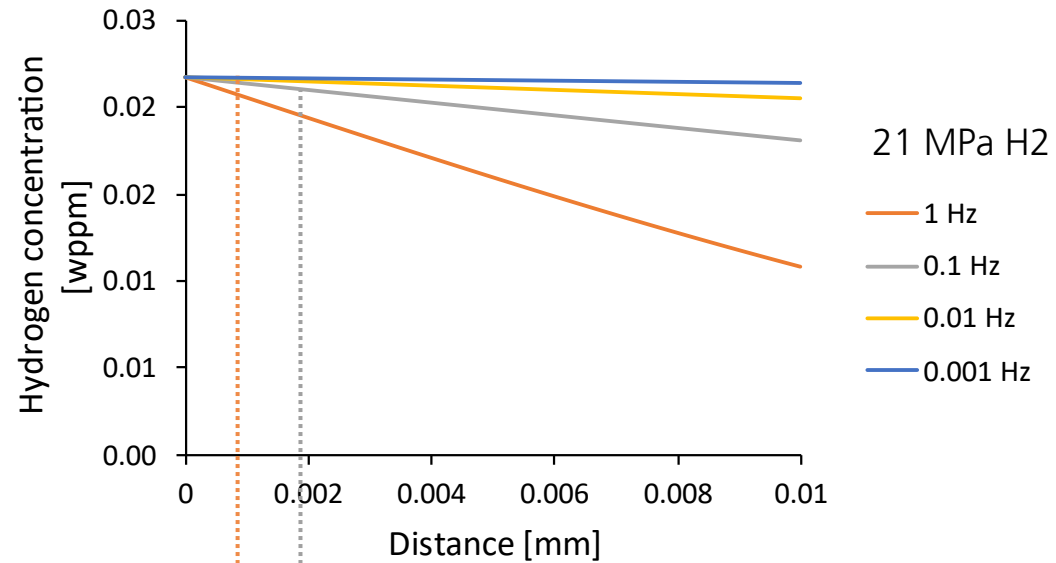
$$D_{316L, RT} = 1.7 \cdot 10^{-16} \text{ m}^2/\text{s}$$

Brass and Chêne. (2005)

Estimation of hydrogen concentration

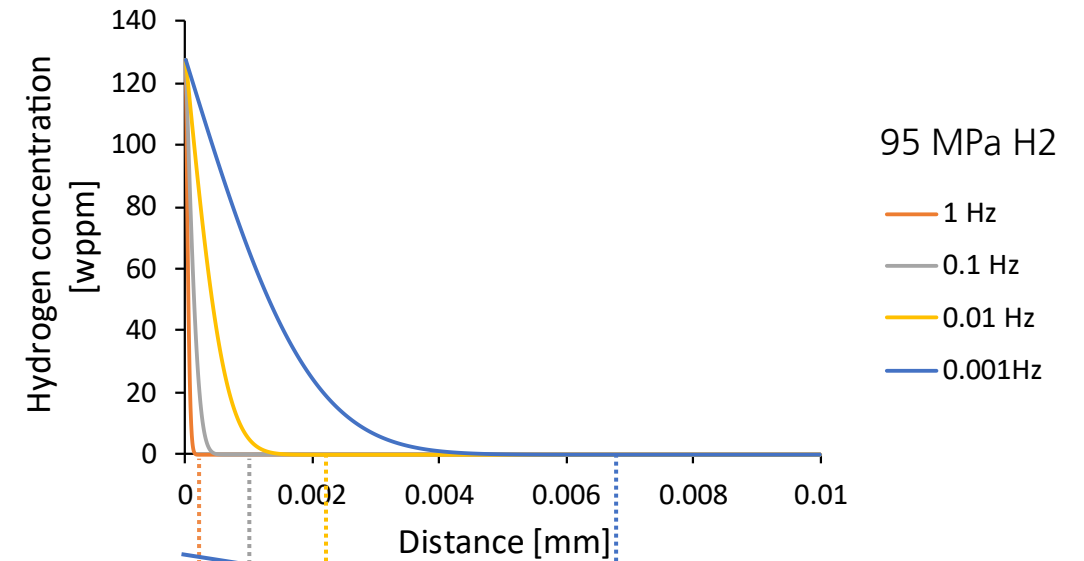
$$C(x, t) = C_0 + (C_1 - C_0) \left(1 - \operatorname{erf} \left(\frac{x}{2\sqrt{Dt}} \right) \right)$$

X52 (BCC)



$$\Delta K = 17.5 \text{ Mpa} \cdot \text{m}^{0.5}$$

Alloy 718 (FCC)



$$\Delta K = 30 \text{ Mpa} \cdot \text{m}^{0.5}$$

How to ensure conservative results for fcc materials and bcc materials at low temperature?

Crack growth smaller than penetration depth per cycle

$$\frac{da}{dN} < x_p = 2\sqrt{Dt} \quad (y)$$

↓
Cycle time

$$C(x_p, y = 0.5) = 0.48 C_0$$

D = diffusivity
 S = solubility
 H_S = formation enthalpy

f = fugacity
 σ_h = hydrostatic stress
 $\bar{V}_H$ = partial molar volume of hydrogen

Precharging at elevated temperature

$$C_{crack\ tip} = C_{precharging}$$

$$S_0 \exp\left(\frac{-H_S}{RT}\right) \sqrt{f} \exp\left(\frac{\bar{V}_H \sigma_h}{RT}\right) = S_0 \exp\left(\frac{-H_S}{RT}\right) \sqrt{f}$$

Experiment at 20 °C and 20 MPa
➤ Precharging at 300 °C and 50 MPa for 2 weeks to saturate the material

Thank you for your attention!

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Exceptional service in the national interest

Materials Selection

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Study Group on Materials Testing and Qualification for Hydrogen Service
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SAND2025-4973PE

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

Context:

High-pressure structural design of pressure vessels and pipelines requires knowledge of hydrogen-assisted fatigue and fracture testing

- **Environment**

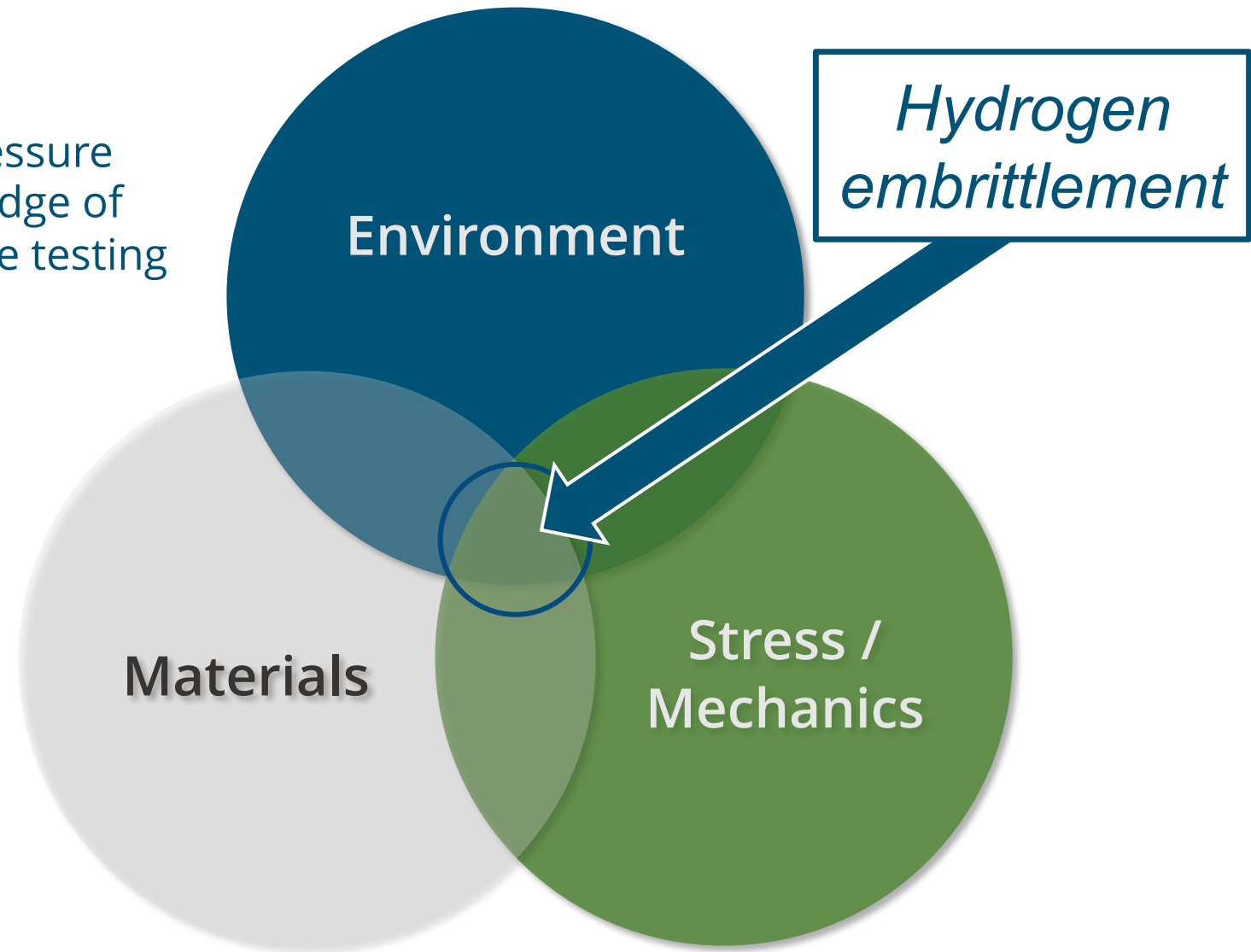
- Hydrogen partial pressure
- Impurities – oxygen/oxides

- **Mechanics**

- Stress ratio (fatigue)
- Fatigue frequency
- Fracture rate

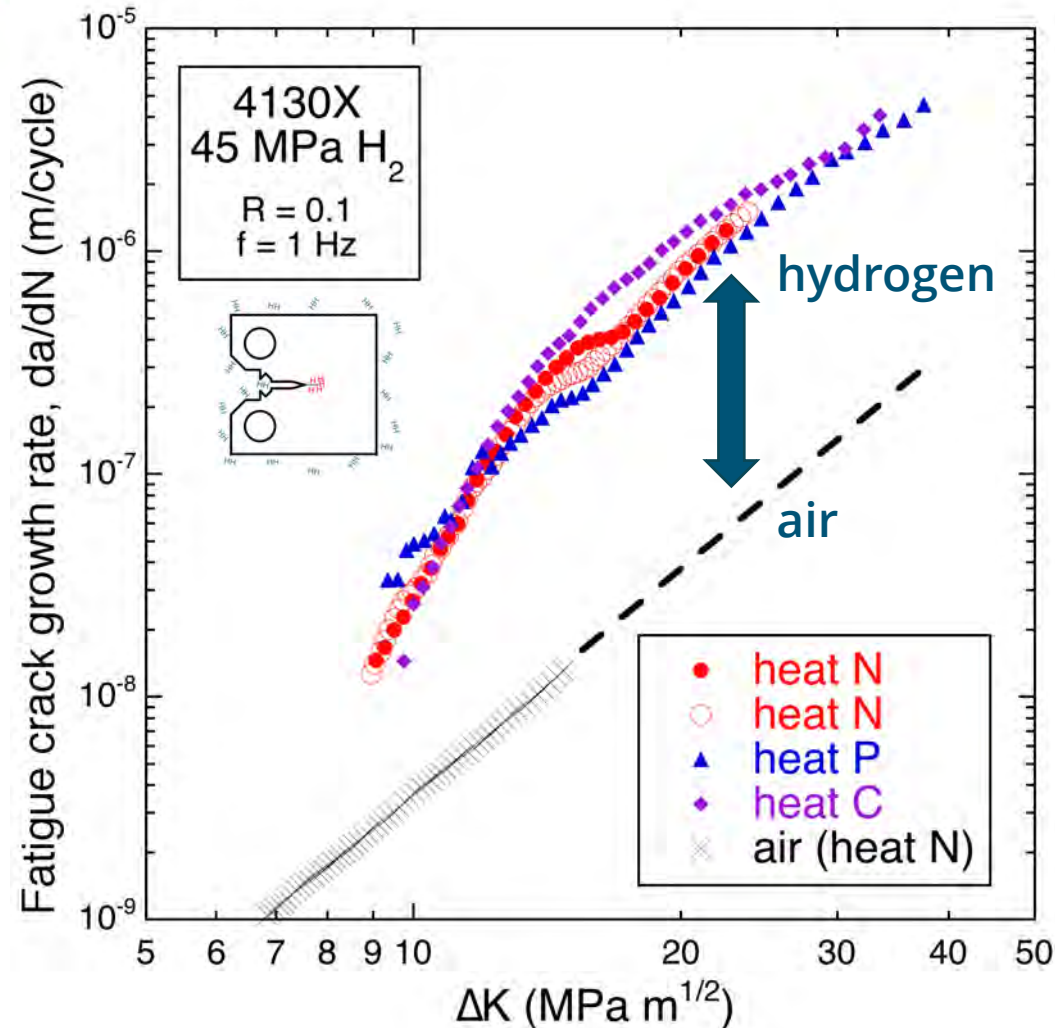
- **Materials**

- Strength
- Microstructure





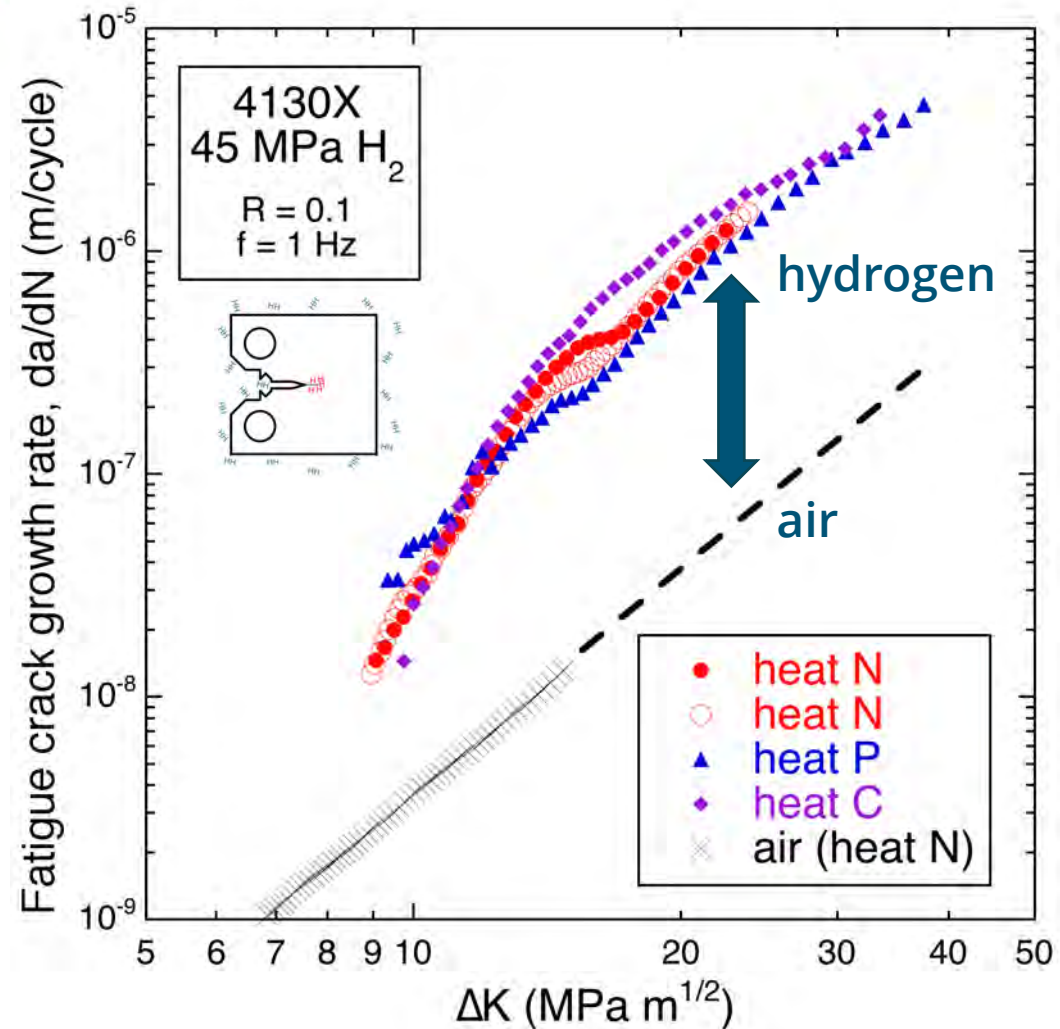
Example: are martensitic steels appropriate for gaseous hydrogen service?



- Cr-Mo and Ni-Cr-Mo steels represent common structural steels with a microstructure of tempered martensite
- These steels show 10x (or more) increase of fatigue crack growth rate
- Fracture resistance of these steels can be reduced by a factor of 2 or more



Example: are martensitic steels appropriate for gaseous hydrogen service?



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Q&T Cr-Mo and Ni-Cr-Mo steels are commonly used for hydrogen pressure vessels

- Transportable gas cylinders (140-420 bar)
- Fuel tanks on FC forklifts (~350 bar)
- Cascade storage systems for refueling stations (up to ~1,000 bar)



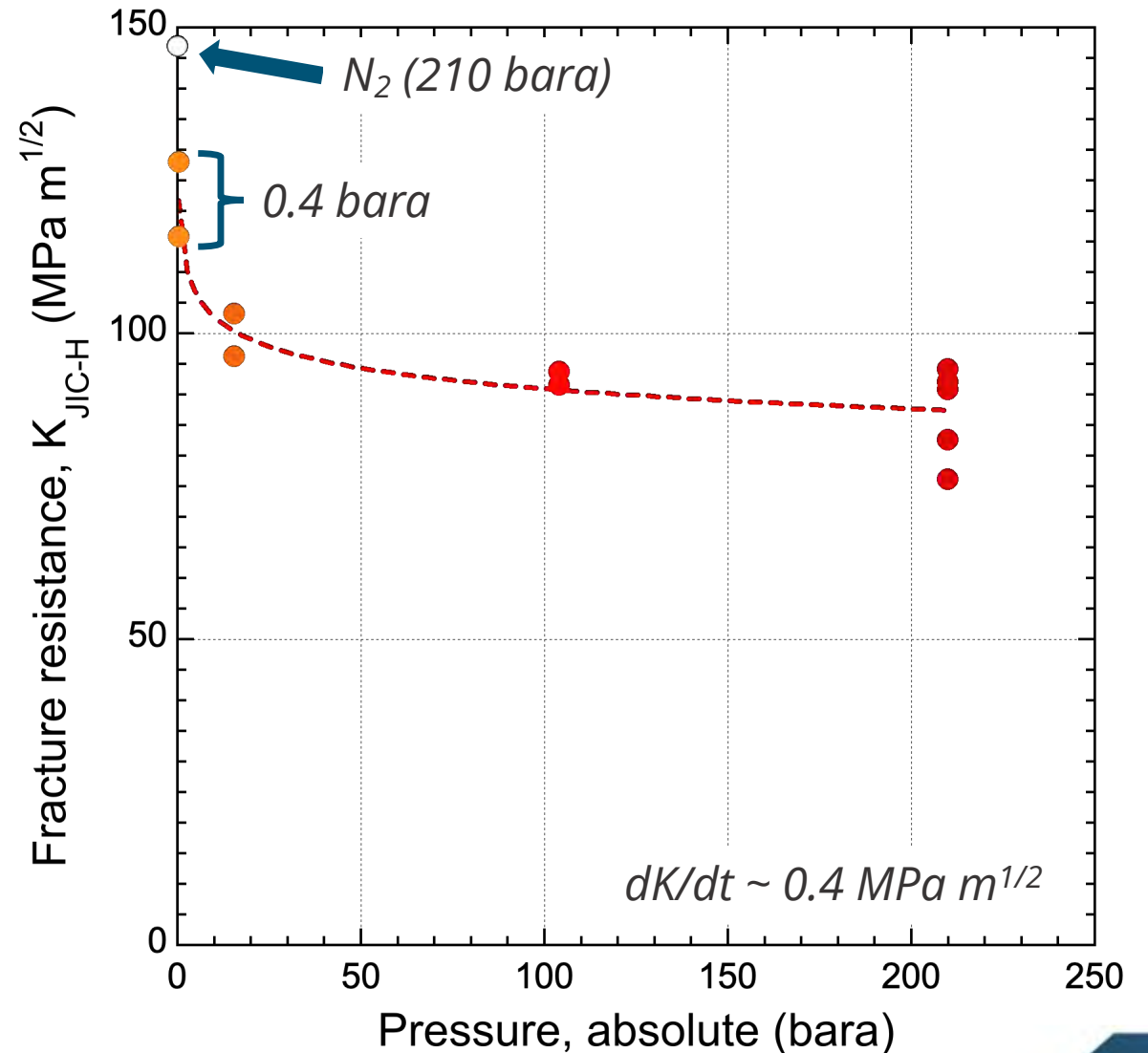
A diverse range of materials are used in hydrogen service

Material	Recommended Condition	Materials performance	Common hydrogen usage	Example alloys
γ stainless steels (solid-solution strengthened)	- Ni > 8 wt% - Minimize magnetic phases - Strain-hardened condition can be acceptable	- Substantial reduction of tensile ductility - Reduction of fatigue life in low-cycle regime	Tubing, fittings, valve bodies, etc (>1,000 bar)	304/304L 316/316L XM-11 XM-19
γ stainless steels (precipitation hardened)	Avoid overaged condition	Substantial reduction of fracture toughness ($\sim 50 \text{ MPa m}^{1/2}$)	Bosses, pressure volumes (>1,000 bar)	A-286
Martensitic stainless steels	- Tensile strength < 900 MPa - use only with <u>extreme caution</u>, especially for high strength conditions	- Fracture toughness < $10 \text{ MPa m}^{1/2}$ in high strength conditions - Fatigue crack growth increased by factor of 10 to 100	Valve stems, and sub-assemblies	17-4PH PH13-8Mo 15-5PH
Carbon steels	Tensile strength < 600 MPa (higher strength conditions may be suitable)	Fatigue crack growth increased by factor of 10 or more at high ΔK (greater than $\sim 15 \text{ MPa m}^{1/2}$)	Line pipe (<150 bar)	API X42 - X70 ASTM A516 (X80-120)
Low alloy steels (Q&T Cr-Mo /Ni-Cr-Mo)	Tensile strength < 900 MPa	Fatigue crack growth increased by factor of 10 or more at high ΔK ($> 8 \text{ MPa m}^{1/2}$)	Transportable gas cylinders, stationary storage (>1,000 bar)	ASTM A372, ASTM A723
Aluminum alloys	Avoid tempers susceptible to stress corrosion cracking	No known effects of gaseous hydrogen	Pressure vessel liners (>1,000 bar)	6061



Fracture resistance measurements show the expected decrease with pressure

- As shown in the literature, fracture resistance shows a modest influence at high pressure (>10 bar)
- Larger influence of pressure is apparent at low pressure (<10 bar)
- An influence of hydrogen on fracture resistance is observed for very low pressure (<1 bar)





Conservative performance metrics of steels in hydrogen service are often known - and just as often misunderstood

- Industry requires fatigue and fracture properties for high-pressure design
 - These measurements are challenging in high-pressure hydrogen
 - Methodologies to conservatively accelerate laboratory testing are needed
- Research activity and literature on H-assisted fatigue and fracture are compromised by tendency to make assumptions and extrapolate results
 - Rigorous control of environmental test conditions is underappreciated
- Commonly misunderstood (sometimes misrepresented) phenomena include
 - Influence of frequency on measurement of fatigue crack growth rate
 - Critical testing rates during measurement of fracture resistance
 - Role of oxygen and oxides in hydrogen-assisted fatigue and fracture



PVP2025-152431

Considerations of Fatigue Design in H2 Service

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Mahendra Rana, Consultant

July 24, 2025

Montreal, QC

Making our world more productive

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Outline



- Fatigue design concept and code rules for pressure equipment
- Industry experience with pressure vessels and piping in H₂ service
- H₂ effects on material properties from a different perspective
- Data to reconcile the perceived difference between industry experience and material behavior in H₂ environments
- Conclusions

Fatigue Design Concept and Code Rules



- The goal of fatigue design is to provide a design life and protect against fatigue failures before the design life at intended cyclic stress conditions.
- Once the design life is reached, it is a common practice to perform inspection and/or FFS to extend the life beyond the original design life.
- Different codes and standards provide different design curves, design life calculations can be significantly different.
- ASME BPV Section VIII Division 2 Part 5 provides rules for pressure vessel fatigue design.
 - Notch stress method
 - Structural stress method
- Notch stress method: code provides explicit rules on peak stress calculations.
- Fatigue life is also dependent on weld details and inspection levels (fatigue strength reduction factor).

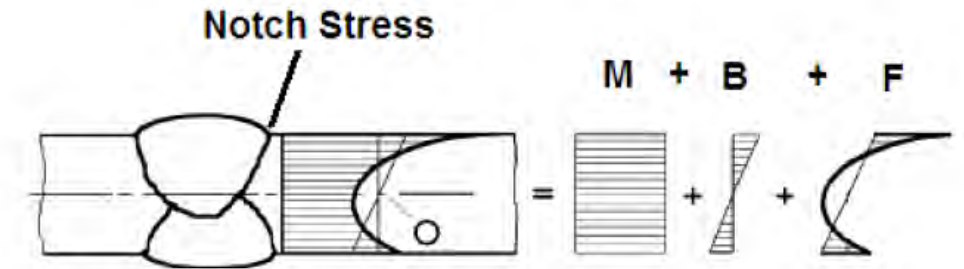


Table 5.12
Weld Surface Fatigue-Strength-Reduction Factors

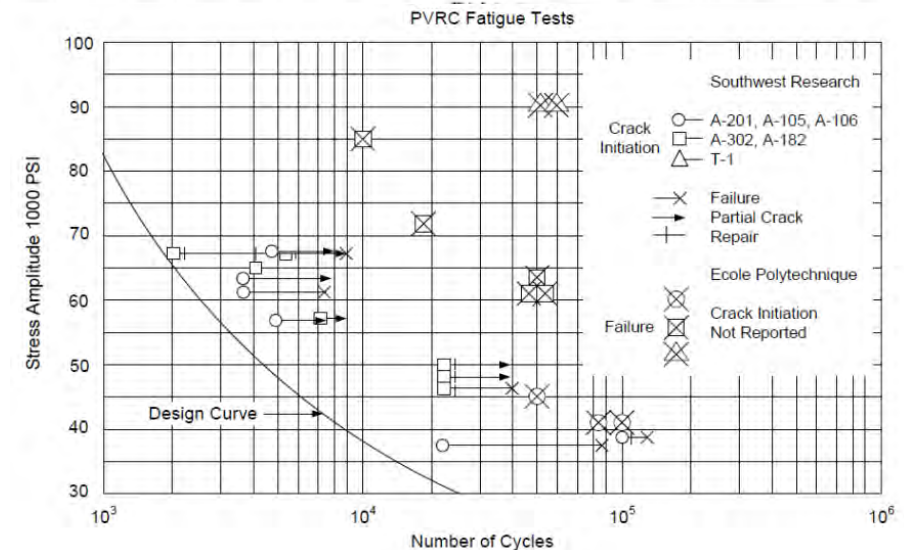
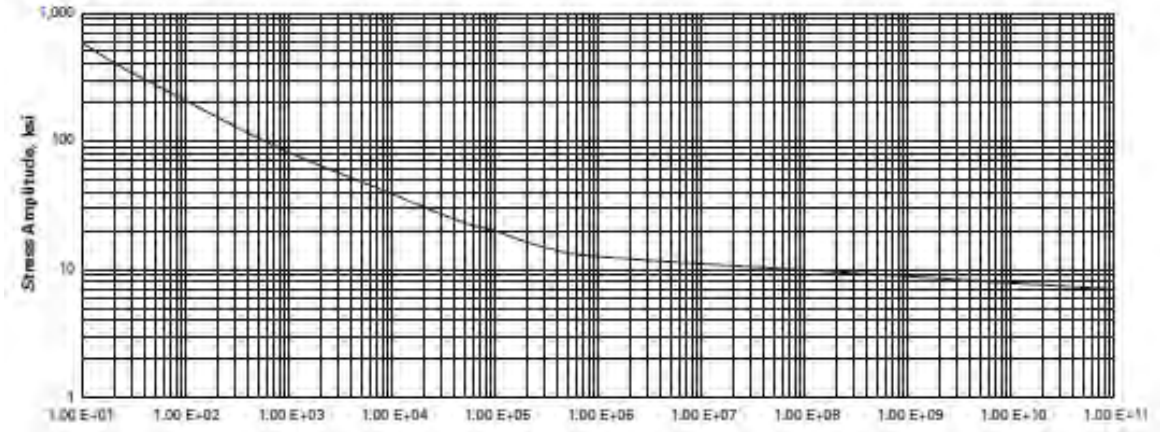
Fatigue-Strength-Reduction Factor	Quality Level	Definition
1.0	1	Machined or ground weld that receives a full volumetric examination receives MT/PT examination and a VT examination
1.2	1	As-welded weld that receives a full volumetric examination, and a MT/PT and VT examination
1.5	2	Machined or ground weld that receives a partial volumetric examination that receives MT/PT examination and VT examination
1.6	2	As-welded weld that receives a partial volumetric examination, and receives MT/PT and VT examination
1.5	3	Machined or ground weld surface that receives MT/PT examination (visual), but the weld receives no volumetric examination
1.7	3	As-welded surface that receives MT/PT examination and a VT examination, but the weld receives no volumetric examination
2.0	4	Weld has received a partial or full volumetric examination, and the VT examination, but no MT/PT examination
2.5	5	VT examination only of the surface; no volumetric examination nor
3.0	6	Volumetric examination only
4.0	7	Weld backsides that are nondefinable and/or receive no examination

ASME Fatigue Design Curves



- The ASME fatigue design curves are based on smooth bar fatigue data, with a margin of 2 on stress, or 20 on cycles.
- The margins are utilized to account for various factors: material, environment, surface, size etc. **They are never meant to be a safety factor.**
- The ASME fatigue design curves have been successfully used in aggressive environments including LWR/BWR in nuclear industry.
 - A study by ANL and PVRC demonstrated “a factor of 4 decrease in fatigue life due to environments is acceptable and does not require further fatigue evaluation” (Chopra and Shack, JPV 1999/2 Vol. 121 P. 49)
- Combination of Div. 2 fatigue design rules and best engineering practice in fabrication controls has served industry very well for equipment operated in cyclic conditions in aggressive environments for past decades.

Figure 3-F.1
Fatigue Curve for Carbon, Low Alloy, Series 4XX High Alloy, and High Tensile Strength Steels for
Temperatures Not Exceeding 700°F — $\sigma_{UTS} \leq 80$ ksi



Industry Experience with Pressure Vessels and Piping in H₂

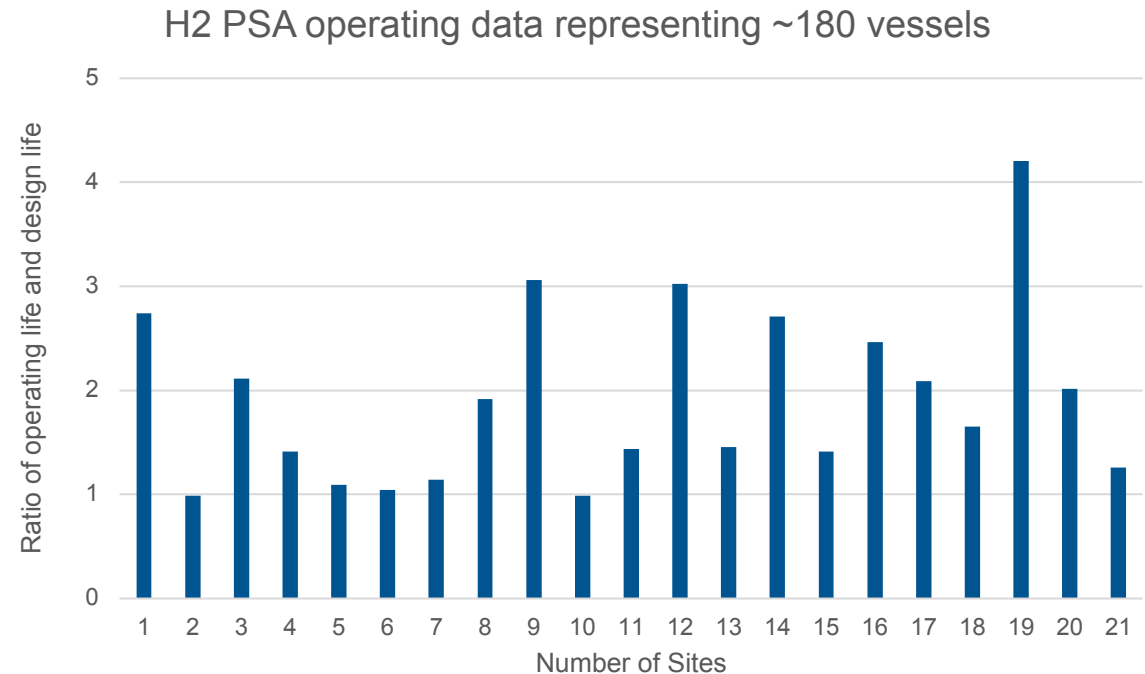


- Long and successful history with H₂ in production, transportation and storage
- Commercial materials have been successfully used.
 - Near ambient temperatures
 - Carbon steels, austenitic stainless steels
 - Cryogenic H₂:
 - Conventional Type 304SS construction, welding qualified per ASME code
 - Elevated temperatures
 - CrMo alloy steels, stainless steels, Ni based alloys
- Key: limiting the material strength/hardness with good engineering practice in fabrication

Industry Experience with High Cycle H2 Vessels



- H2 PSA vessels operate at very high cycles in H2 service
 - Carbon steel construction
 - ASME Section VIII Division 1 with fatigue design
 - H2 pressure: several hundred psi
 - Operating cycles > 1 Million cycles
- High pressure storage vessels
 - Forged high strength alloy steels, ASME SA-372
 - ASME Section VIII Division 1 with fatigue design
 - Operating cycles ~ >10000 cycles
- High pressure gas transport cylinders
 - High strength alloy steels
 - DOT 3AA and 3AAX
 - H2 pressure: several thousand psi
 - Operating cycles ~ >10000 cycles
- Successful experience in fatigue design using Div. 2 fatigue design curve without consideration of H2 effect



With proper inspection, these vessels continue to operate after reaching the original design life.

H2 Effects on Materials from a Different Perspective

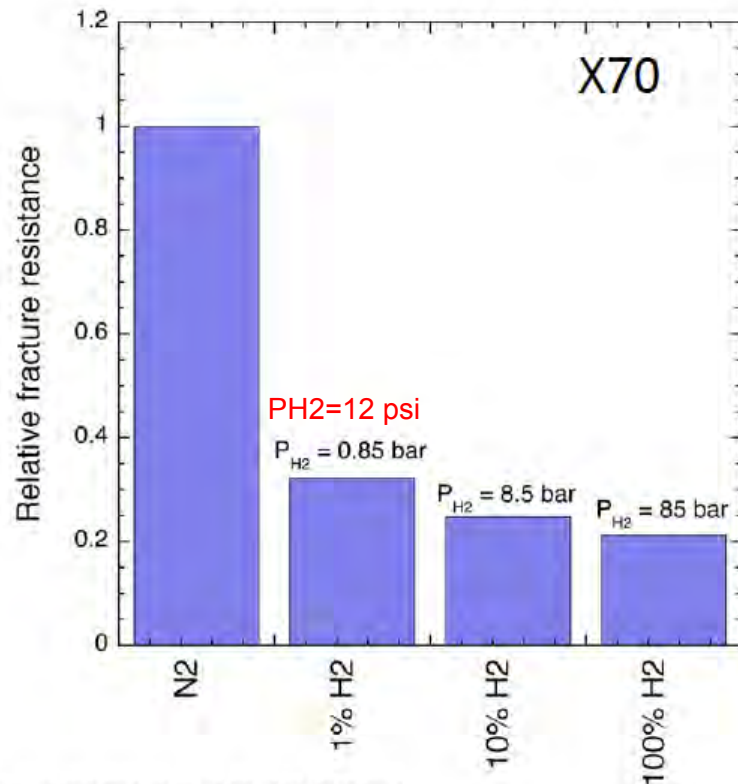


- Materials community are passionate to reveal the detrimental effects of H₂ on mechanical properties of materials.
 - >50% reductions in ductility
 - >50% reductions in fracture toughness
 - 10-20 times increase in fatigue crack growth rate
- It is important for designers to identify if the test conditions are really applicable to design conditions
- Designer must consider many factors
 - Material properties
 - Stress design
 - Fabrication details
 - Inspection and testing
- Designers can take advantage of certain conditions where the H₂ effect is sufficiently low and its impact to design and service life is negligible.

Example: Fracture Toughness in H₂



- The true H₂ effect must be evaluated under application conditions
- Relative comparison can be misleading.



PVP2018-84658

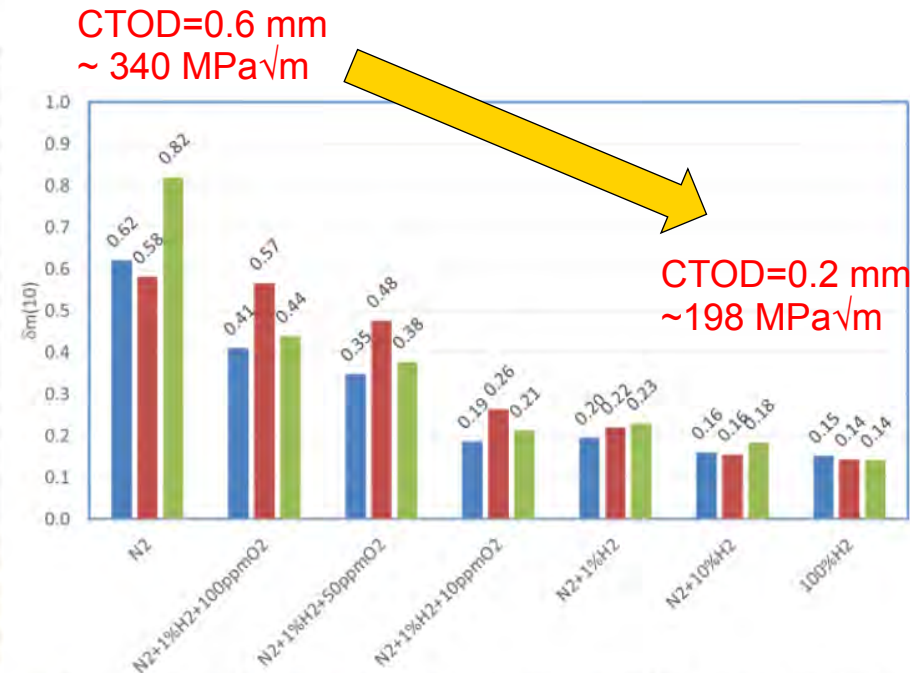


Figure 3: API X70 CTOD depending on the gas content

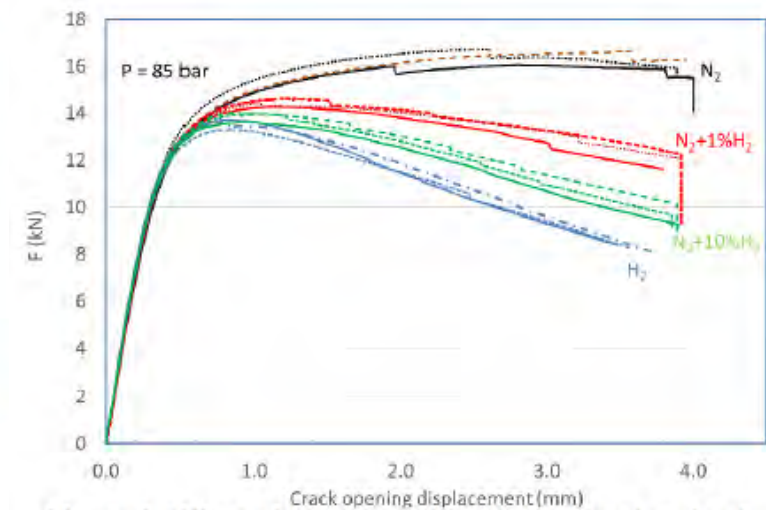
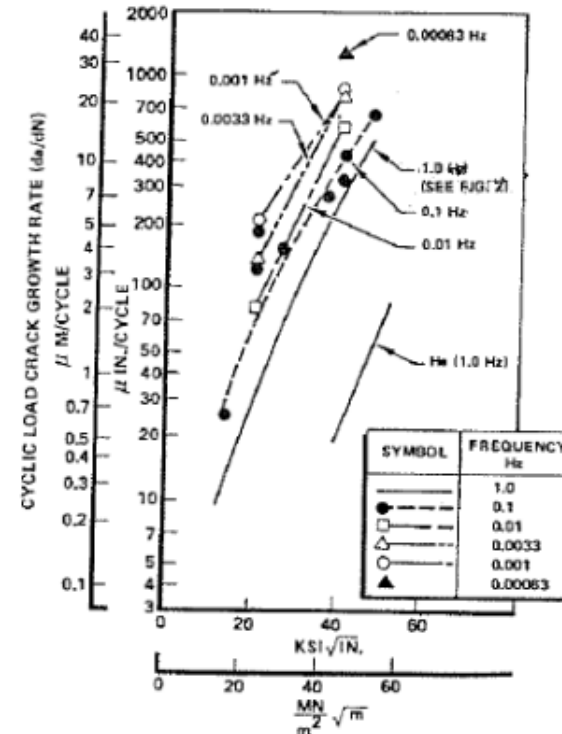


Figure 2: Effect of H₂ content in a N₂+H₂ blend on load-crack opening curves

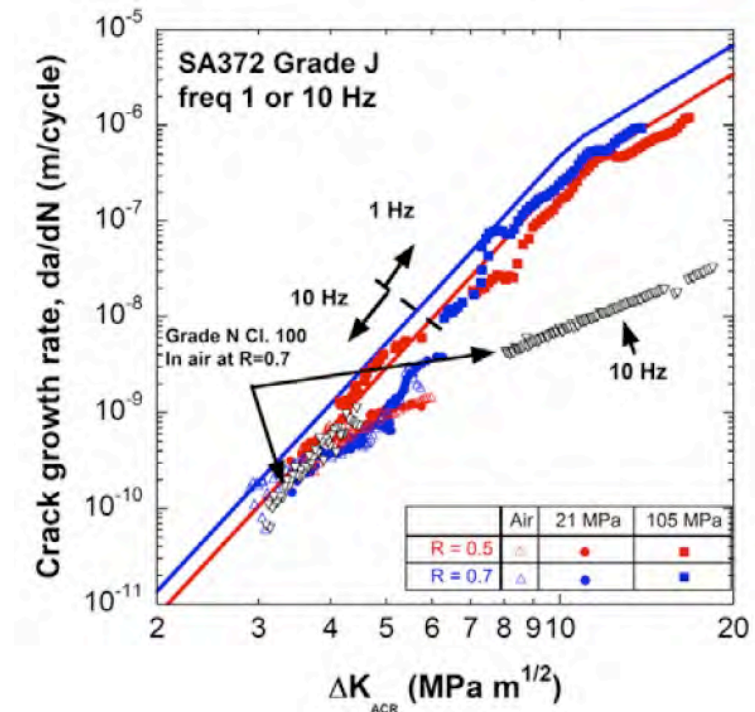
Effects of H2 on da/dN



- H2 effects on da/dN has been known for decades.
 - Significantly accelerated da/dN
- Recent data reveals the same trend and has extended the da/dN data to a higher pressure range and low ΔK regions
 - H2 has no effect on threshold cyclic stress intensity factor ΔK_{th} .
- It is a common consensus that H2 has no effect on crack initiation.
- If a design minimize any stress concentration and follow code allowable stresses, a successful design can be achieved without the need to consider the effect of H2.



Walter and Chandler, 1976
SA-105 da/dN in 15000 psi H2
and in He

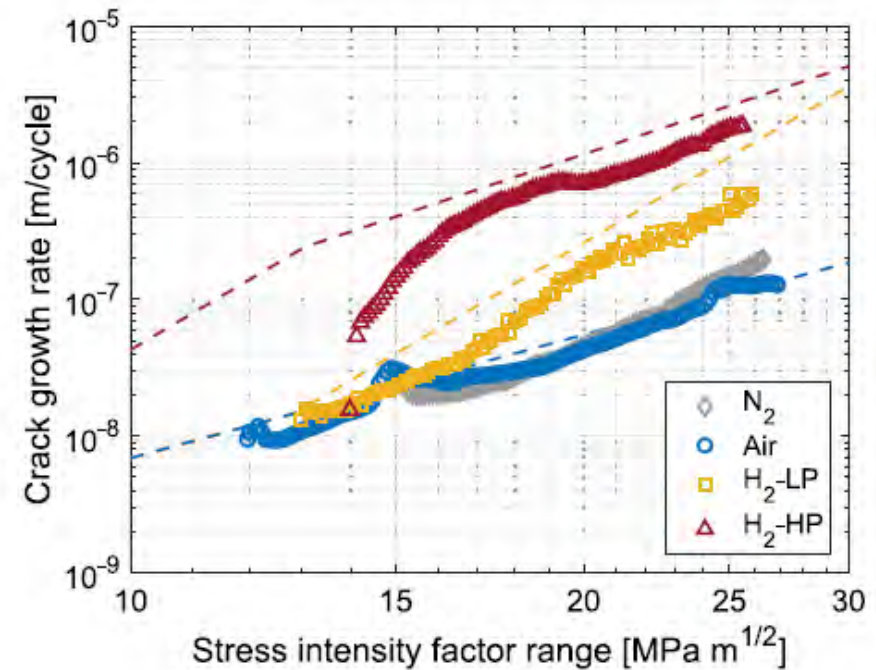
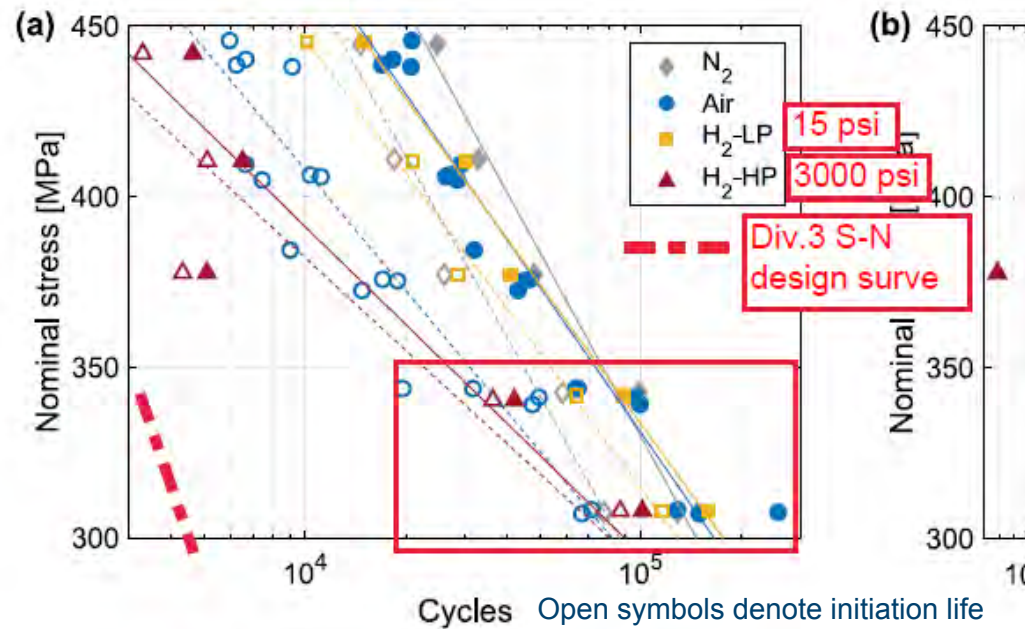


da/dN in 3000 psi H2, 15000 psi H2 and in air
Ref: PVP2020-21263

Fatigue Initiation Data in High Pressure Hydrogen



- X52 notched specimens with $K_t=3.9$, tested in 3000 psi and 15 psi H₂, crack initiation is monitored by DCPD.
- H₂ has a negligible effect on crack initiation at 15 psi or 3000 psi H₂ (in fact, initiation life is longer in H₂ than air due to detrimental effect of moisture) at nominal $S_a \sim 50$ ksi (peak stress= 400 ksi), while da/dN data shows classic higher crack growth rates in H₂.

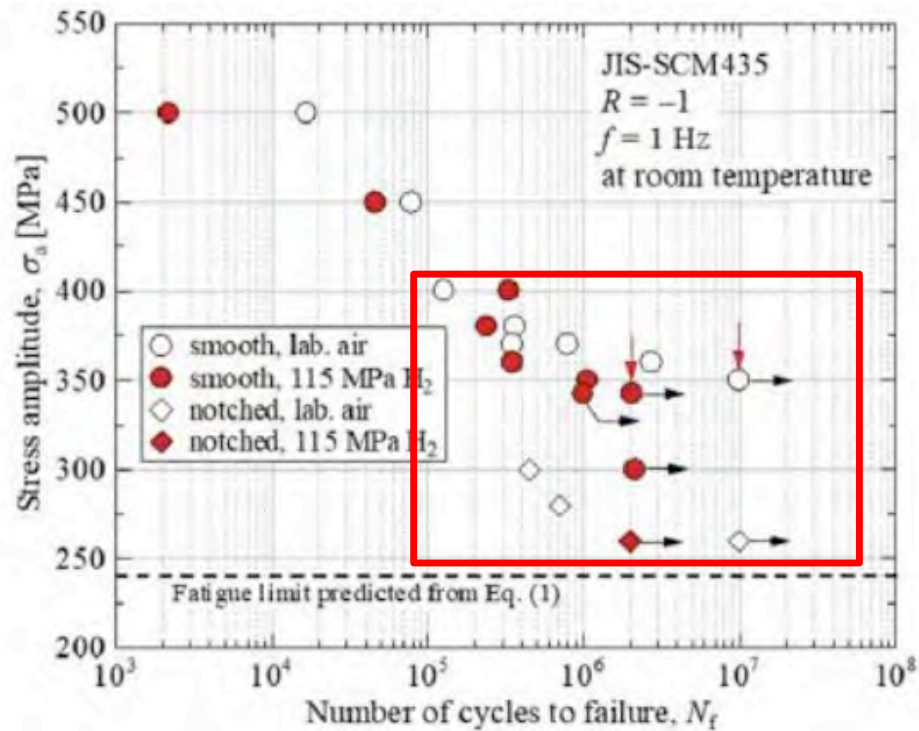


F. D. Leon-Cazares et al., Inter. J Hydrogen Energy
<https://doi.org/10.1016/j.ijhydene.2024.02.292>

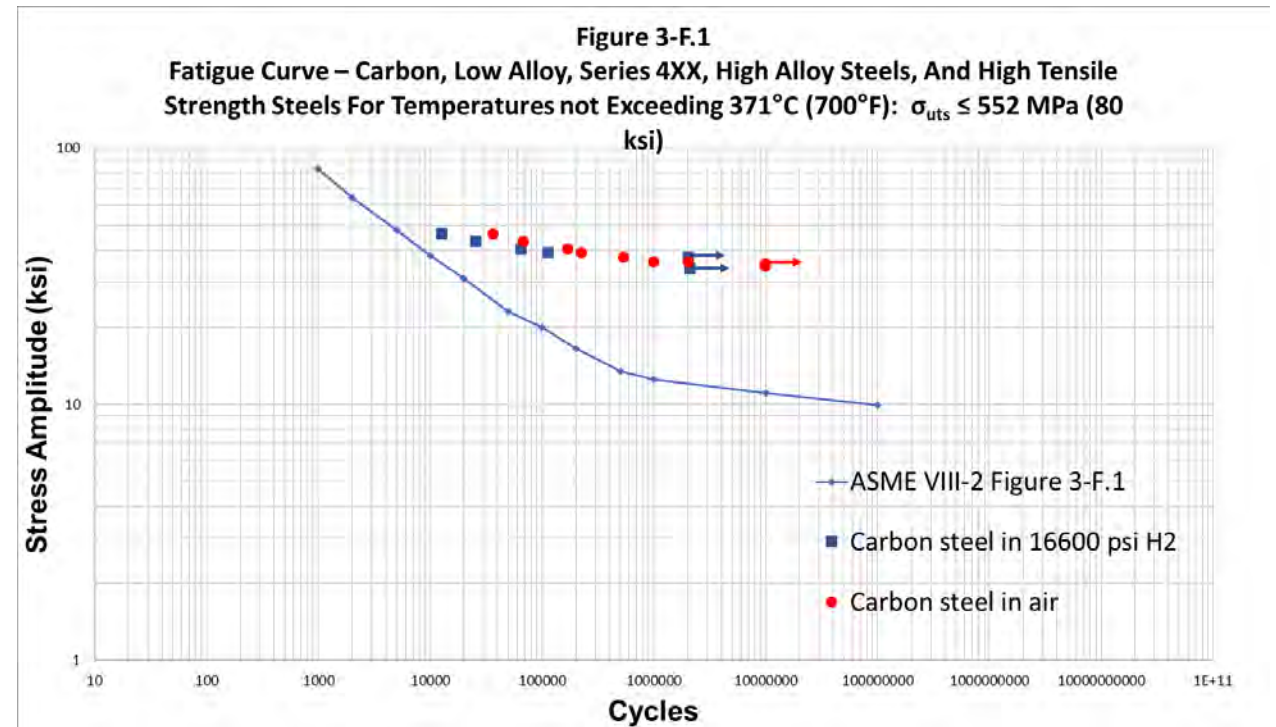
S-N Data in High Pressure Hydrogen (Stress Controlled)



- Cr-Mo Steel (4130X): YS=97 ksi, UTS=120 ksi, smooth and notched specimens tested in 16700 psi H₂
- H₂ has a negligible effect on fatigue life at $S_a < \sim 60$ ksi (peak stress = 120 ksi)
- S-N design curve is applicable.



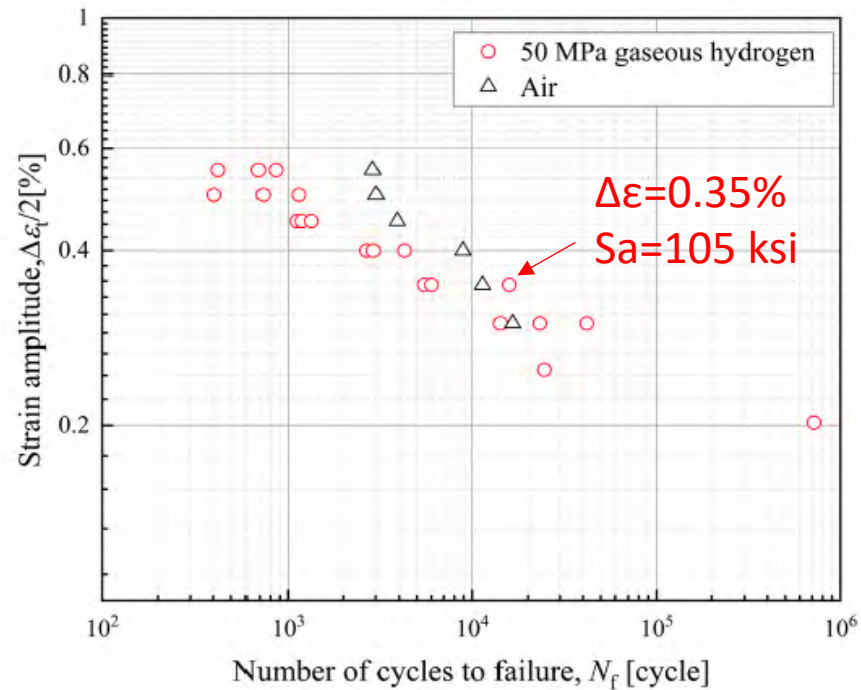
Y. Ogawa et al., Inter. J Hydrogen Energy, 43(2018)20133-20142



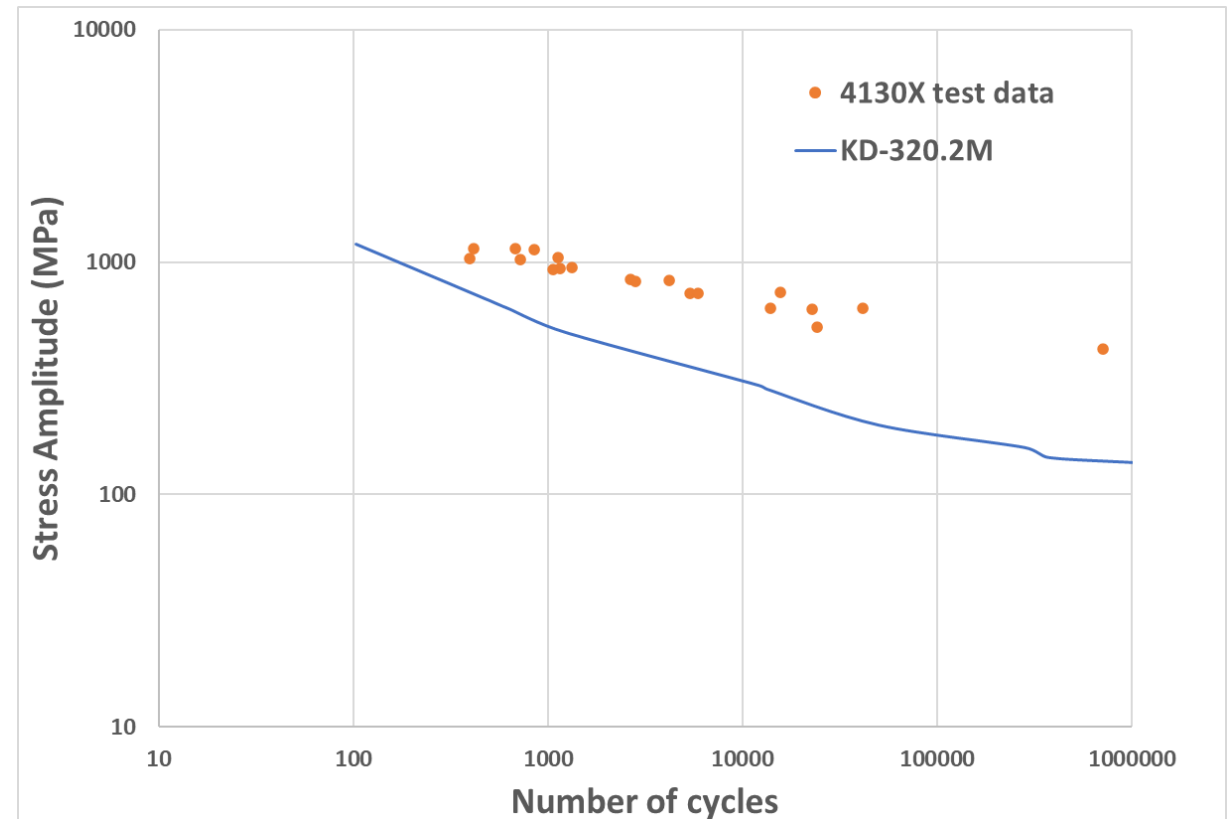
S-N Data in High Pressure H2 (Strain Controlled)



- Cr-Mo Steel (4130X): YS=100 ksi, UTS=120 ksi, smooth and notched specimens tested in 7250 psi H2
- H2 has a negligible effect on fatigue life at $S_a < \sim 100$ ksi (peak stress = 200 ksi)
- S-N design curve is applicable.



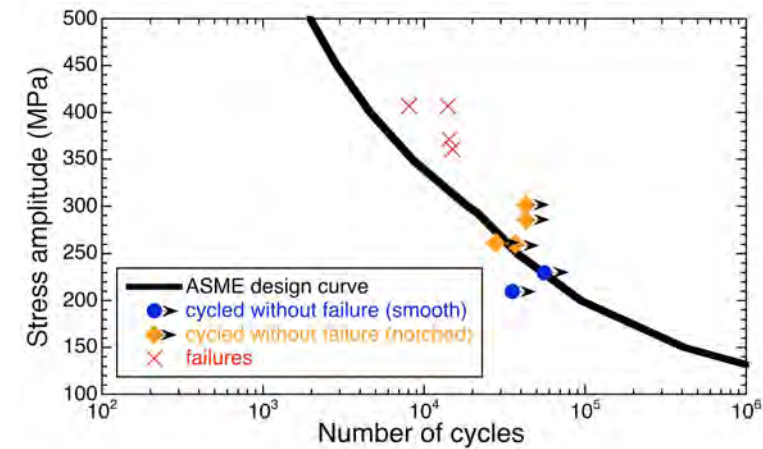
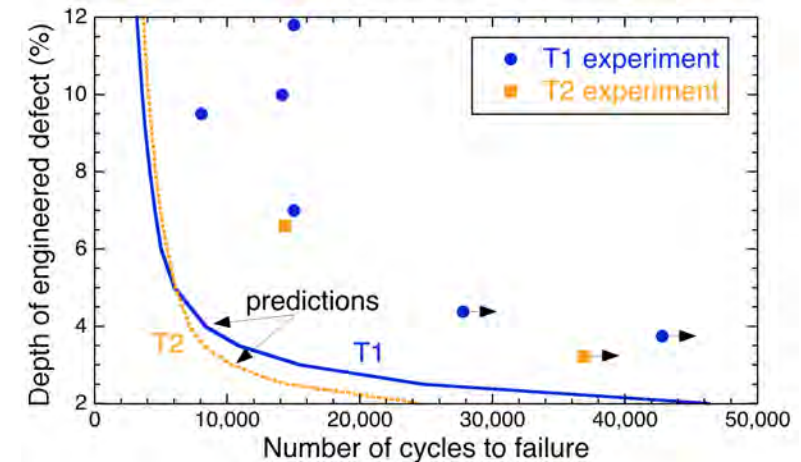
J. Zheng et al., Inter. J Hydrogen Energy, 84(2024) 1042-1049



Actual Vessel Test Data (Small Flaws)



- Vessels tested in cyclic pressure H2
 - 4130X vessel: UTS=109-123 ksi
 - H2 pressure: 500 to 6350 psi
 - Artificial flaw: semi-elliptical flaw 2-10% wall thickness
- The fatigue life predicted by da/dN (KD-10) is substantially lower than the actual life.
- Actual fatigue life significantly exceeded Div. 3 S-N design curve in air.
- Fatigue design using S-N design curve without consideration of H2 is acceptable.



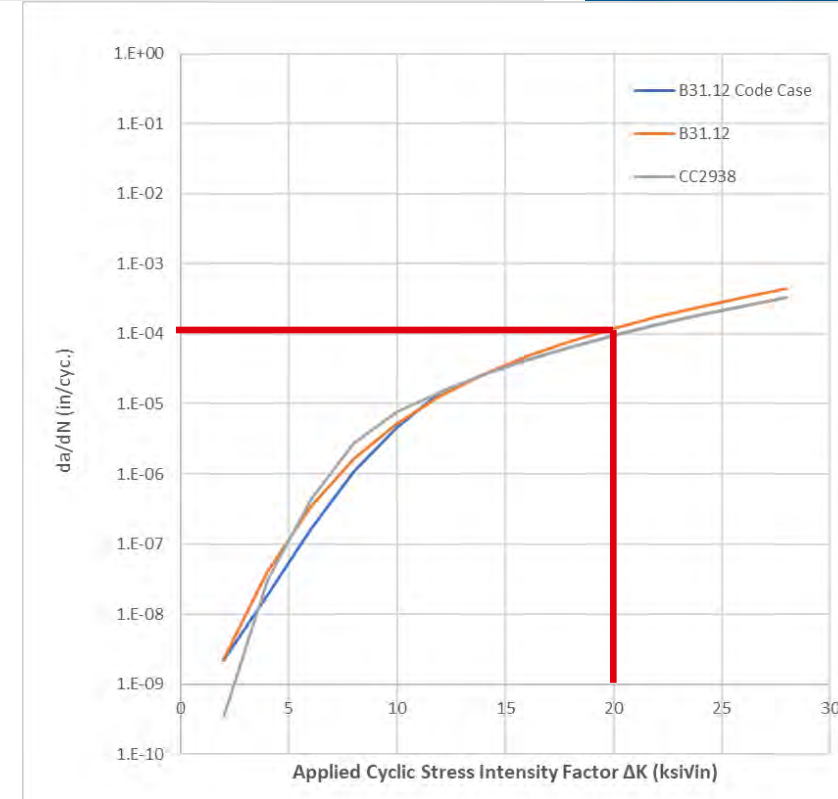
C. San Marchi et al, PVP2012-78709

Actual Vessel Test Data (Large Flaws)



- Welded vessels tested in cyclic pressure H2
 - ASME SA-53, Gr. A, seam welded
 - NPS 2, Sch. 40 (OD=60 mm, t=3.9 mm)
 - Notch in weld: $a/t=0.5$, $2c=20$ mm
 - H2 Pressure: 1000-4000 psi
- Very high stress (nominal stress=YS) and high stress intensity factor ($K_{\max}=26.5 \text{ ksi}\sqrt{\text{in}}$, $\Delta K=20 \text{ ksi}\sqrt{\text{in}}$), starting $da/dN \sim 10^{-4} \text{ in/cyc.}$
- Failure cycle=636 vs. predicted cycles=347 by da/dN

Even with very large flaws and high stresses, crack propagation does not start at cycle 1.

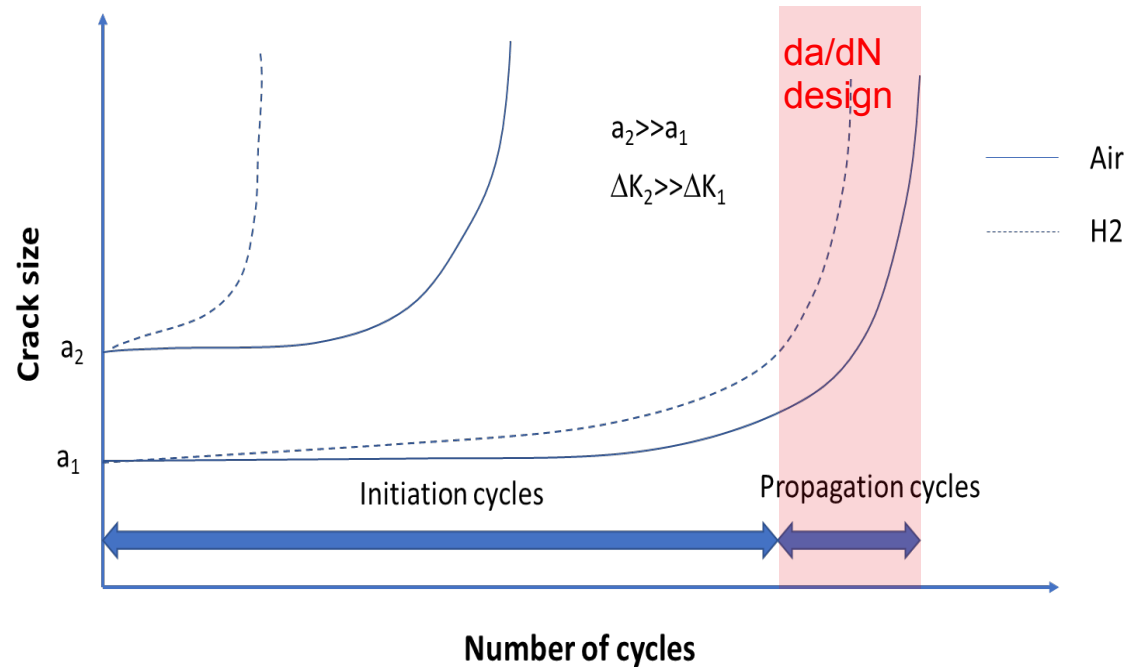


C. San Marchi et al, IPC2024-134173

Fatigue Crack Initiation vs Propagation



- The total fatigue life is consisted of cracking initiation life and propagation life.
- S-N based design assumes the total life is dominated by the initiation cycles, ie, end of life once a crack initiates.
- da/dN based design assumes existing flaws while ignoring the cracking initiation life.
- S-N based design is more appropriate when the total life is dominated by crack initiation.



Fatigue Life	Crack initiation cycles	Cracking propagation cycles
S-N	✓	✗
da/dN	✗	✓

When fatigue design is based on crack initiation, H2 has a minimum effect on design life

Example on Conservatism of da/dN Design



- Material: SA-372 Gr. J Cl. 70, $t=1''$
- VIII-3 Design stress = 61 ksi, operating cyclic stress range = 38 ksi, $S_a=19$ ksi
- Semi elliptical surface flaw $a=0.063''$ ($a/t=0.063$), $2c=0.375''$
- Using air S-N: life=1,000,000 cycles
- Using air da/dN, life=120,000 cycles, ~88% life reduction from S-N design.
- Using H2 da/dN (Div. 3 Code Case 2938-2) at 15 psi H2, ~99% reduction from S-N design.

VIII-3 S-N in air	VIII-3 da/dN in air	da/dN in H2 (CC2938-2)
1,000,000 Cycles	120,000 Cycles	11,000 cycles at PH2=15 psi

da/dN based design is inherently more conservative than S-N based design.

Summary



- Industry has a long and successful experience in pressure vessels and piping under high cycle H₂ service.
- The successful experience is attributed to the conservatism in existing fatigue design rules (without consideration of H₂) and other engineering and fabrication controls.
- The successful experience can be explained by laboratory test data in terms of the hydrogen effect on fatigue life and cyclic threshold stress intensity factor in fatigue crack growth.
- When design and failure criteria are based on crack initiation, the H₂ effects on fatigue crack growth rate do not need to be considered.
- S-N based design without additional penalty factor is satisfactory in most of engineering applications.
- More conservatism da/dN based on design may be appropriate where crack growth is a significant portion of total life (high stresses with potential large flaws/notches).