Converting Subsea Pipelines for Hydrogen

Nicholas Waple, Wood
Senior Pipeline Engineer

February 2024

Agenda

- Industry Experience
- Available Codes and Standards
- Material Implications and Concerns
  - Fracture Toughness Degradation
  - Fatigue Crack Growth Rates
  - Design Solutions and Code Gaps
  - Case Study ECA
  - Key Challenges Offshore
- Influence of H2 Blends / Impurities
- Summary

Industry Experience

- Longstanding experience in 100% hydrogen pipeline transport.
- Predominantly onshore delivering hydrogen to industrial/ petrochemical plants
- (Mostly) purpose built and designed in accordance with pipelines codes and standards / best practice
  - Pipe material: Steel, typically lower strength API 5L grades (X52 or lower)
  - Typically, low design stresses (30%-50% SMYS) - 87% operated below 50% SMYS
  - 99% are 20-inch or smaller

Region	Onshore (km)	Offshore (km)
U.S.	2,608	-
Europe	1,598	-
Rest of World	337	-
Total	4,542	0

Oil & Gas Pipelines ≈2,120,000km

wood.

Codes and Standards

- Hydrogen pipelines are not new, however the codes and standards that govern them are not mature
- Few standards make recommendations against hydrogen specific design challenges
- Development of other standards is underway including DNV, CSA Z662:19, and ASME B31.12
- The DNV H2Pipe JIP (of which Wood is a participant) aims to develop a recommended practice for offshore hydrogen pipeline design and conversion, supplementing DNV-ST-F101

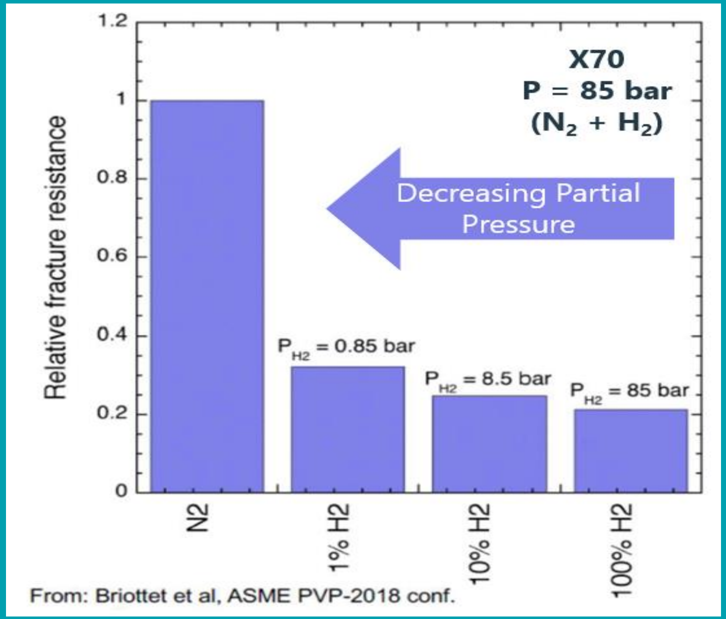
Code	Hydrogen service within scope	Hydrogen specific material requirements considered
ASME B31.12 [1]	✓	✓
IGEM/TD/1 (Sup. 2)	✓	✓
DVGW G 409	✓	✓
API RP 1111	✗	✗
AS/NZ 2885.1 [3]	Update Under Development	
ASME B31.3 [2]	✓	✗
ASME B31.8 [2]	✓	✗
BS EN 14161	✓	✗
BSI PD 8010-1	✓	✗
CSA Z662:19	Update Under Development	
DNVGL-ST-F101	✓	✗
EN 1594	Update Under Development	
ISO 13623	✓	✗
NEN 3650/51	✓	✗

Note:
1) Considered the governing code within the pipeline industry for hydrogen service.
2) Superseded by ASME B31.12 for application to hydrogen pipelines.
3) Guideline for blending hydrogen into pipelines and gas distribution networks under development by Standards Australia

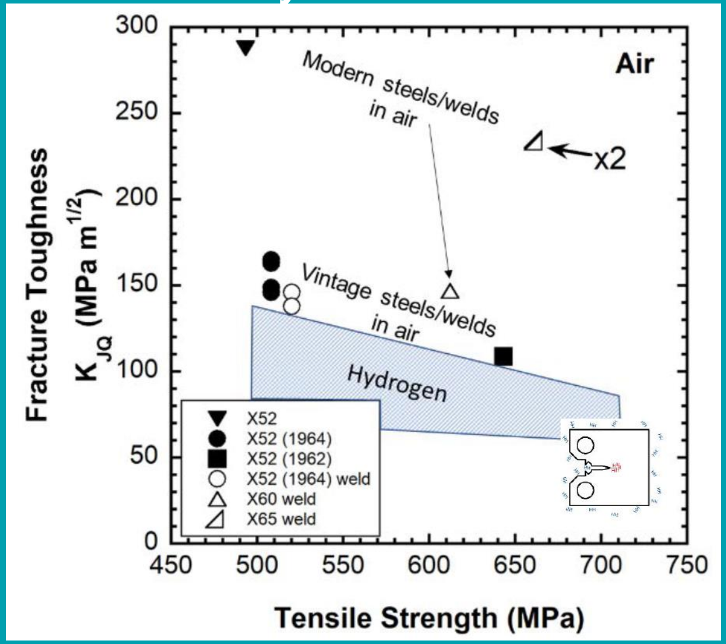
Fracture Toughness Degradation

- Hydrogen reduces material resistance (effective toughness) to propagation of pre-existing cracks (e.g. fatigue cracks) under static stress
- Multiple tests have been conducted to display the impact on toughness
- Results indicate strong detrimental effect of hydrogen on effective toughness. 1% hydrogen (0.85 Bara) was as severe effect as 100% hydrogen
- Use of oxygen inhibitor (100ppm) has been shown to significantly reduce embrittlement effects
- Testing results to date suggest:
  - Similar toughness performance from vintage and modern steels
  - Low sensitivity to yield strength
  - High sensitivity to microstructure, leading to large variation in performance between steels of matching grade

Effect of H_2/N_2 mixtures on toughness



Sensitivity to Material Grade



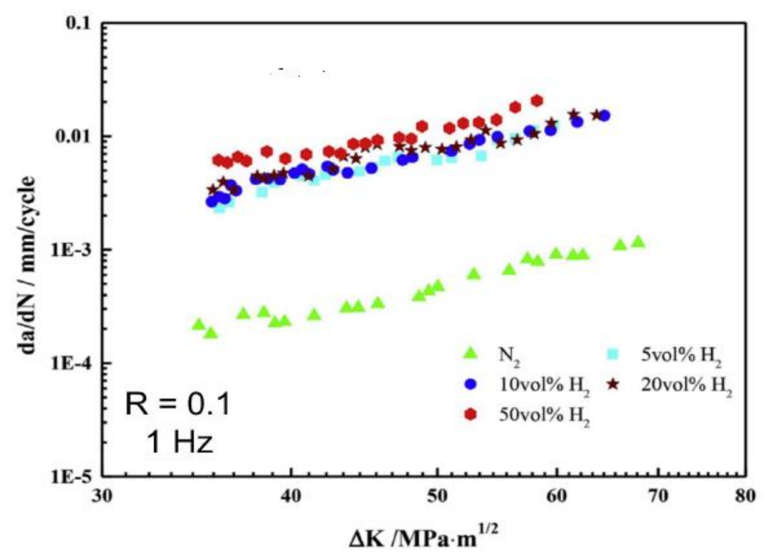
From: SANDIA National Laboratories, 2022

Fatigue Crack Growth

- Hydrogen may increase fatigue crack growth rate by factor of 10 to 30 or more relative to in air / gas
- Effect of 5 % hydrogen (6 Bara) is nearly as severe as 50 % hydrogen (60 Bara)
- Testing results to date suggest low sensitivity insensitive to linepipe grade
- DNV H2Pipe JIP currently ongoing to produce H_2 S/N curve

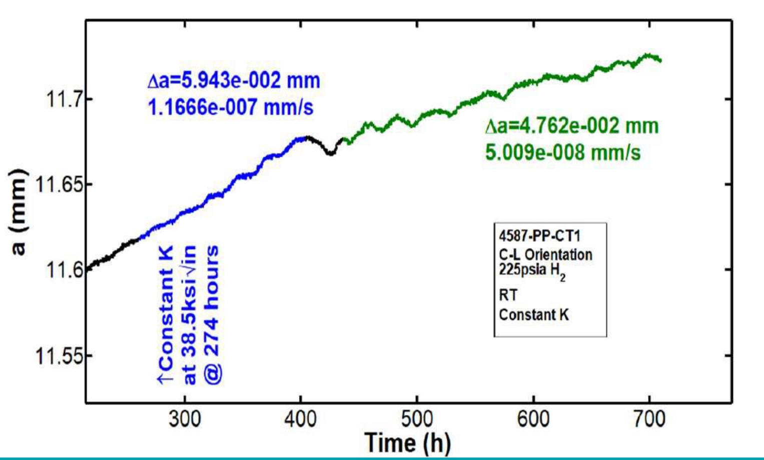
- Ripple loads (small amplitude cyclic loading) have been shown to allow for stable static crack growth under high stress conditions
  - Subcritical crack growth to be further investigated on H2Pipe JIP including effects of different micro structure and loading history

Effect of H_2/N_2 mixtures on fatigue crack growth rate (120 bar total pressure)



From: HyResponse

Time Dependant Crack Growth



From: Shell (ISOPE, PVP 2023)

ASME B31.12 Options for Conversion

Option A (Low Stress Design)

Based on a cautious interpretation of operational experience, rather than defined technical requirements

- Limited to ≤X70, de-rated to X52 equivalent (approx.)
- Reduction in allowable stress (DF≤0.5)
- Material restrictions in line with traditional sour hydrocarbon service

Many Natural Gas pipelines may not be qualified against Hydrogen limits without unacceptable pressure de-rating

Option B (High Stress Design)

Technically justifiable fracture mechanics-based approach

- Equivalent Natural Gas design (DF ≤ 0.72, ≤ X80)
- Material qualification via fracture toughness testing of hydrogen charged specimens
- Based on fracture mechanic's approach (ECA)
  - Traditional for offshore sour service to justify design stresses (Static and cyclic)

Introduces significant material sampling and testing requirements

Case	Case Description (Natural Gas to Hydrogen)	Design Code	Energy Ratio
Like for Like	Matching Operating Pressures in between Natural Gas and Hydrogen	ASME B31.12 - Option B	87%
De-rating	De-rated hydrogen Service	ASME B31.12 - Option A	55%
Velocity Limit	De-rated hydrogen Service and standard ASME B31.12 gas velocity limit	ASME B31.12 - Option A	30%

Notable Gaps in ASME B31.12

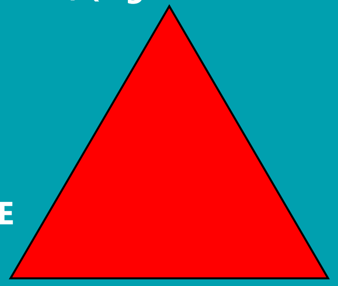
Qualification Testing

- LEFM constant displacement testing methods following ASME B31.12 are not conservative
- ASME B31.12 Option B – Very low toughness requirement K1H= 55MPaM0.5 (CTOD =0.02mm)
- Growing industry consensus on use of Elastic Plastic methods (EPFM) to reduce conservatism

Material Sampling

- Material Sampling requirements of 1 per mile
  - More practical sampling frequencies should be technically driven
  - Need identified for common “groupings” to reduce reliance on destructive sampling

FM Analysis (ECA)

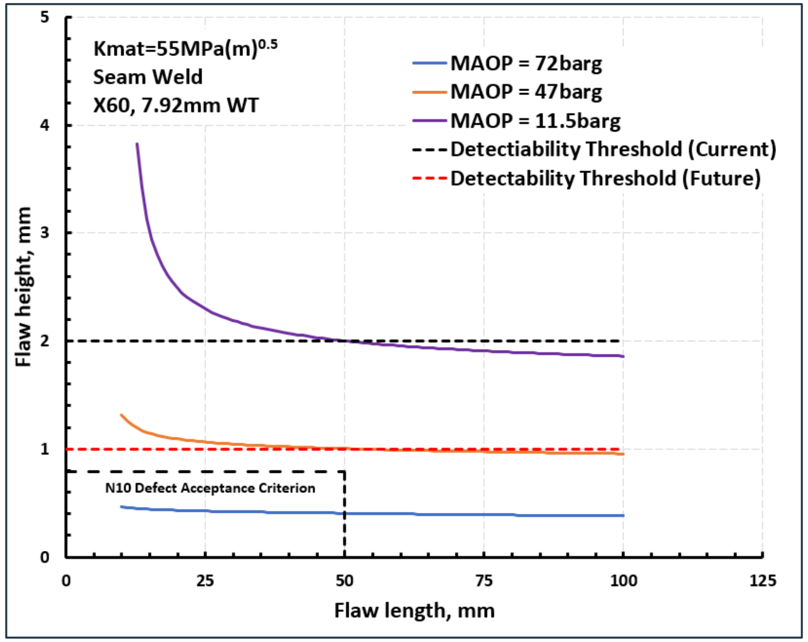


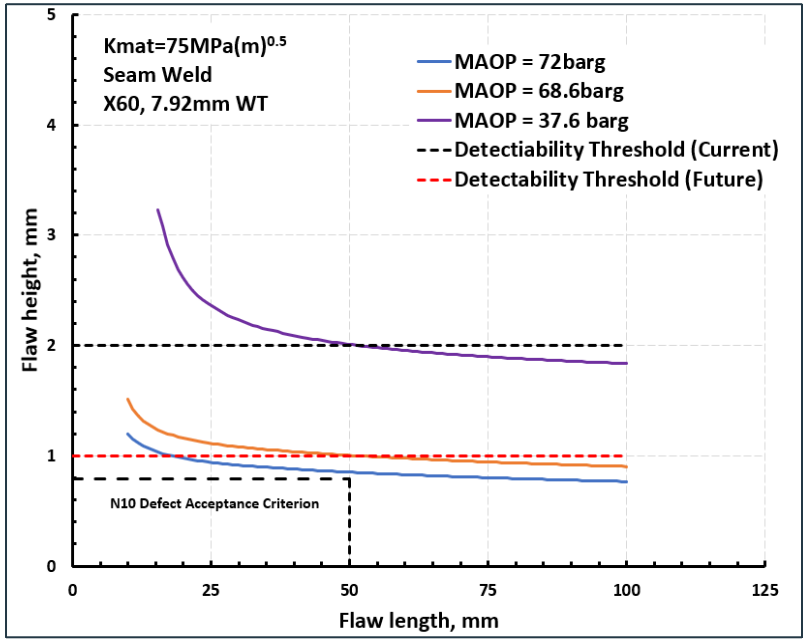
Results of FM Assessment: X65, 16-inch OD, 20mm thickness, Design Factor =0.72.

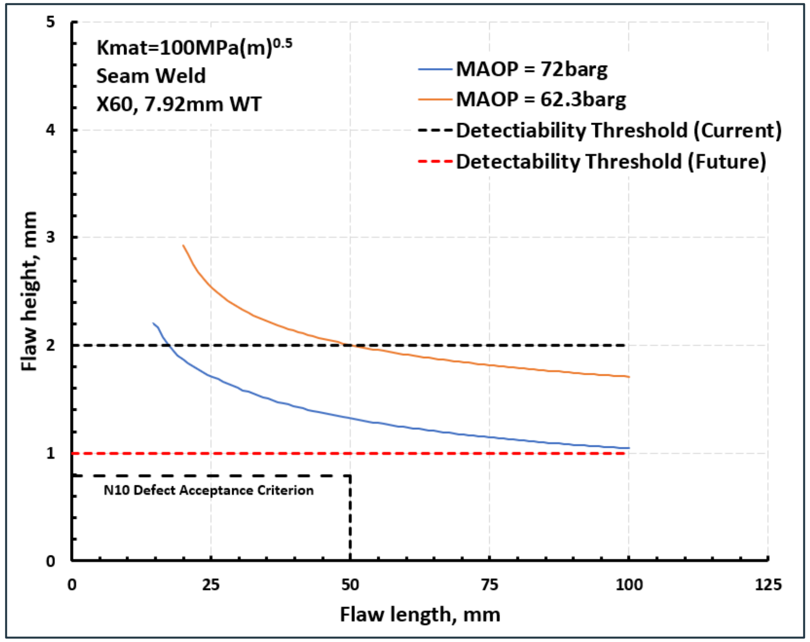
Pipe Type	Flaw Size Case	Flaw Length, . mm	Flaw Depth. , mm	Toughness, K, MPaM 0.5	CTOD, Toughness, mm
HFW/ SMLS	N10 Mill AUT	50	2	55	0.02
LSAW	N10 Mill AUT	50	2	92	0.05
LSAW	N5 Mill AUT	50	1.25	70	0.03

Case Study ECA

- Fracture assessment results demonstrate the need for improvements in crack detection capabilities from the current 2mm threshold
- Inspectability is critical. ILI capabilities to detect and measure anomalies well before they endanger containment is limited







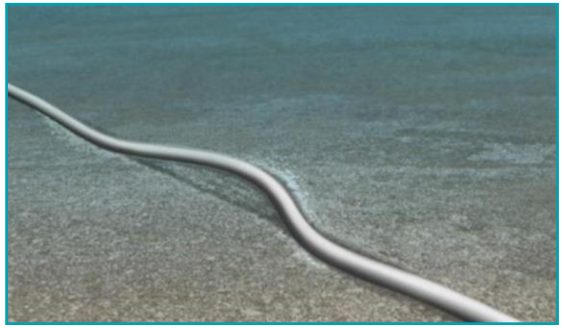
If the critical cracks are too small to be detected, pressure de-rating may be required

wood.

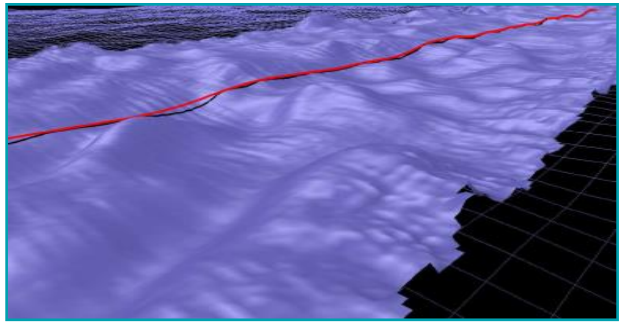
High Stress Design – Key Challenges Offshore

- High longitudinal/bending stresses
- High strain loading (e.g. global buckling, accidental loading)
- Fatigue loading (e.g. VIV & storage cycles)
- Material sampling
  - Significant variation in performance between "similar" steels

High stress design approach offshore will require tighter control of spans and damage than for NG

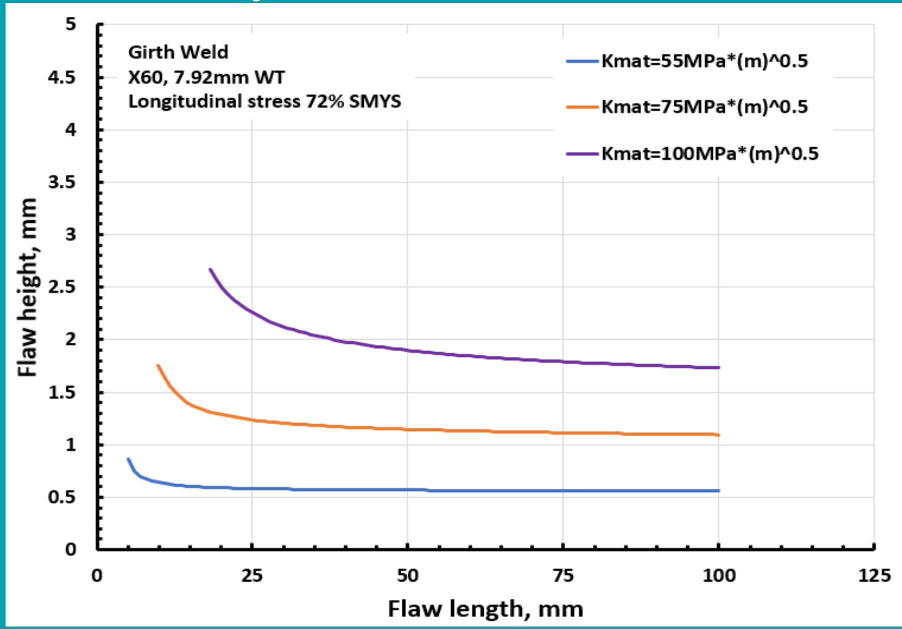


Lateral buckling fatigue subsea

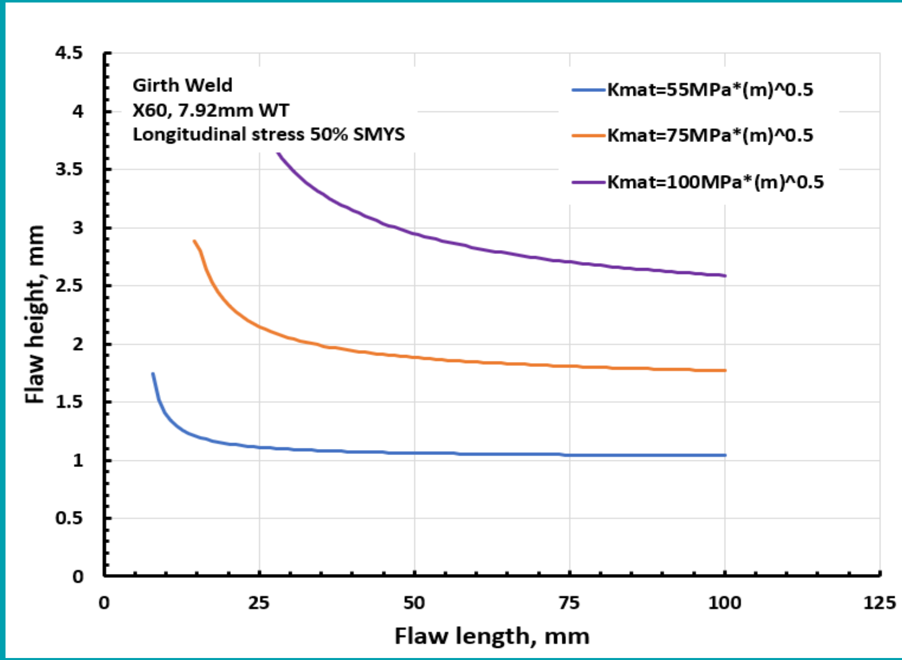


Span fatigue subsea

Case Study ECA – Girth Weld (72 % SMYS)



Case Study ECA – Girth Weld (50 % SMYS)

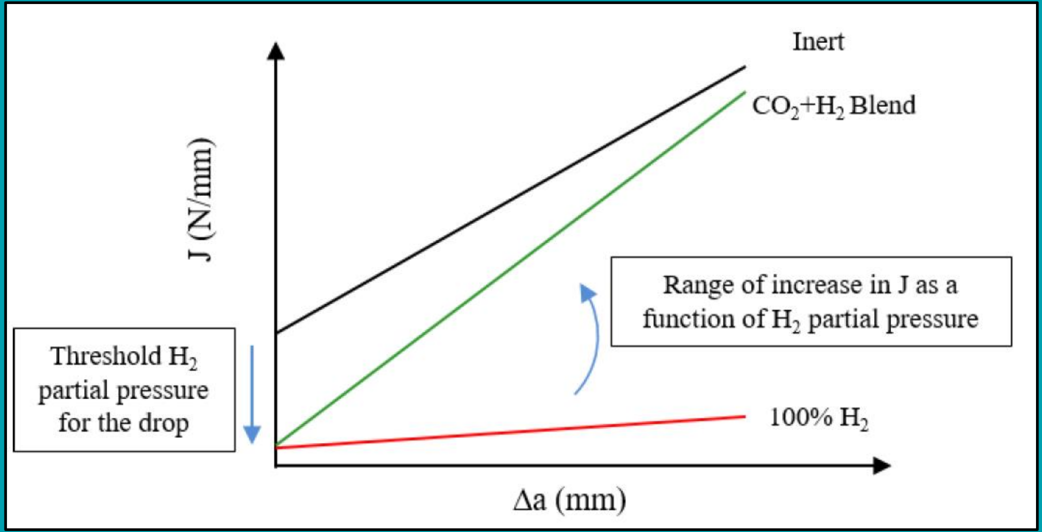


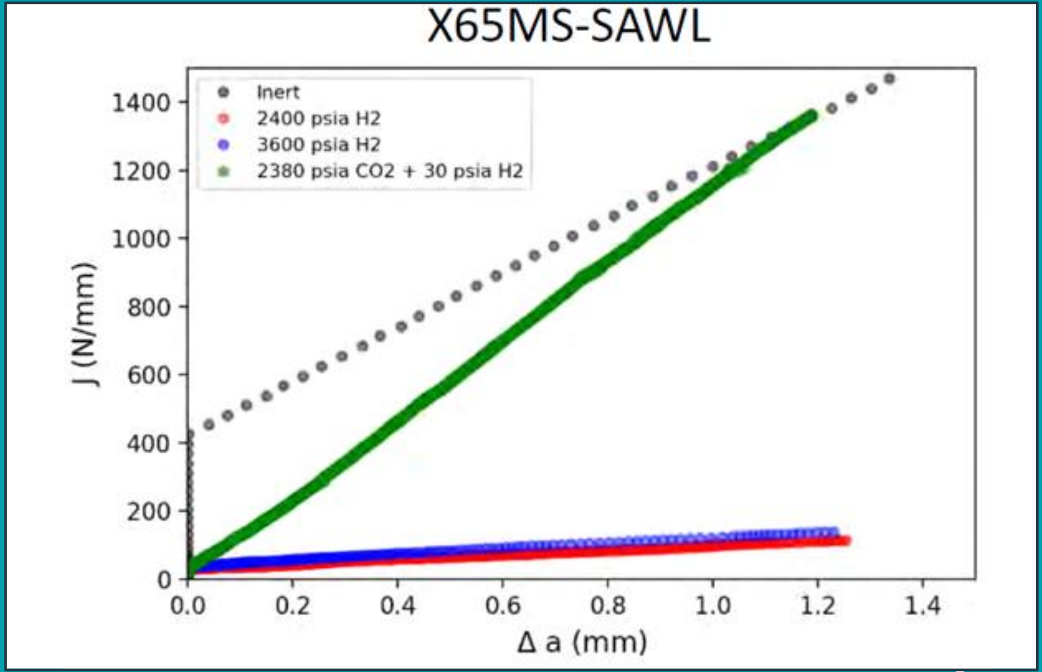
Influence of Hydrogen Impurities

- Inconsistencies between test data and standards on the impact of low blend ratios
- Allowable hydrogen minimum partial pressure (H_2 %) injected into natural gas?
  - <1 Bara hydrogen has been demonstrated to have a significant effect

- Similar effects seen for H_2 impurities within CO_2
  - 1% H_2 impurity in dense phase CO_2 has been demonstrated to impact initiation fracture toughness
  - The impact on fracture toughness of H_2 as an impurity in CO_2 stream should be considered for the CO_2 pipeline specification

Impact of 1% H_2 Impurity within Dense Phase (~165 bar) CO_2



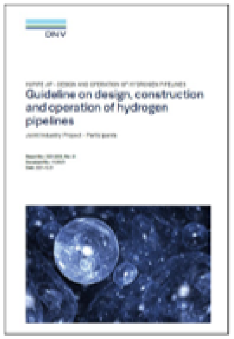


ExxonMobil, test results presented at EFS-2023 Conference, June 2023

Summary

- Significant progress has been made over the last years in understanding of the effects of hydrogen environment on materials resistance to fracture and relevant damage mechanisms
- The focus of H_2 conversion work to date has been onshore. Further challenges are anticipated offshore
- The industry is still awaiting widely recognised guidance for the conversion of subsea pipelines for H_2 service
  - DNV H2Pipe JIP and DNV-ST-F101 supplement to be released in 2025

Phase 1	Phase 2	Phase 3
2021 - 2023	2023 - 2025	2025
1. FMECA	**1. Special Design scenarios considerations**	
2. State-of-the-art	**2. Effect on H2 on crack growth resistance and deformation capacity**	
3. Guideline	**3. Hydrogen Uptake**	
4. Mechanical Testing	**4. Risk Assessment Study**	
5. Running Fracture	**5. Update on Guideline Document**	



wood.