Hydrogen Pipelines Technical Challenges

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Background

- One of the key challenges of transporting hydrogen in steel pipelines is the potential degradation in the fracture toughness and fatigue properties of the pipe steel due to Hydrogen Embrittlement.
- Currently, there are approximately 1,600 miles of hydrogen pipelines in operation in the United States with an excellent safety record.
- Most of the existing hydrogen pipelines in the US share the following features:
  - 20” diameter or less
  - Constructed using API 5L Grade X52 or lower
  - Operate at Design Factors of 0.50 or lower
- There is industry interest in extending hydrogen pipelines to higher grade steel line pipe and higher Design Factors.

ASME B31.12-2019

- ASME B31.12 is the only Code or Standard that covers the design of hydrogen pipelines.
- ASME B31.12 contains two Design Options:

Option A (Prescriptive Design Method)

  - Max Design Factor limited to 0.50 for Class 1 and 2 Locations
  - No Specific Material Qualification Testing required to assess Hydrogen Embrittlement

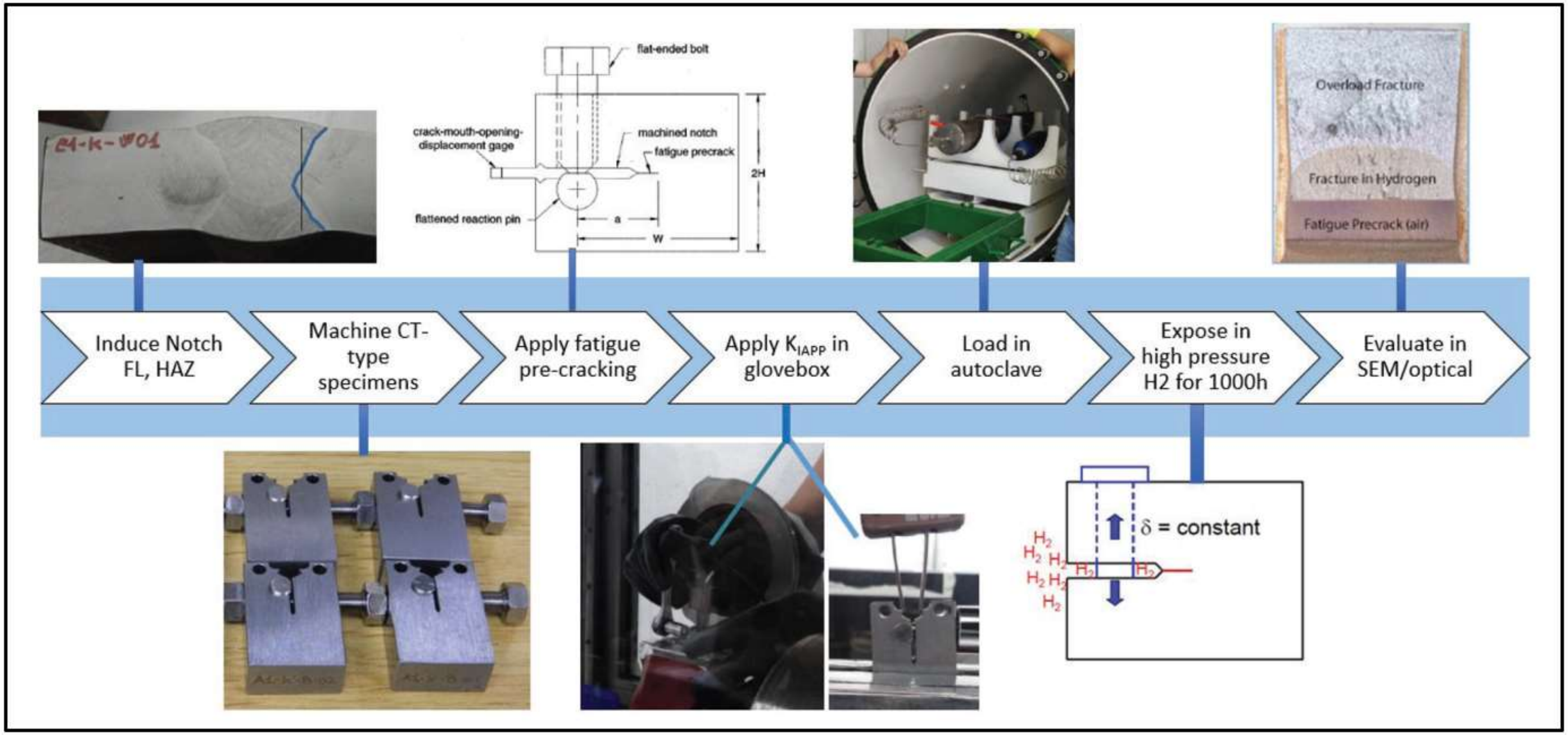
Option B (Performance Based Design Method)

  - Design Factor limited to 0.72 for Class 1 and 2 Locations
  - Specific Material Qualification Testing required to assess Hydrogen Embrittlement
  - The principal requirement is that the material should be qualified to demonstrate adequate resistance to fracture in hydrogen gas at or above the design pressure using the applicable rules of ASME BPVC, Section VIII, Division 3 (3).

ASME B31.12 : Option B

- The Option B Material Qualification Testing determines the threshold toughness (K_{1H}) below which sustained load cracking will not occur in hydrogen service.
    - The minimum measured K_{1H} shall be > 55 MPa√m* or a K value for a t/4 x 1.5t surface flaw at Design Pressure.
- ASME KD-1040 permits testing under both constant load or constant displacement for 42 Days (1,000 hrs).
- If the subcritical crack growth exhibited by the test specimen does not exceed 0.01 in. (0.25 mm), then the material is characterized as suitable for hydrogen service and K_{1H} is determined as follows:
    - Constant Load : $K_{1H} = K_{1APP}$
    - Constant Displacement : $K_{1H} = 50\% \ K_{1APP}$

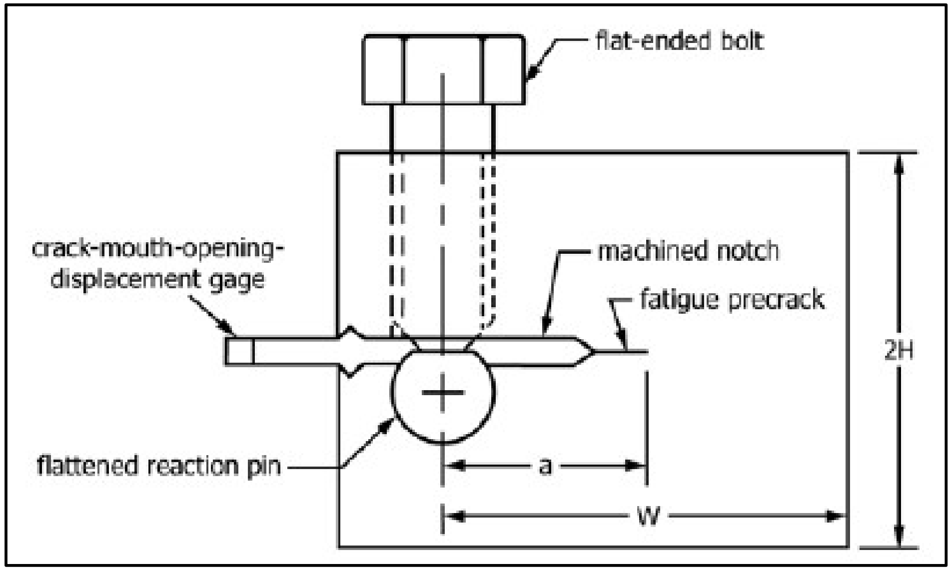
CPW Tests : Constant Displacement



- Induce Notch FL, HAZ
- Machine CT-type specimens
- Apply fatigue pre-cracking
- Apply K_{IAPP} in glovebox
- Load in autoclave
- Expose in high pressure H2 for 1000h
- Evaluate in SEM/optical

Constant Displacement Fracture Tests

- ASTM E1681 / ASME B31.12 / ASME KD-1040



$$K_I = [V_m E / W^{1/2}] f(a/w)$$

$$f(a/W) = [1 - a/W]^{1/2}\,[0.654 - 1.88\,(a/W) + 2.66\,(a/W)^2 - 1.233\,(a/W)^3]$$

This Equation implies that for specimens of the same size the applied K is the same for a given CMOD.

- Preload the CT Specimen and then expose the specimen to a Hydrogen Environment for a Fixed Duration (42 Days).
- Break the specimen open and examine for sub-critical crack growth

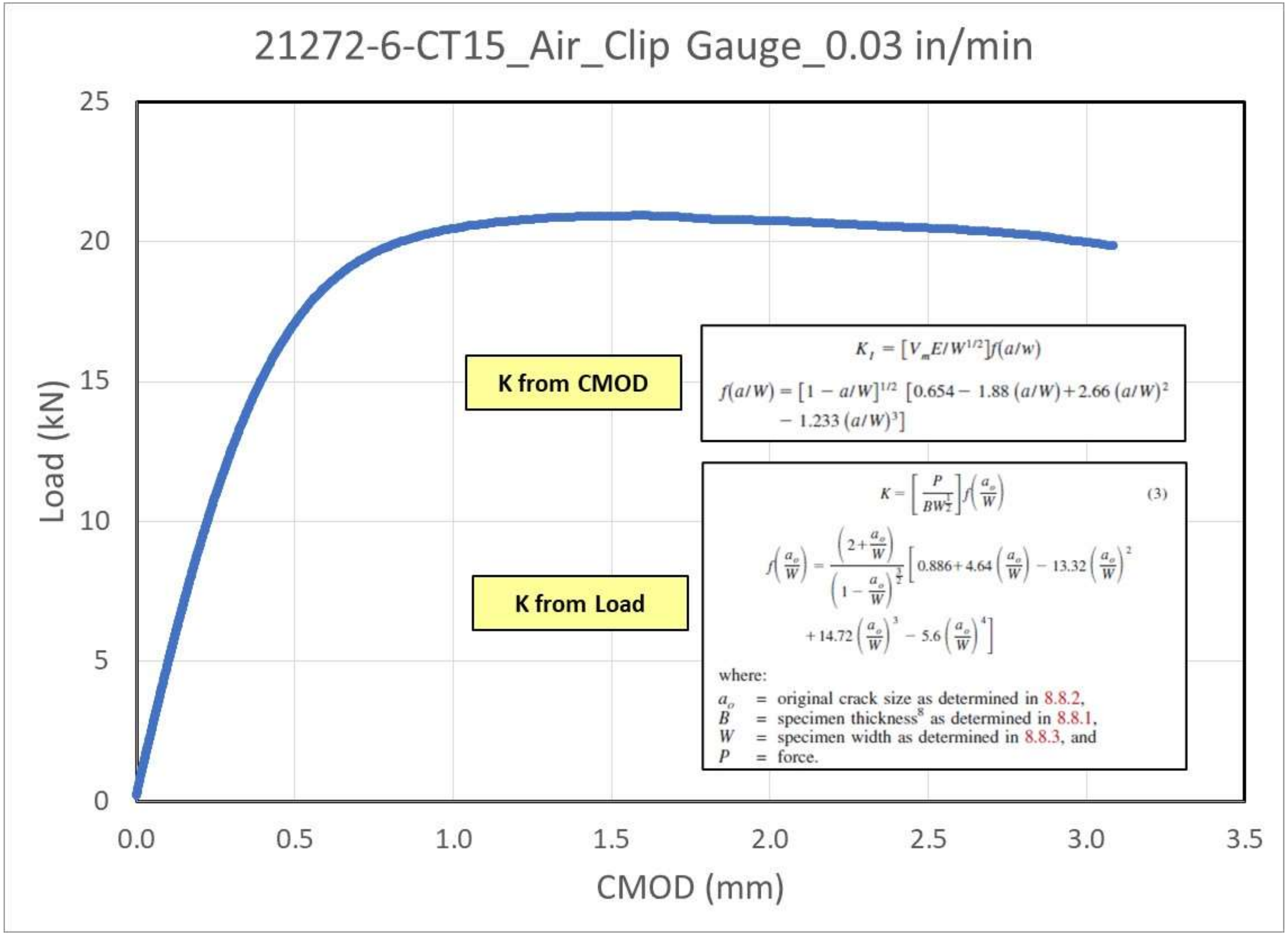
Constant Load Fracture Tests

- ASTM E1681 / ASME B31.12 / ASME KD-1040
  - SENB Specimens
  - Compact Tension (CT) Specimens
- Preload the Specimen and then hold the specimen under Constant Load in a Hydrogen Environment for a Fixed Duration (42 Days).
- Break the specimen open and examine for sub-critical crack growth .

$$K = \left[\frac{P}{BW^{\frac{1}{2}}} \right] f\left(\frac{a_o}{W} \right)$$

This Equation implies that for specimens of the same size the applied K is the same for a given Load.

EWI JIP 1/2T CT (CPW)



K from CMOD

$$K_I = [V_m E / W^{1/2}] f(a/w)$$

$$f(a/W) = [1 - a/W]^{1/2} \, [0.654 - 1.88\,(a/W) + 2.66\,(a/W)^2 - 1.233\,(a/W)^3]$$

K from Load

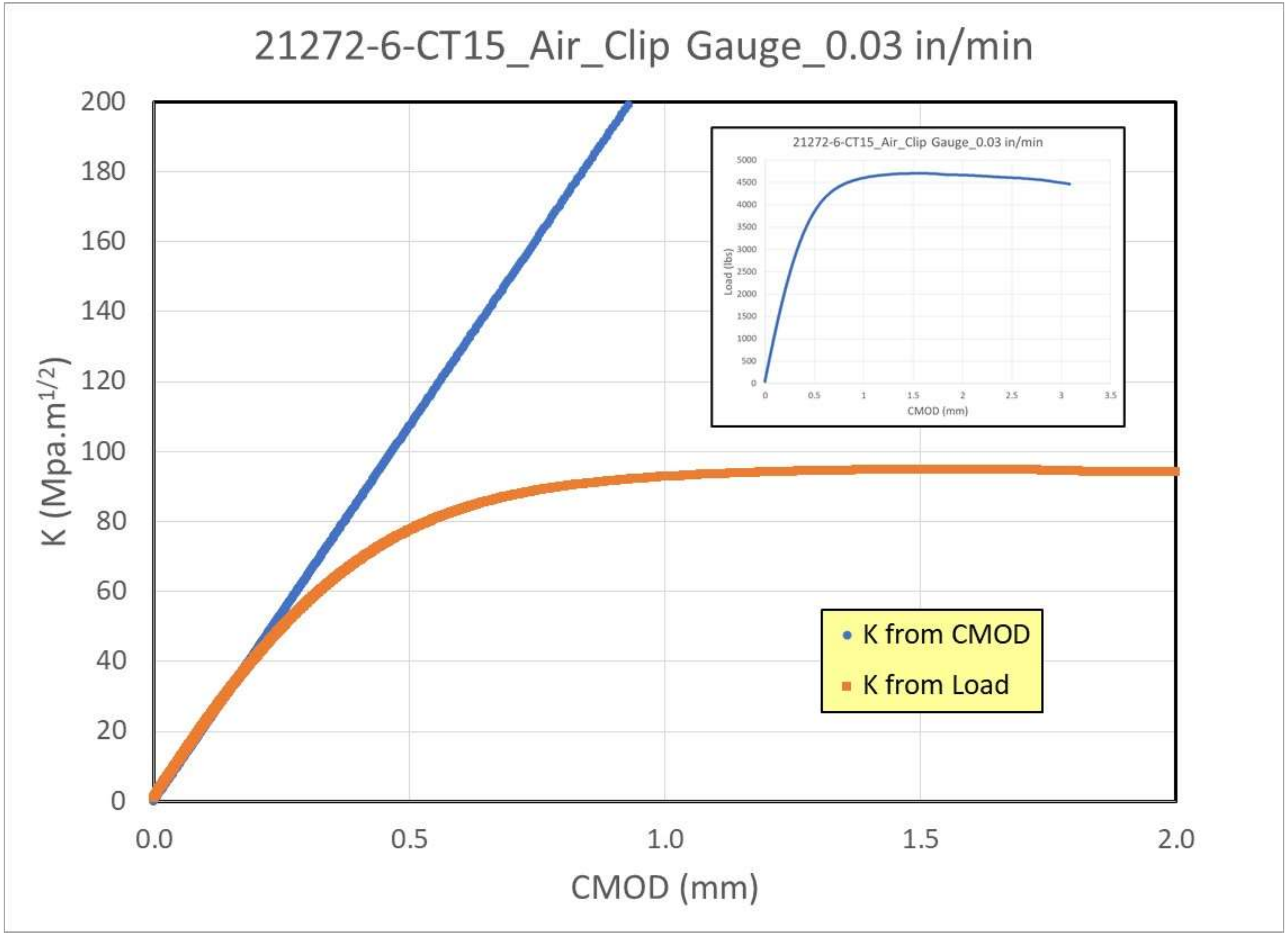
$$K = \left[\frac{P}{BW^{\frac{1}{2}}}\right] f\left(\frac{a_o}{W}\right) \qquad (3)$$

$$f\left(\frac{a_o}{W}\right) = \frac{\left(2+\frac{a_o}{W}\right)}{\left(1-\frac{a_o}{W}\right)^{\frac{3}{2}}}\left[0.886 + 4.64\left(\frac{a_o}{W}\right) - 13.32\left(\frac{a_o}{W}\right)^2 + 14.72\left(\frac{a_o}{W}\right)^3 - 5.6\left(\frac{a_o}{W}\right)^4\right]$$

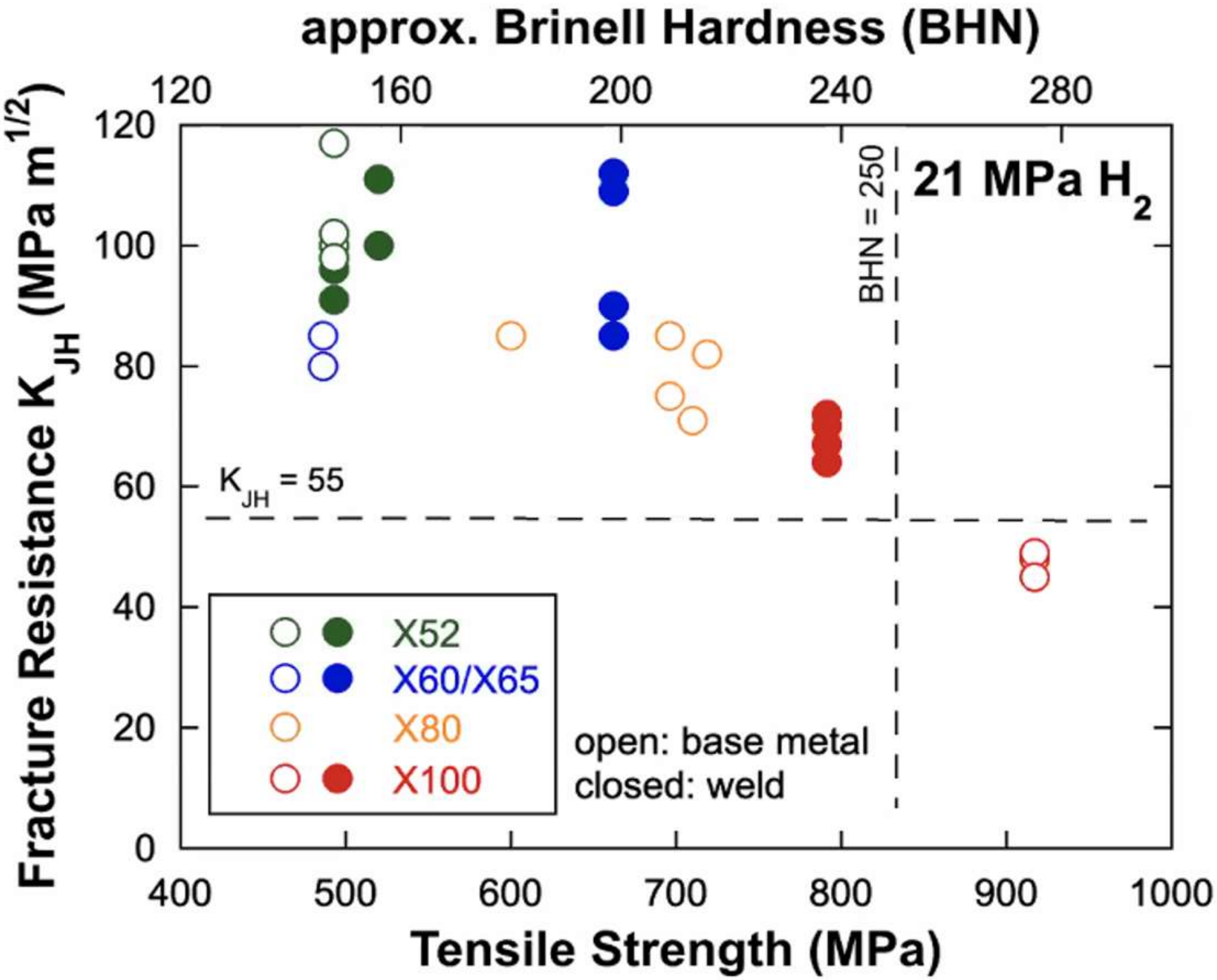
where:

a_o = original crack size as determined in 8.8.2,
B = specimen thickness[8] as determined in 8.8.1,
W = specimen width as determined in 8.8.3, and
P = force.

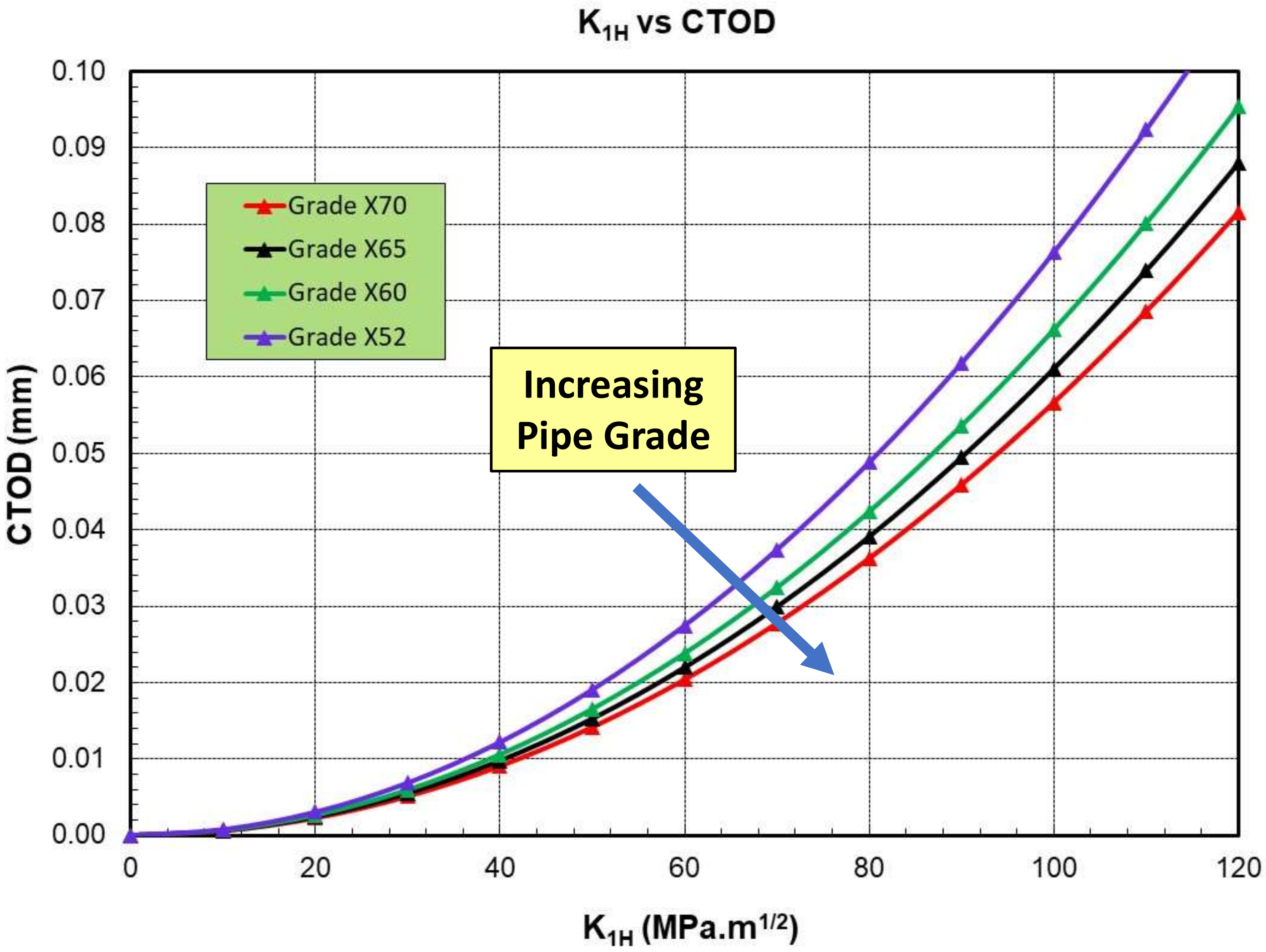
K from CMOD vs K from Load



HyBlend Project : Slow Rising Load



K_{1H} vs CTOD



- Appendix A of API 1104 requires CTOD values ≥ 0.050 mm before an Engineering Critical Assessment (ECA) can be performed.

Desktop Study

Determine the feasibility of constructing Hydrogen Pipelines from higher grade linepipe and operating Hydrogen Pipelines at higher Design Factors.

- The Desktop Study considered both pipe seam welds and girth welds.
- Most research on Hydrogen Pipelines has focused on pipe seam weld performance.
- Concerns that girth weld performance is more limiting than seam welds due to:
  - Higher Allowable Stress
  - Increased potential for flaws in girth welds

Analysis Matrix

- The study determined the K_{1H} toughness requirements for the following Design Options:

Parameter	Range
Pipe Grades	X52, X60 and X70
Pipe Diameters	24, 36 and 48”
Design Factors	0.50, 0.60 and 0.72
Longitudinal Stress	50, 60, 70, 80 and 90% SMYS
Internal Pressure	1,440 psi (9.93 MPa)

Target Flaw Sizes

- Determine K_{1H} requirements for the following flaw sizes:
  - Seam Welds : 3 x 25 mm and 5 x 50 mm
  - Girth Welds : 3 x 50 mm and 5 x 50 mm

- Original Pipe Manufacture (as per API 5L PSL2)
  - 1.5 x 10 mm : Max Flaw Size that may escape detection
- Seam Welds
  - 3 x 25 mm : Low Fatigue Demand
  - 5 x 50 mm : High Fatigue Demand
- Girth Welds
  - 3 x 50 mm : API 1104 Workmanship
  - 5 x 50 mm : Target ECA Flaw Acceptance Criteria

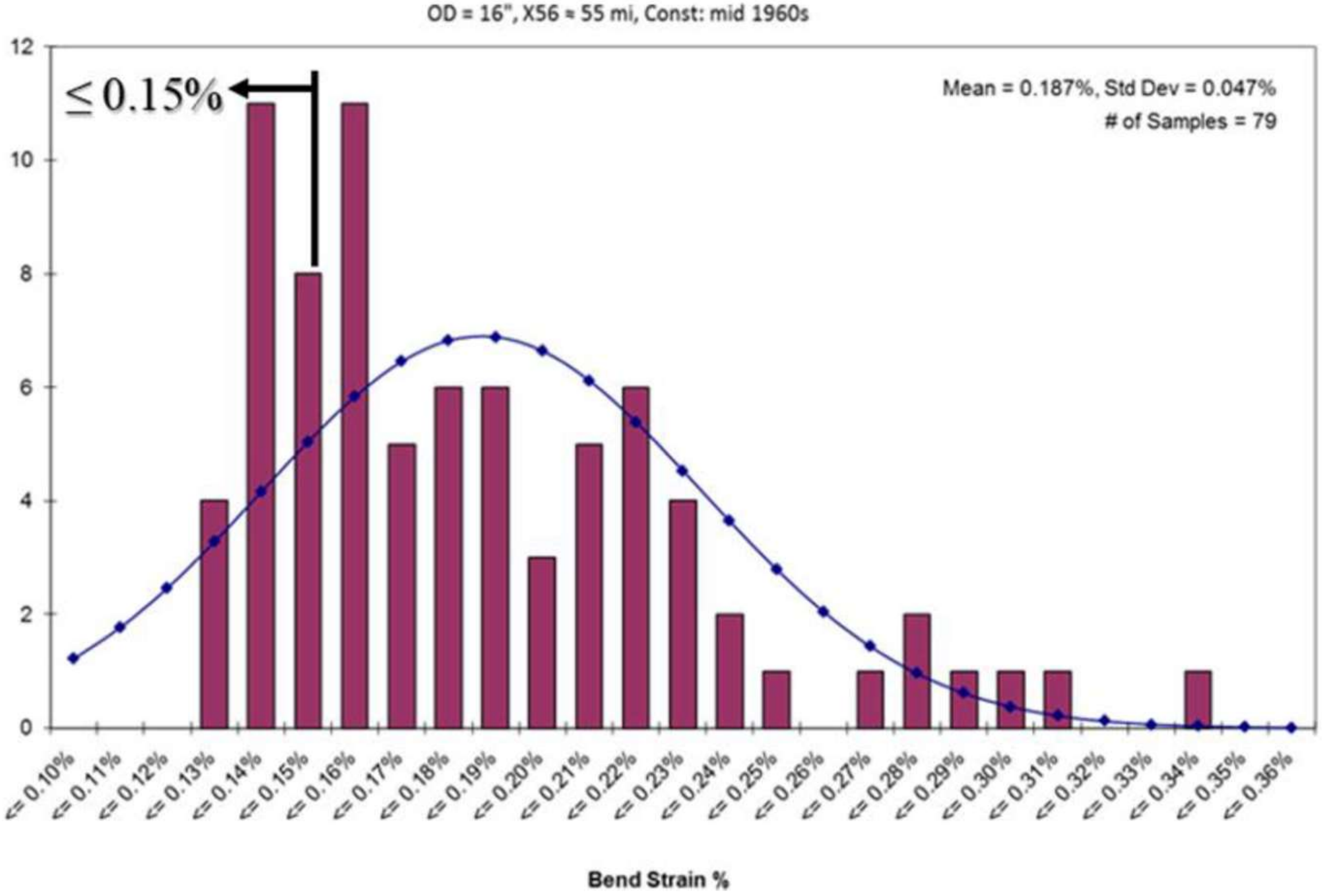
ECA Procedures

- Seam Welds
  - BS 7910 Fracture Analysis (Option 2)
  - Internal Surface Flaws
  - Specified Min Tensile Properties
  - No Residual Stress
  - No Fatigue Loading (Can be significant for seam welds)
- Girth Welds
  - API 1104 Appendix A
  - Surface Flaws
  - Specified Min Tensile Properties
  - No Residual Stress
  - No Fatigue Loading (Generally not significant)

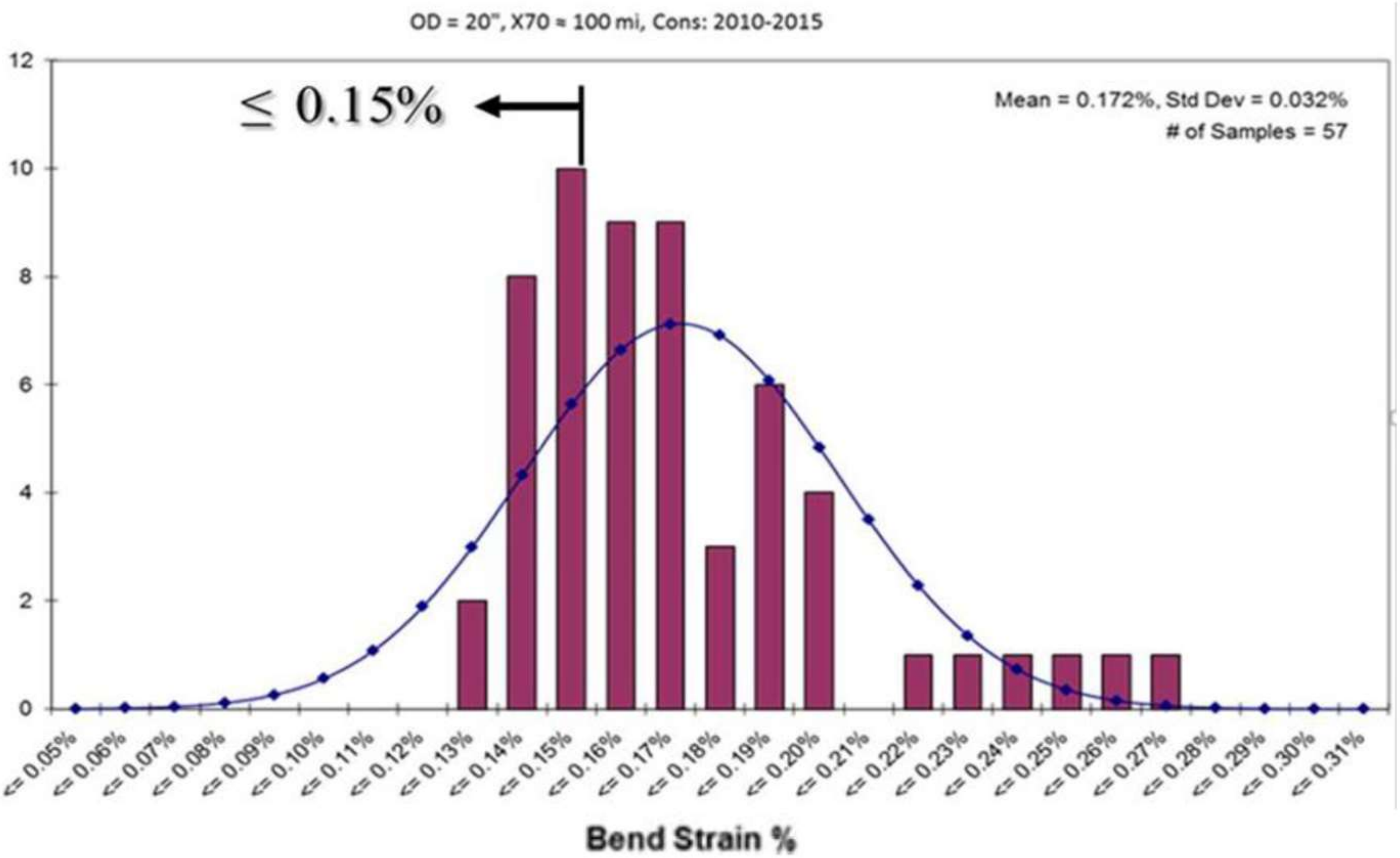
Longitudinal Strain

- Although longitudinal stresses in pipelines are generally less that 50 – 60 % SMYS, recent pipeline surveys using Inertial Measurement Units (IMUs) have confirmed that longitudinal stresses up to 90% SMYS (Bending Strains in the range 0.28 – 0.34%) can occur at isolated locations.
- The trend to inspect pipelines with IMU tools follows a number of low strain girth weld failures in Grade X70 pipelines in the USA over the last 10 years.

IMU Results : 16” X56 (1960s)



IMU Results : 20” X70 (2010 - 2015)



Seam Weld Results

Seam Weld ECA Results

Internal Pressure
1,440 psig (9.93 Mpa)

Low Fatigue Demand

Grade X70 : 3 x 25 mm

OD (inch)	Design Factor		
	0.50	0.60	0.72
24	🟩	🟩	🟩
36	🟩	🟩	🟩
42	🟩	🟩	🟩
48	🟩	🟩	🟩

Grade X60 : 3 x 25 mm

OD (inch)	Design Factor		
	0.50	0.60	0.72
24	🟩	🟩	🟩
36	🟩	🟩	🟩
42	🟩	🟩	🟩
48	🟩	🟩	🟩

Grade X52 : 3 x 25 mm

OD (inch)	Design Factor		
	0.50	0.60	0.72
24	🟩	🟩	🟩
36	🟩	🟩	🟩
42	🟩	🟩	🟩
48	🟩	🟩	🟩

Color	K_{1H}
🟩	< 65 MPa√m
🟧	65 - 100 MPa√m
🟥	> 100 MPa√m

High Fatigue Demand

Grade X70 : 5 x 50 mm

OD (inch)	Design Factor		
	0.50	0.60	0.72
24	🟩	🟧	🟥
36	🟩	🟩	🟧
42	🟩	🟩	🟧
48	🟩	🟩	🟧

Grade X60 : 5 x 50 mm

OD (inch)	Design Factor		
	0.50	0.60	0.72
24	🟩	🟩	🟧
36	🟩	🟩	🟧
42	🟩	🟩	🟩
48	🟩	🟩	🟩

Grade X52 : 5 x 50 mm

OD (inch)	Design Factor		
	0.50	0.60	0.72
24	🟩	🟩	🟧
36	🟩	🟩	🟩
42	🟩	🟩	🟩
48	🟩	🟩	🟩

Girth Weld Results

Girth Weld ECA Results

K_{1H} Requirements based on an Axial Stress = 90% SMYS

Grade X70 : 3 x 50 mm

OD (inch)	Design Factor		
	0.50	**0.60**	**0.72**
24	🟧	🟧	🟥
30	🟧	🟧	🟧
36	🟧	🟧	🟧
42	🟧	🟧	🟧
48	🟧	🟧	🟧

Grade X60 : 3 x 50 mm

OD (inch)	Design Factor		
	0.50	**0.60**	**0.72**
24	🟩	🟩	🟩
30	🟩	🟩	🟩
36	🟩	🟩	🟩
42	🟩	🟩	🟩
48	🟩	🟩	🟩

Grade X52 : 3 x 50 mm

OD (inch)	Design Factor		
	0.50	**0.60**	**0.72**
24	🟩	🟩	🟩
30	🟩	🟩	🟩
36	🟩	🟩	🟩
42	🟩	🟩	🟩
48	🟩	🟩	🟩

API 1104 Workmanship

Color	**K_{1H}**
🟩	< 65 MPa√m
🟧	65 - 100 MPa√m
🟥	> 100 MPa√m

Grade X70 : 5 x 50 mm

OD (inch)	Design Factor		
	0.50	**0.60**	**0.72**
24	🟥	🟥	🟥
30	🟥	🟥	🟥
36	🟥	🟥	🟥
42	🟥	🟥	🟥
48	🟧	🟥	🟥

Grade X60 : 5 x 50 mm

OD (inch)	Design Factor		
	0.50	**0.60**	**0.72**
24	🟧	🟧	🟧
30	🟧	🟧	🟧
36	🟧	🟧	🟧
42	🟧	🟧	🟧
48	🟧	🟧	🟧

Grade X52 : 5 x 50 mm

OD (inch)	Design Factor		
	0.50	**0.60**	**0.72**
24	🟩	🟩	🟧
30	🟩	🟩	🟩
36	🟩	🟩	🟩
42	🟩	🟩	🟩
48	🟩	🟩	🟩

ECA Flaw Criteria

Conclusions

- Existing Hydrogen Pipelines operating in the USA have a high margin of safety.
    - Diameter ≤ 20”
    - Pipe Grade ≤ API 5L X52
    - Design Factor ≤ 0.50
- Girth weld performance may be more critical than seam weld performance for new pipelines unless the pipeline experiences large fatigue demand.
- There is scope to move to Higher Pipe Grades (up to Grade X70), larger Pipe Diameters and increased Design Factors but the toughness requirements start to become increasingly demanding.
- Work is required to optimize & standardize fracture toughness test procedures and develop a fracture toughness database for steel in hydrogen service
- It is important to evaluate new Hydrogen pipeline designs to ensure there is an adequate margin of safety.