# Current and Future Challenges in the Pipeline Industry


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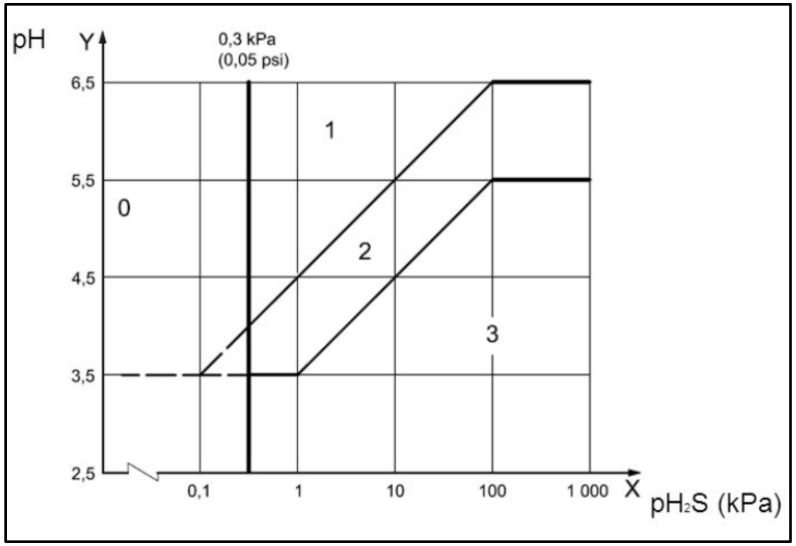
# Presentation Outline

1) Sour Service Pipelines
2) Hydrogen Pipelines
3) $CO_2$ Pipelines

# Sour Service Considerations

- A sour environment is defined as an environment that contains moisture and hydrogen sulfide ($H_2S$).
- Pipelines operating in wet Sour Service ($H_2S$) are susceptible to both:
  - Environmental cracking (SSC & HIC) and
  - Degradation in mechanical properties (Toughness and Fatigue)
- The NACE domain diagram can be used to evaluate the severity of a sour environment with respect to SSC of carbon or low-alloy steel, in terms of pH and $pH_2S$.
- Low pH and high $pH_2S$ represent the most severe sour conditions.

# Sour Service Considerations




- **Region 0 conditions are considered to be non-sour despite low levels of H2S**
- **Region 1 conditions are considered to be mildly sour.**
- **Region 2 is a transition region**
- **Region 3 represents the most severe sour conditions.**
- **SSC can occur in regions 1 to 3.**

- NACE defines an $H_2S$ partial pressure limit (0.3 kPa or 0.05 psia) above which steel chemistry and hardness controls are required to mitigate SSC.
- Although SSC is not a threat at $pH_2S$ levels below 0.05 psia degradation in mechanical properties can occur at $pH_2S$ levels below 0.05 psia

# Sour Service Considerations

- In addition to SSC or HIC, Pipelines that operate in wet $H_2S$ sour service environments can suffer:
    - General Corrosion
    - Hydrogen Diffusion / Hydrogen Embrittlement
- The combination of corrosion and hydrogen embrittlement can impact mechanical properties and must be accounted for in Design
- Since corrosion and hydrogen diffusion are time dependent processes the properties of steel in a sour environment are not only a function of the environment (**pH, pH2S, Inhibitor, Temp** etc.**)** but also **Loading Rates** or **Loading Frequencies.**

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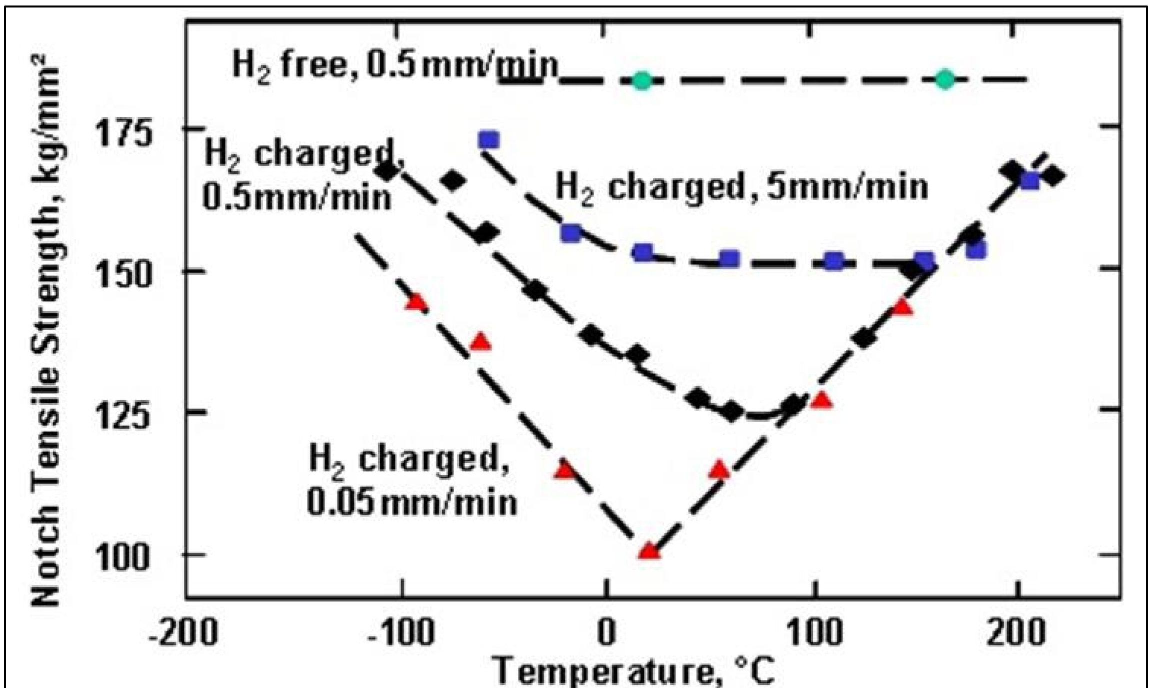
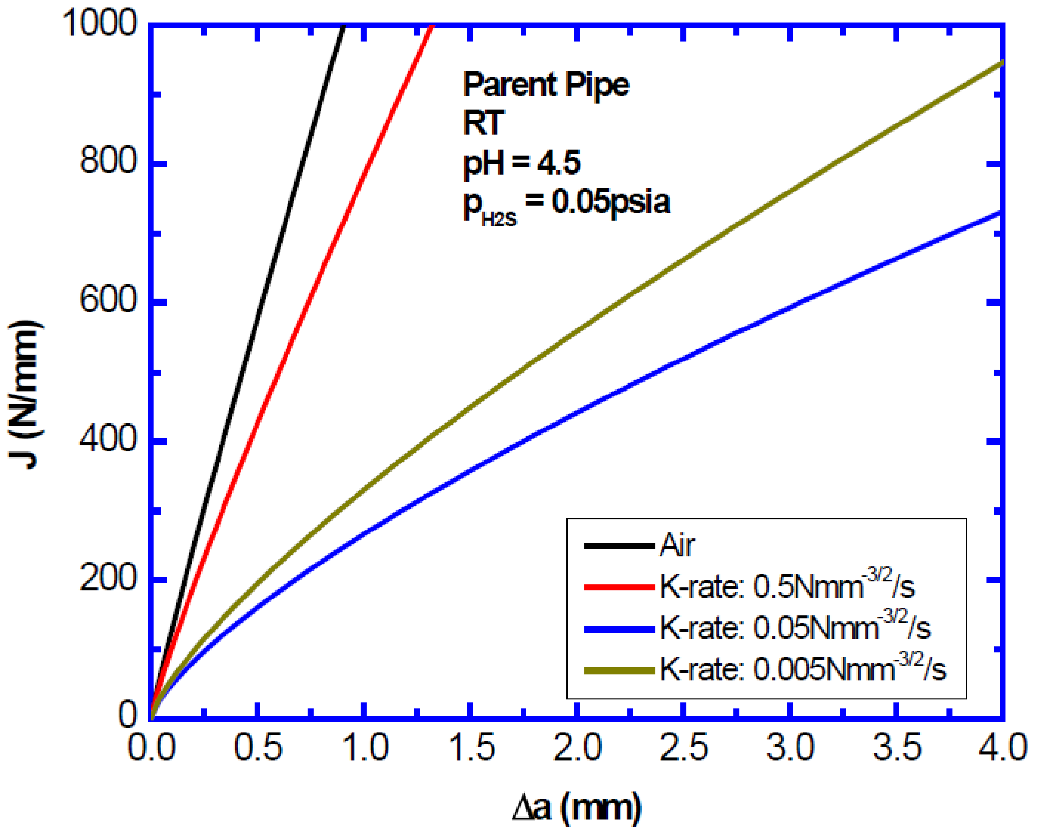
# Hydrogen Embrittlement (HE)

- In addition to Hydrogen Concentration, HE is a Function of Test Temperature and Loading Rate as shown below by data generated by Graville (1967).

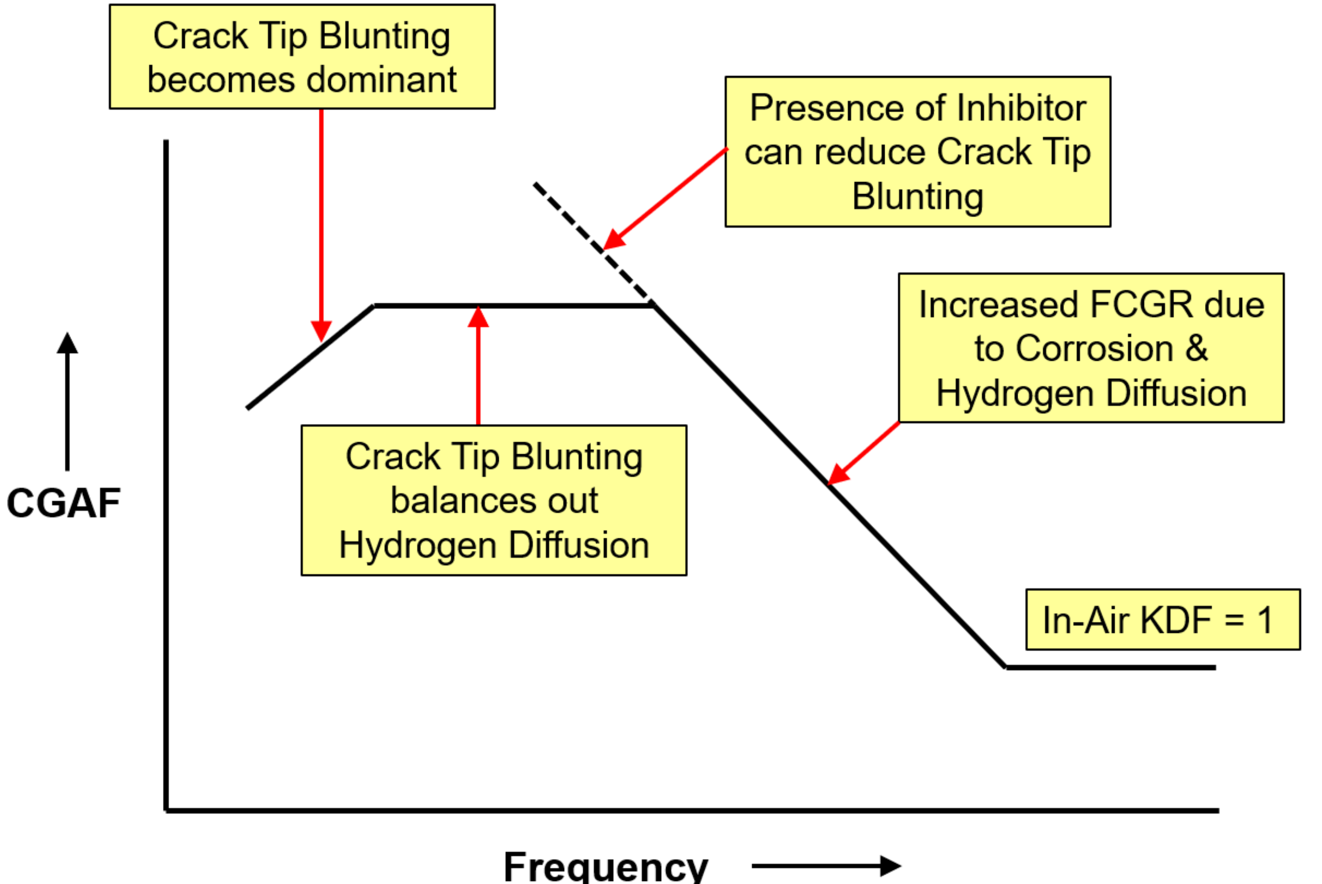


# Sour Service Fracture Toughness

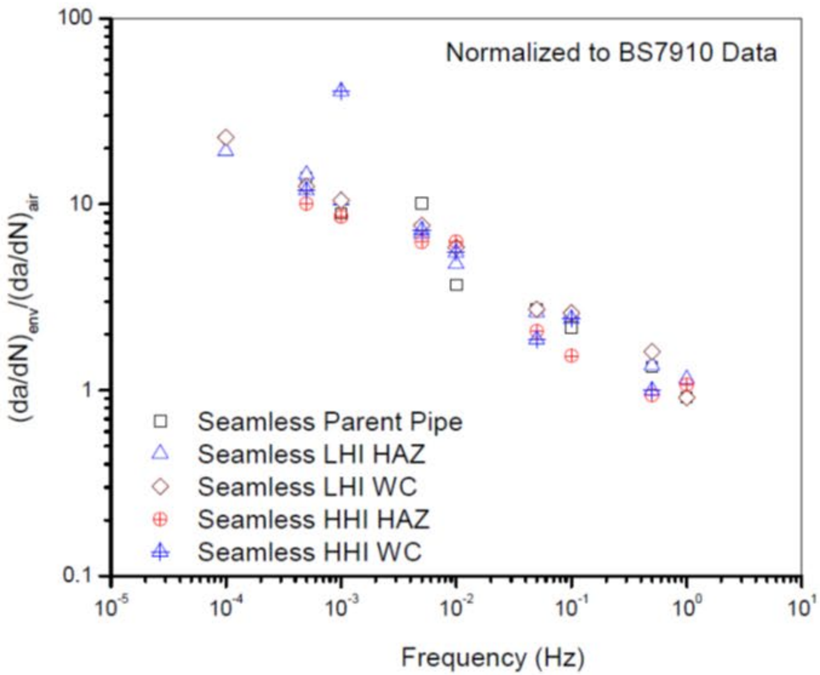


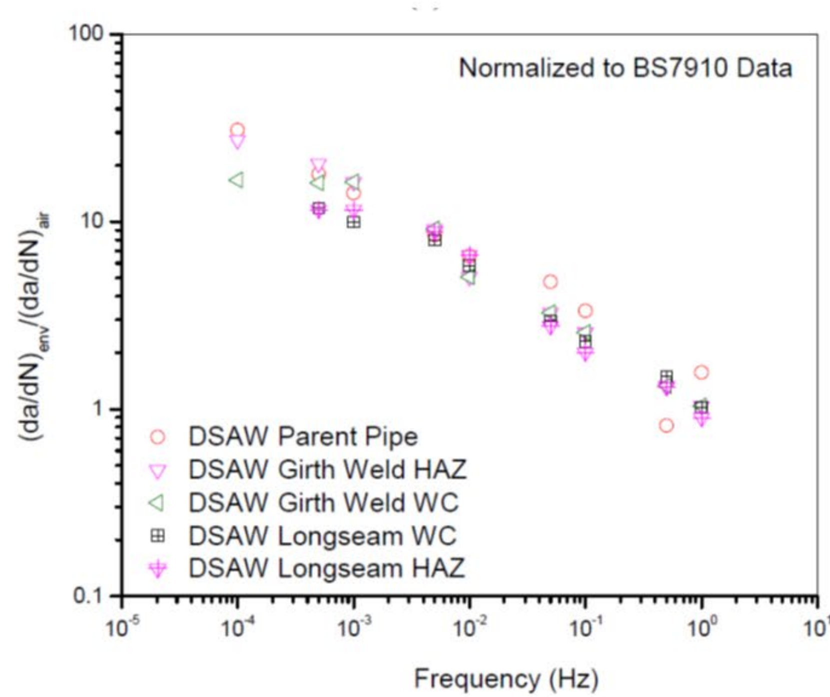

- Unlike In-Air Fracture Toughness Tests that take a few minutes to perform Sour Service Fracture Toughness Tests can take 1 – 2 weeks to perform.

# Effect of Loading Frequency on Fatigue



# Sour Service FCGR Test Data




- In Moderate to Severe Sour Service the Properties tend to become a function of the Environment (Level Playing Field).

# Sour Service : Summary

- In addition to mitigating SSC it is Important to account for Sour Service degradation in Fracture Toughness and Fatigue.
- Test Programs should be performed at appropriate Loading Rates / Loading Frequencies.
- Test Programs can take months to complete.
- Need to leverage existing data to develop provisional sour service properties and perform Limited Tests to validate results.

# Hydrogen Pipelines

- Hydrogen pipelines are NOT new!!
- There are approximately 1,600 miles of hydrogen pipelines currently being operating 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

# Hydrogen Pipelines

- Just like Pipelines that operate in Sour $H_2S$ Service, Hydrogen Pipelines are also susceptible to Hydrogen Embrittlement.
  - Reduced Ductility
  - Reduced Material Toughness
  - Reduced Fatigue Performance
- Hydrogen embrittlement occurs when atomic hydrogen is absorbed into the steel.
- Hydrogen migrates to regions of high stress or local plastic deformation.

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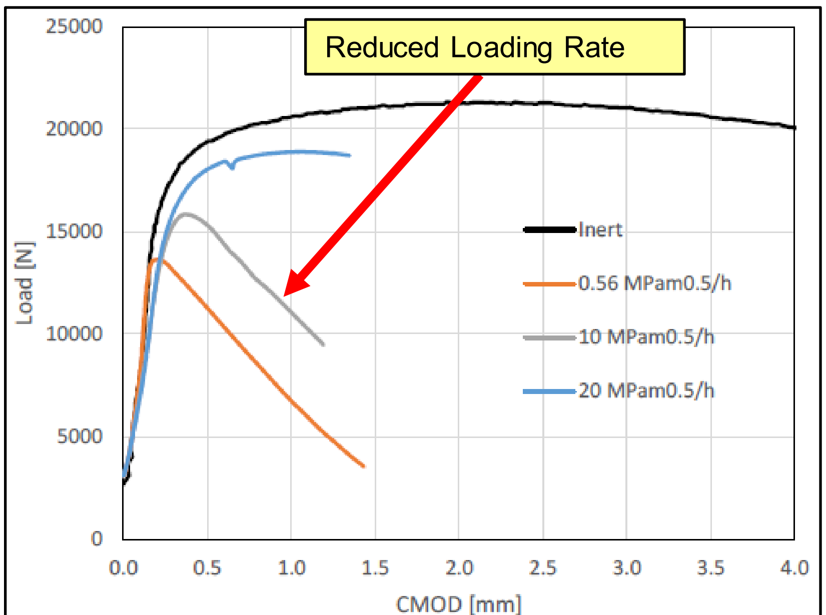
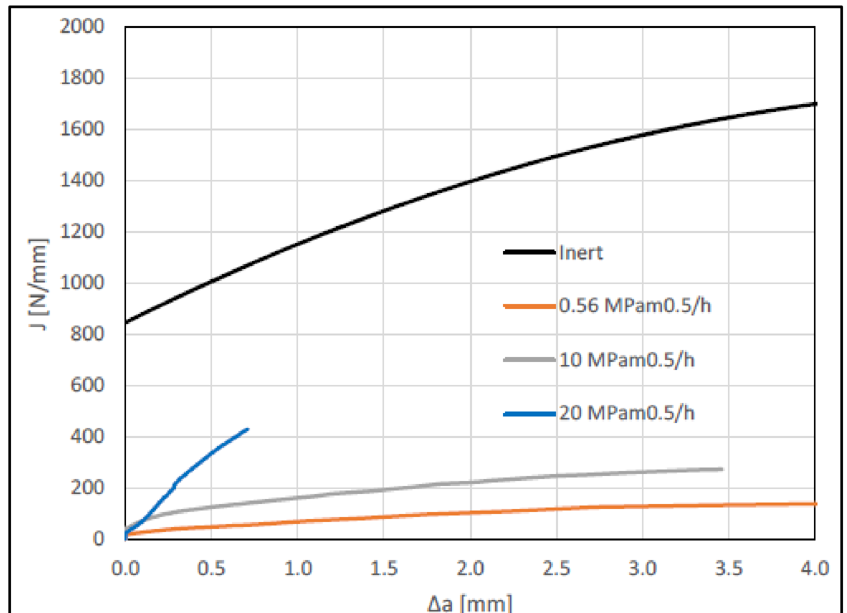
# Hydrogen Embrittlement (DNV JIP)

- Fracture Toughness Tests performed in a Hydrogen Environment also exhibit a Loading Rate dependence.

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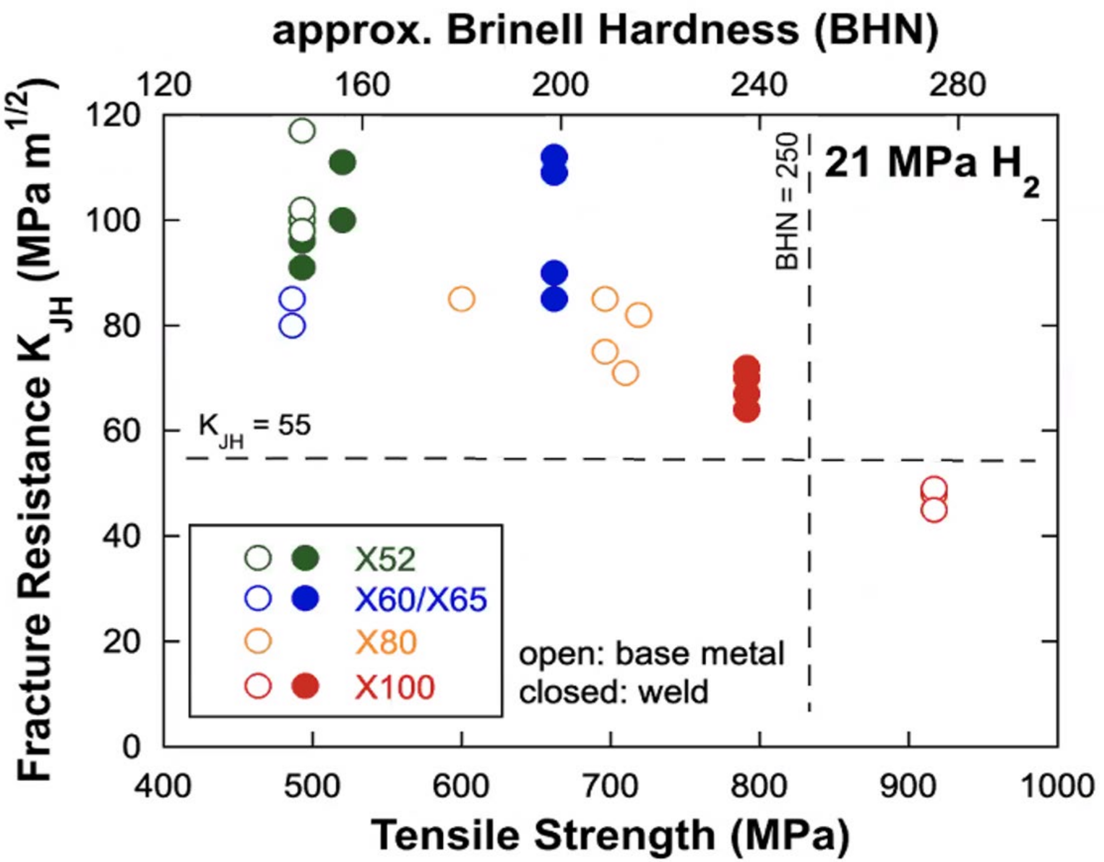
# HyBlend Project : Slow Rising Load

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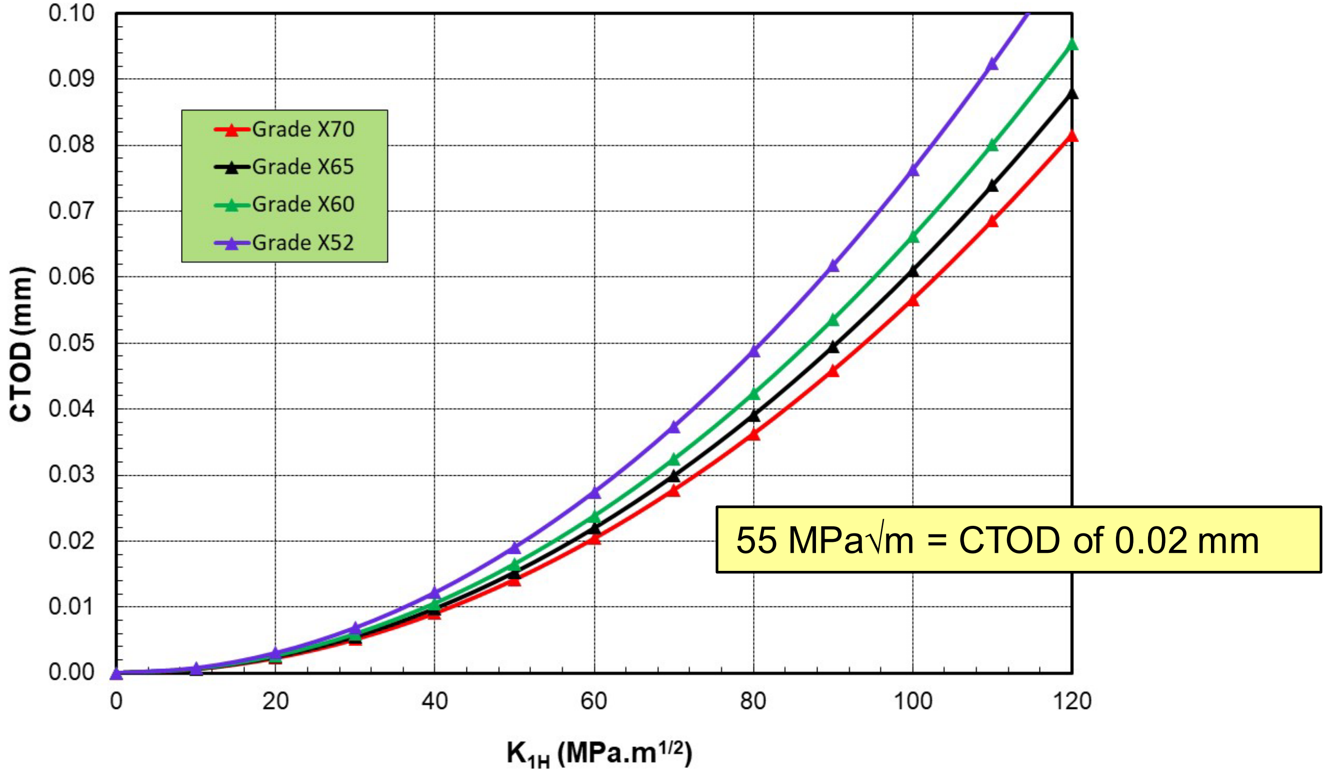
# $K_{1H}$ vs CTOD




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

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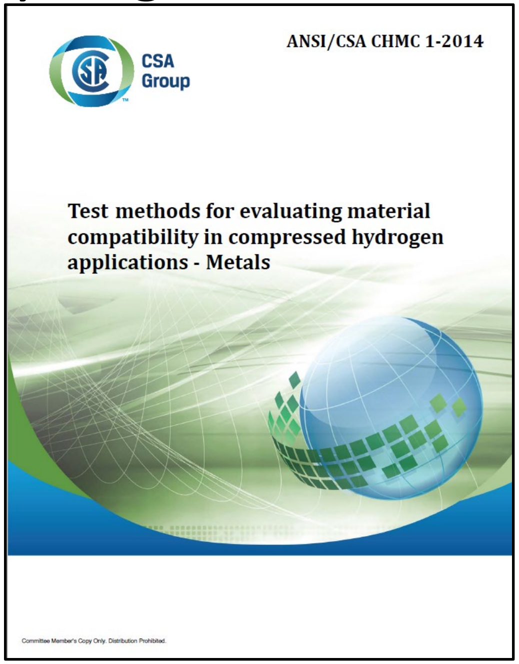
# Hydrogen Fracture Toughness Test Methods

1) ASME B31.12 – 2019 " Hydrogen Piping and Pipelines"
   - Constant Load or Constant Displacement Tests
2) ANSI / CSA CHMC 1-2014, "Test methods for Evaluating Material Compatibility in Compressed Hydrogen Applications – Metals"
   - Slow Rising Load Tests

**ASME B31.12**

- ASME B31.12 Procedure originally developed for Heavy Wall Pressure vessels.
- It is not suited for Pipeline Applications
- Many Pipe Mills are currently using ASME B31.12 to verify that their pipe is qualified for Hydrogen Service



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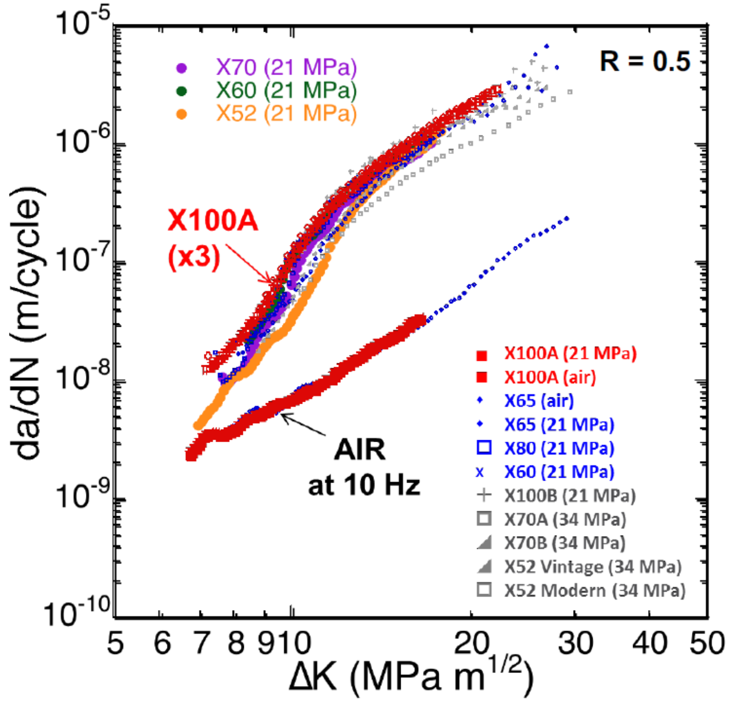
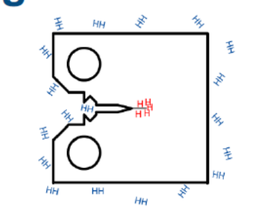
# Hydrogen Pipelines : Fatigue




- A wide variety of pipeline steels display nominally the same fatigue response in high-pressure gaseous hydrogen
- The effect of pressure on fatigue crack growth rates is modest for high-pressure hydrogen



Crack Growth Acceleration Factor (CGAF) can vary from 5 (low Δσ) to 30-50 (high Δσ)

Low partial pressure of hydrogen has nominally same effect as pure hydrogen on pipeline steels

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# $CO_2$ Pipelines : Major Challenges

- Corrosion Control
  - Material Selection
  - Avoid Water drop Out during Operation
- Fracture Control
  - $CO_2$ Decompression
  - Saturation Pressure
- There are currently 5,300 miles of $CO_2$ pipelines in the U.S., but in the next few decades, that number is predicted to grow to more than 65,000 miles.
- The expected growth in $CO_2$ pipelines is tied to a nationwide push for more carbon capture and storage (CCS) to reduce green-house gases.

# Fracture Control

- The main objective of a Fracture Control Plan is to develop the material toughness requirements that are necessary to ensure that:

1) **Brittle fracture will not occur under normal operating conditions.**
2) **The pipeline has adequate resistance to fracture initiation (rupture).**
3) **In the unlikely event of a pipeline rupture fast ductile (tearing) fracture will be arrested.**

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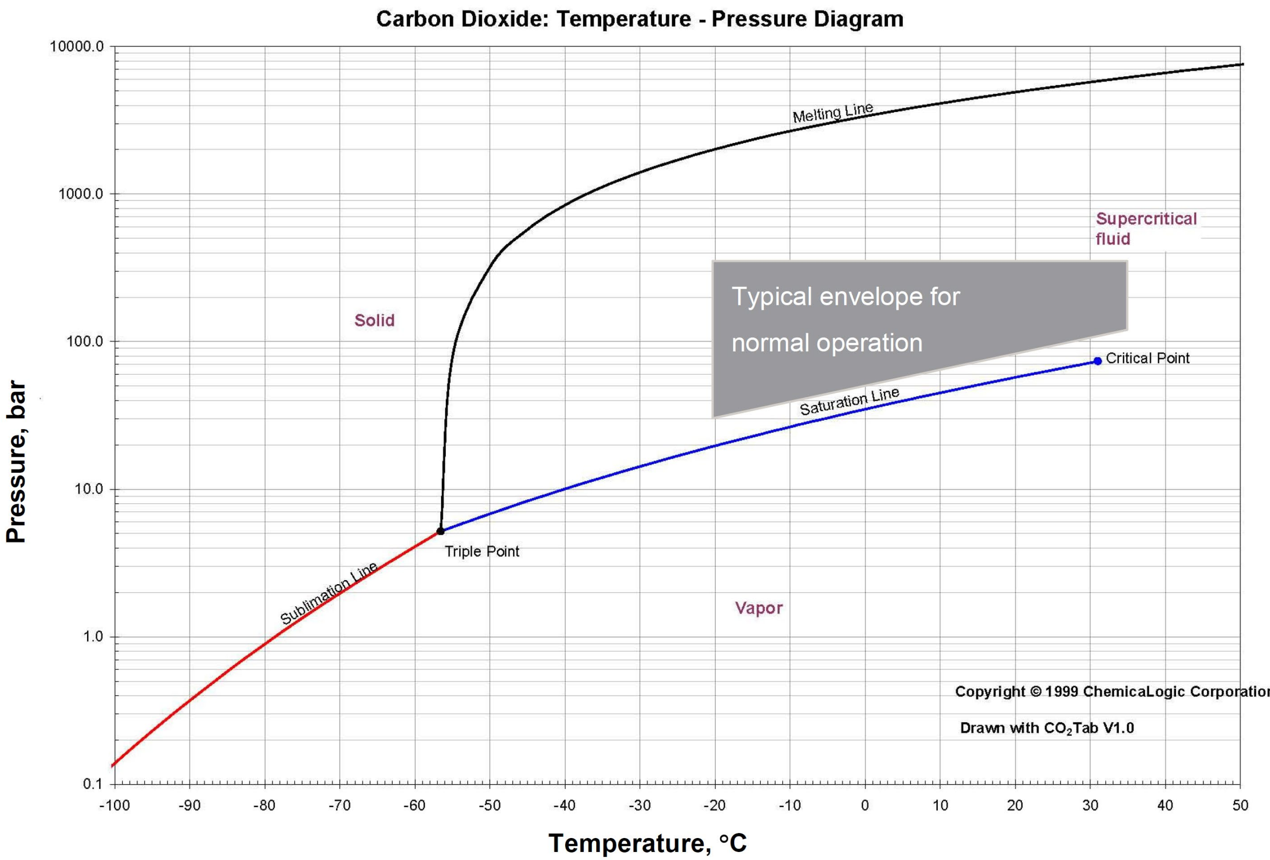
# $CO_2$ Phase Diagram




**1,440 psi approx 100 bar**

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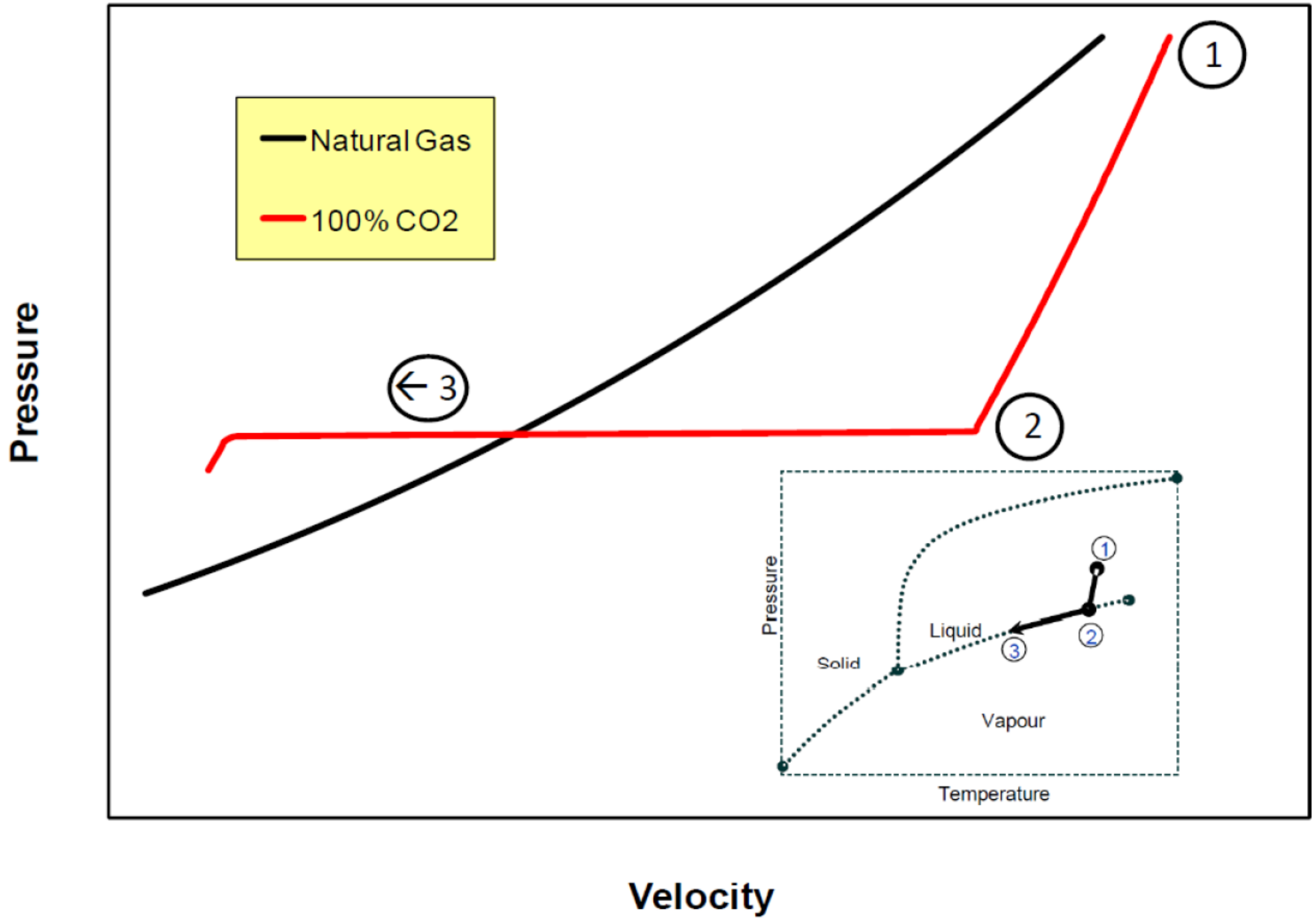
# $CO_2$ Decompression



# $CO_2$ Pipelines

- In the case of $CO_2$ pipelines, the saturation pressure is the key parameter that defines the toughness required to arrest a running fracture.
- Fracture arrest can be assessed by simply comparing the "Arrest Pressure" with the "$CO_2$ Saturation Pressure".
- Fracture arrest is guaranteed if the Arrest Pressure is higher than the Saturation pressure.
- If Fracture Arrest is NOT guaranteed then Crack Arrestors are required to ensure Fracture Control.

# Natural Gas vs $CO_2$ Pipelines

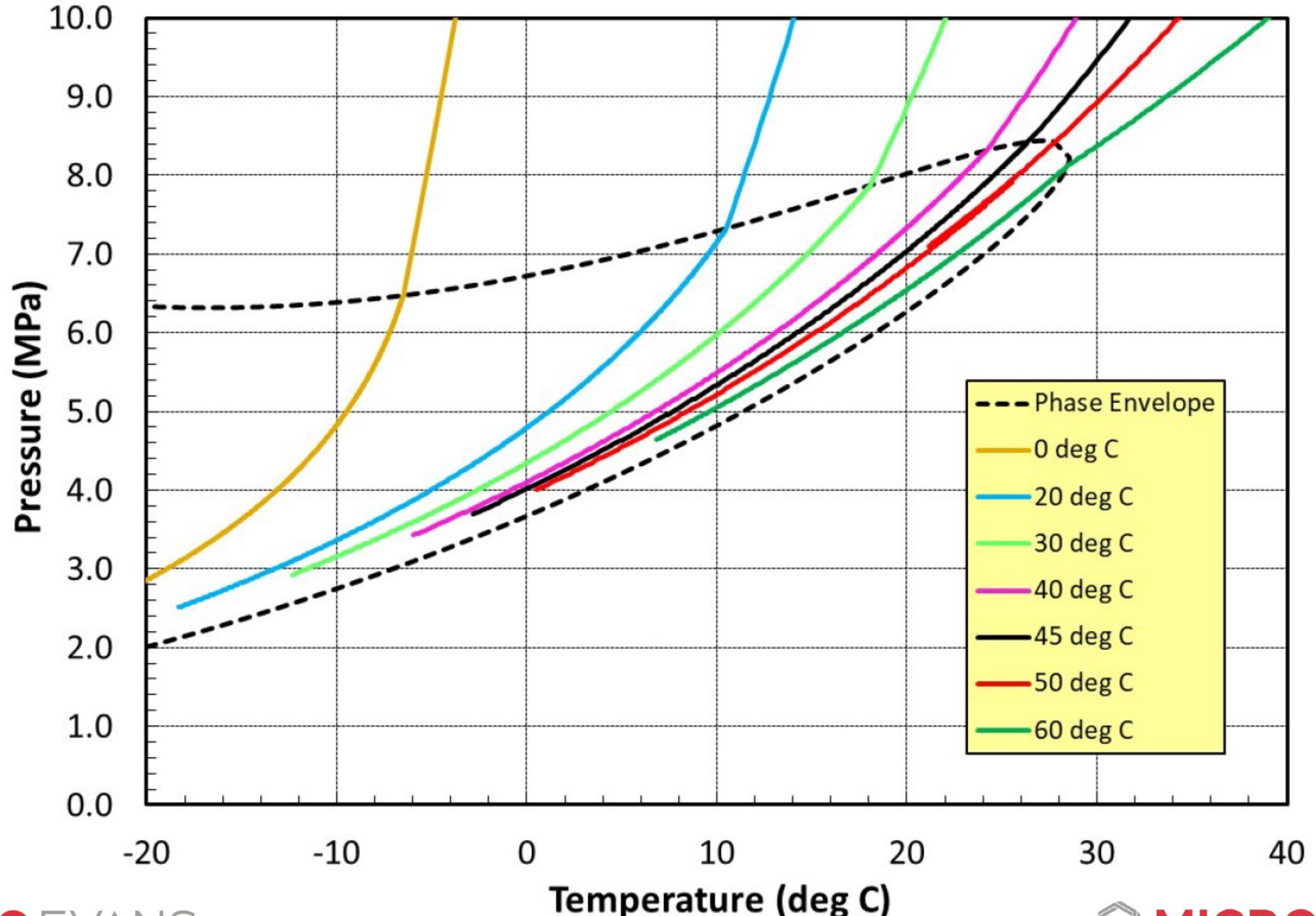
## Natural gas (CH4) pipelines

- The Worst Case Decompression response is at the Lowest Operating Temperature.

## Dense Phase CO2 pipelines

- The Worst Case Decompression response generally occurs at the Maximum Operating Temperature (downstream of Compressor Stations).
- $CO_2$ pipelines that operate in the gas or vapor phase can exhibit different trends.

# Phase Envelope and Decompression



# $CO_2$ Decompression Behavior

- The Decompression response and Saturation Pressure of CO2 Pipelines is very dependent on:
  - Gas Composition (Impurities)
  - Gas Temperature
  - Pressure
- Impurities like $N_2$, $H_2$ or $CH_4$ can significantly increase Saturation Pressure.
- Modelling the Gas Decompression behavior requires specialist computer programs.
- GasDecom (most widely used decompression program) can be unstable when analyzing very rich gas mixtures or $CO_2$ mixtures.  Furthermore, GasDecom can't handle gas mixtures containing $H_{2,}$ $O_2$ and $H_2S$.

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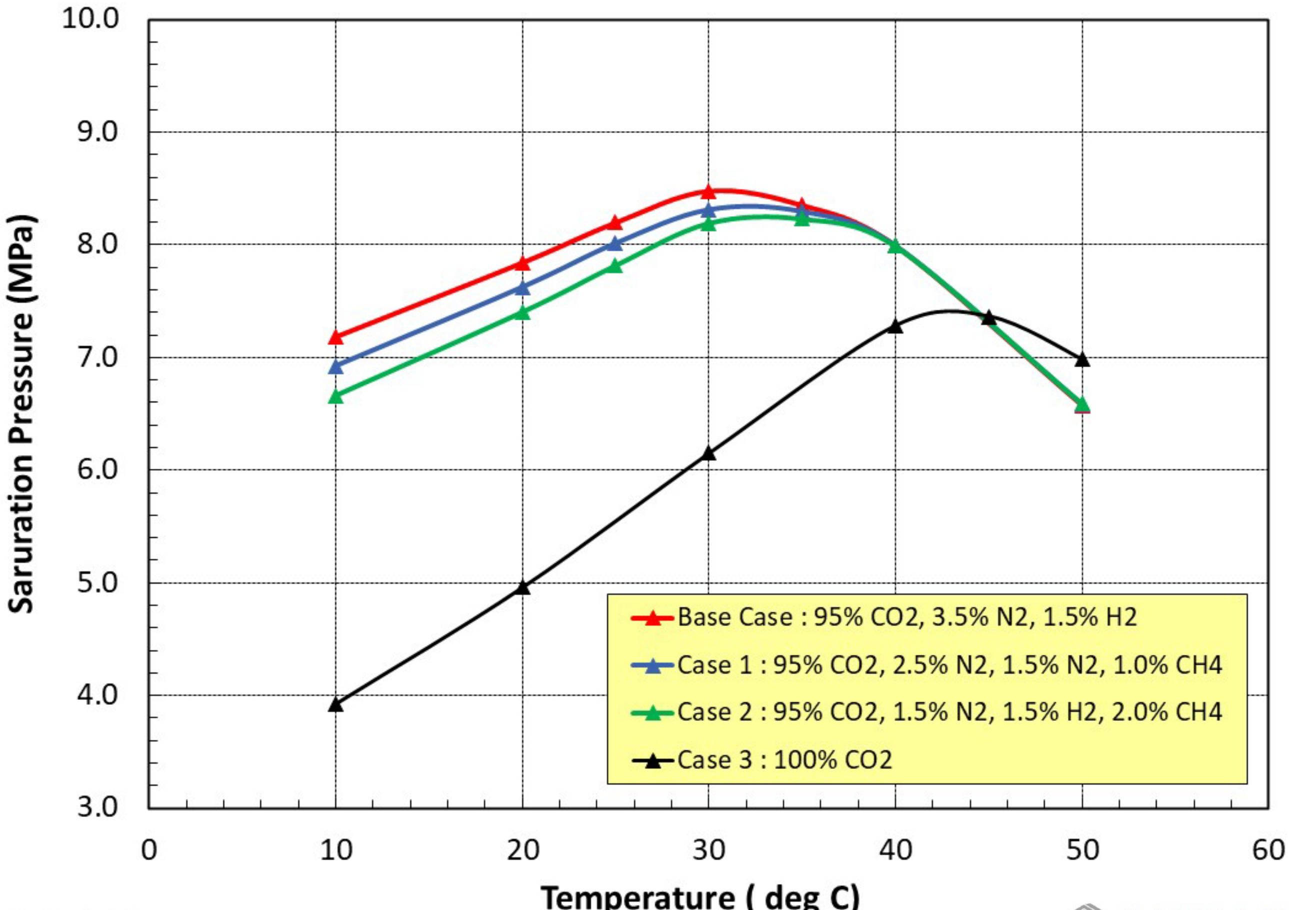
# Saturation Pressure vs Temperature

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# Fracture Control : Pipeline Design

- It is important to determine the $CO_2$ decompression response (particularly the saturation pressure) over the full range of operating pressure and temperature.
- The $CO_2$ gas composition (including impurities) and the pipeline operating conditions need to be well defined at the early stages of the design, so that the implications for achieving fracture propagation control can be addressed.
- In most cases (with planning during Pipeline Design) Fracture Control can be guaranteed with modest Charpy Toughness (e.g., < 150 J) for Pipe Diameters up to 24”.

# Summary

- Sour Service, Hydrogen and CO2 Pipelines present different Technical Challenges.
  - Corrosion Performance
  - Fracture Toughness
  - Fatigue Performance
  - Fracture Control
- It is important that Pipelines are designed to account for the challenges and materials / welding procedures are suitably qualified.
- Test Programs can take extended time periods and are expensive, so it is important to leverage existing Programs and Test Results wherever possible.

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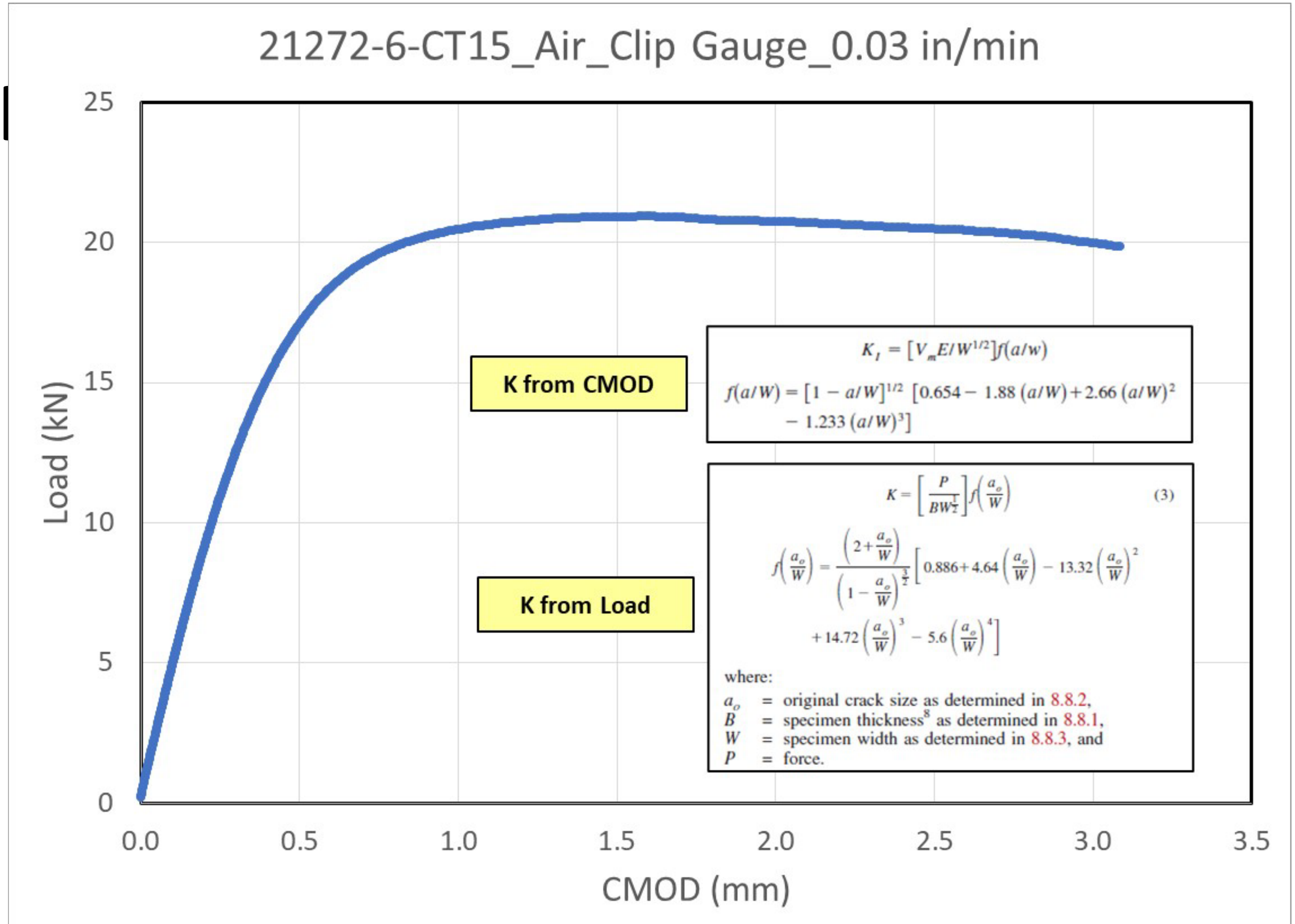

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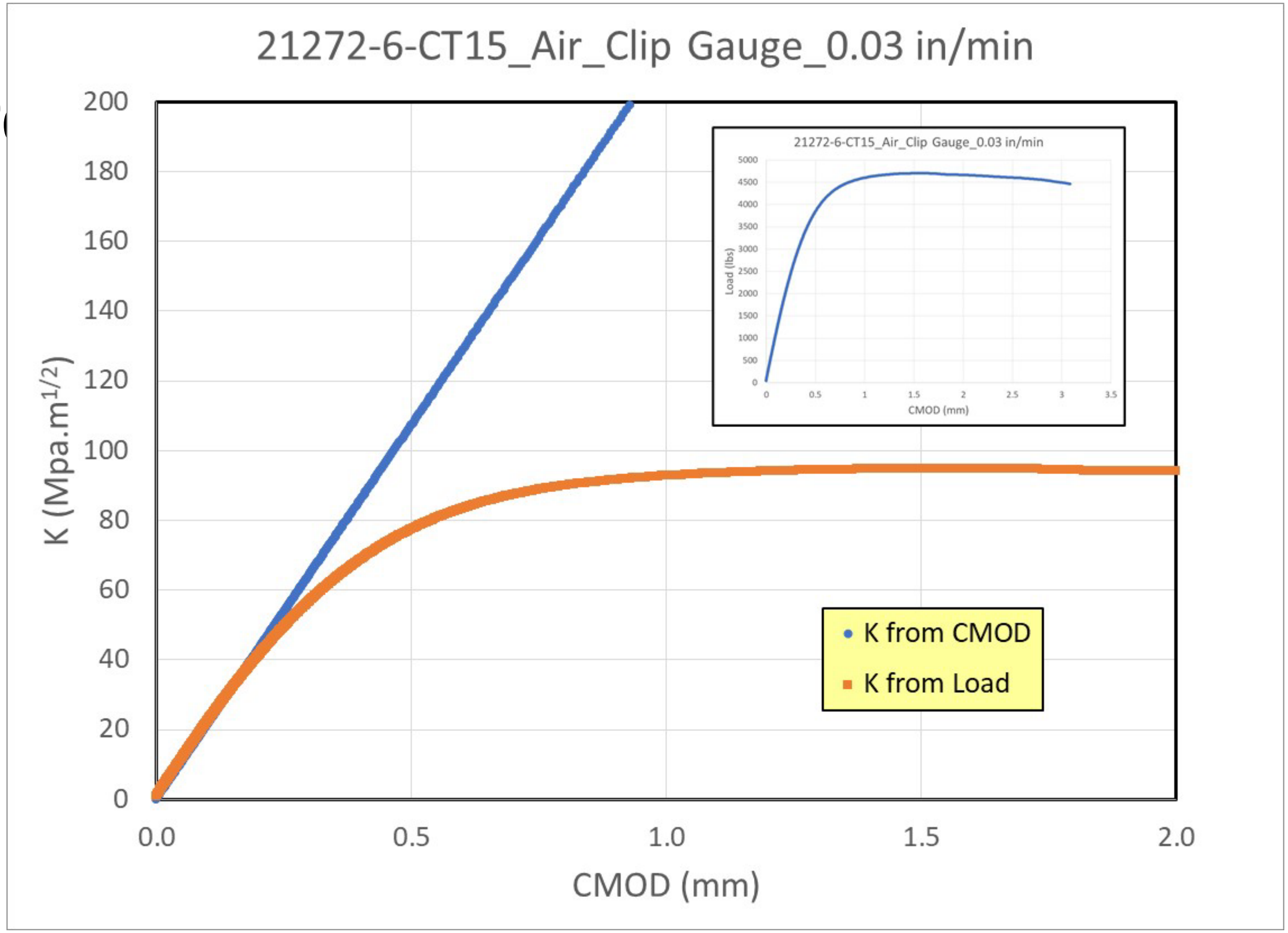

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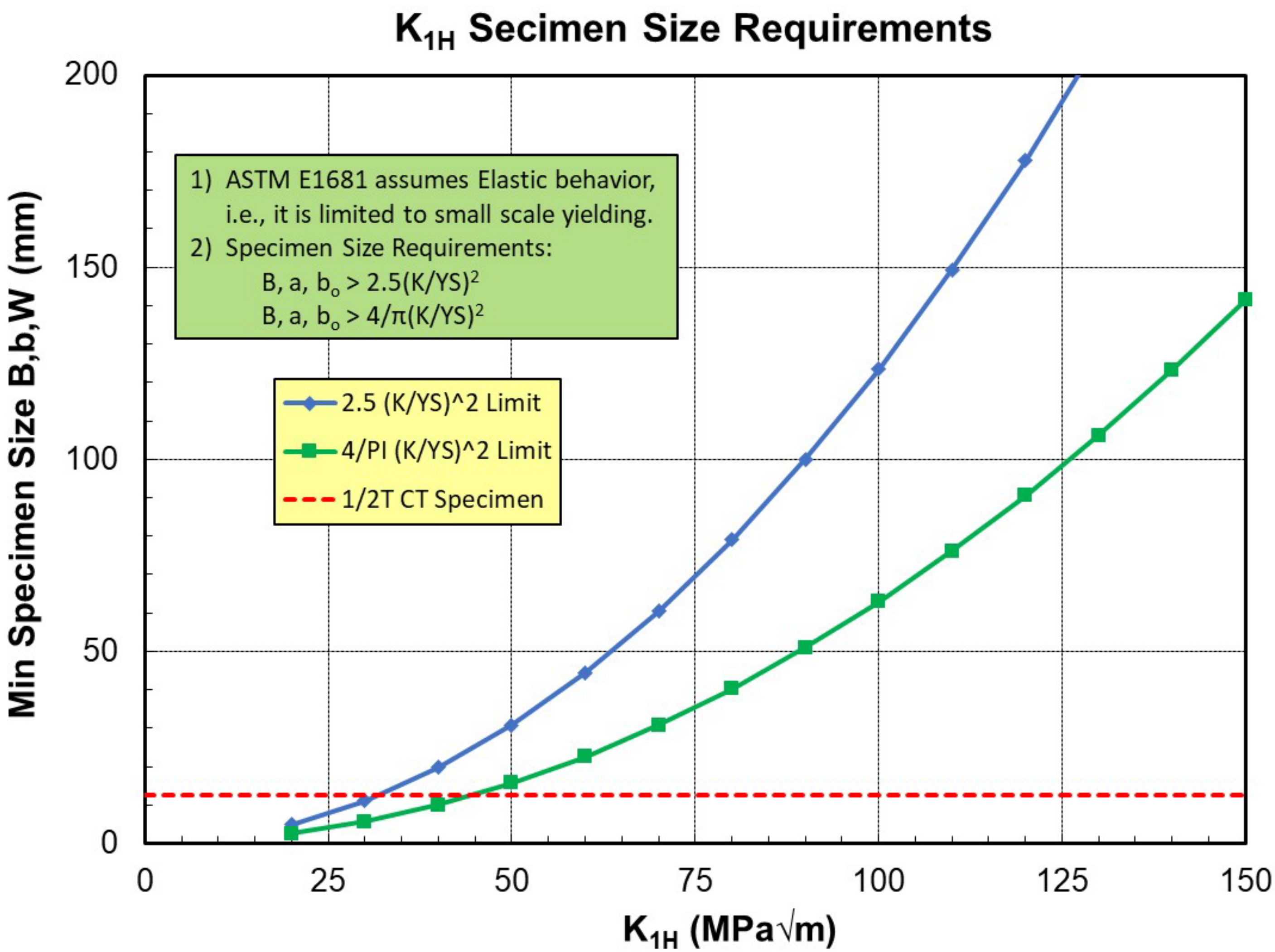

# ASME B31.12 – 2019 : Summary

Although the Fracture Toughness Test Procedures recommended in ASME B31.12 may be well suited for Heavy Wall pressure vessel applications they are not appropriate for hydrogen pipelines (Thinner Wall).

The ASME B31.12 Test Procedures can be used to rank materials and demonstrate hydrogen compatibility, but the values derived from these tests have limited applicability for hydrogen pipelines.

The ASME B31.12 Fracture Toughness Guidelines need to be updated to reflect Best Practice.

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# ANSI / CSA CHMC 1-2014

The Fracture Toughness Test Procedure in ANSI / CSA CHMC 1-2014 is much closer to Best Practice.

- Slow Rising Load Tests (0.1 – 1.0 MPa√m/minute)
- Underlying Standard ASTM E1820 (J / CTOD)
- CT or SENB Specimens
- Initiation Toughness defined as $J_{0.2/BL}$ or $CTOD_{0.2/BL}$

ANSI / CSA CHMC 1-2014 also provides excellent guidance on:

- Hydrogen Gas Purity Requirements