Better Standards, Better Life

International Conference on Hydrogen Safety
September 13, 2017, Hamburg, Germany

Compatibility and Suitability of Existing Steel Pipelines for Transport of Hydrogen-Natural Gas Blends

U.B. Baek and S.H. Nahm
Korea Research Institute of Standards and Science
W.S. Kim
Korea Gas Corporation
J.A. Ronevich and C. San Marchi
Sandia National Laboratories

KRISS 한국표준과학연구원 Sandia National Laboratories

Outline

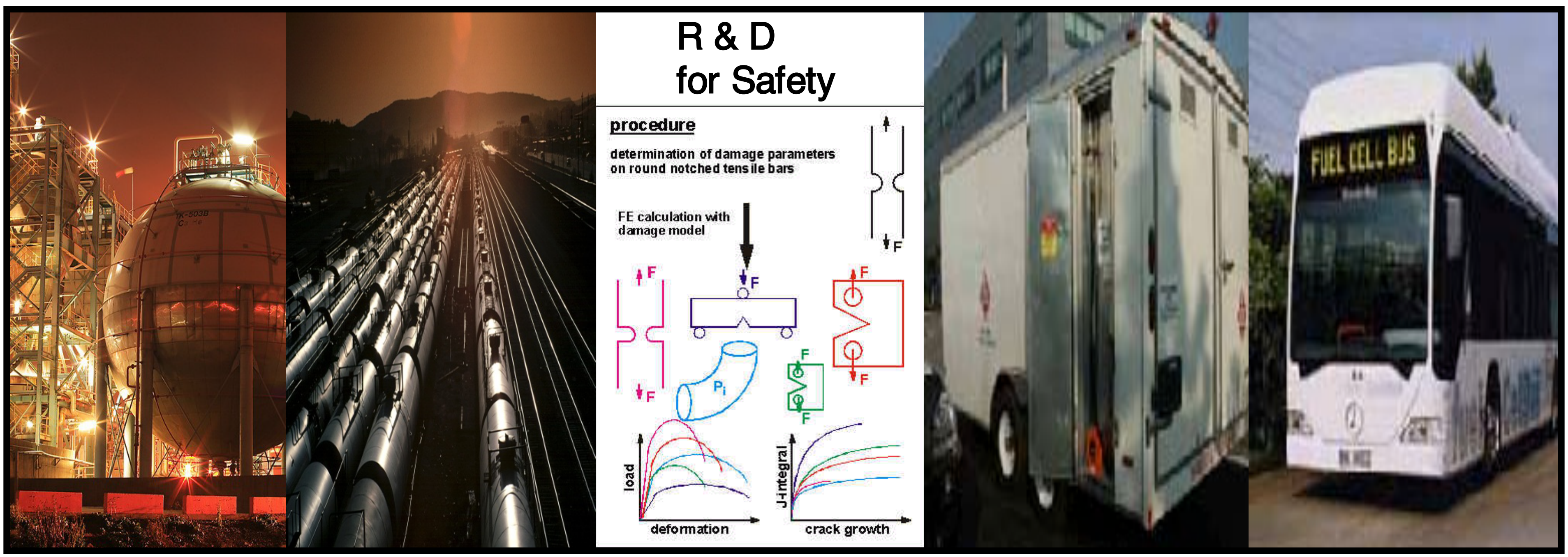
1. Background
2. Overview of fracture mechanics based assessment
3. Representative fatigue and fracture data measured in hydrogen
4. Example life calculations based on idealized cracks

Background

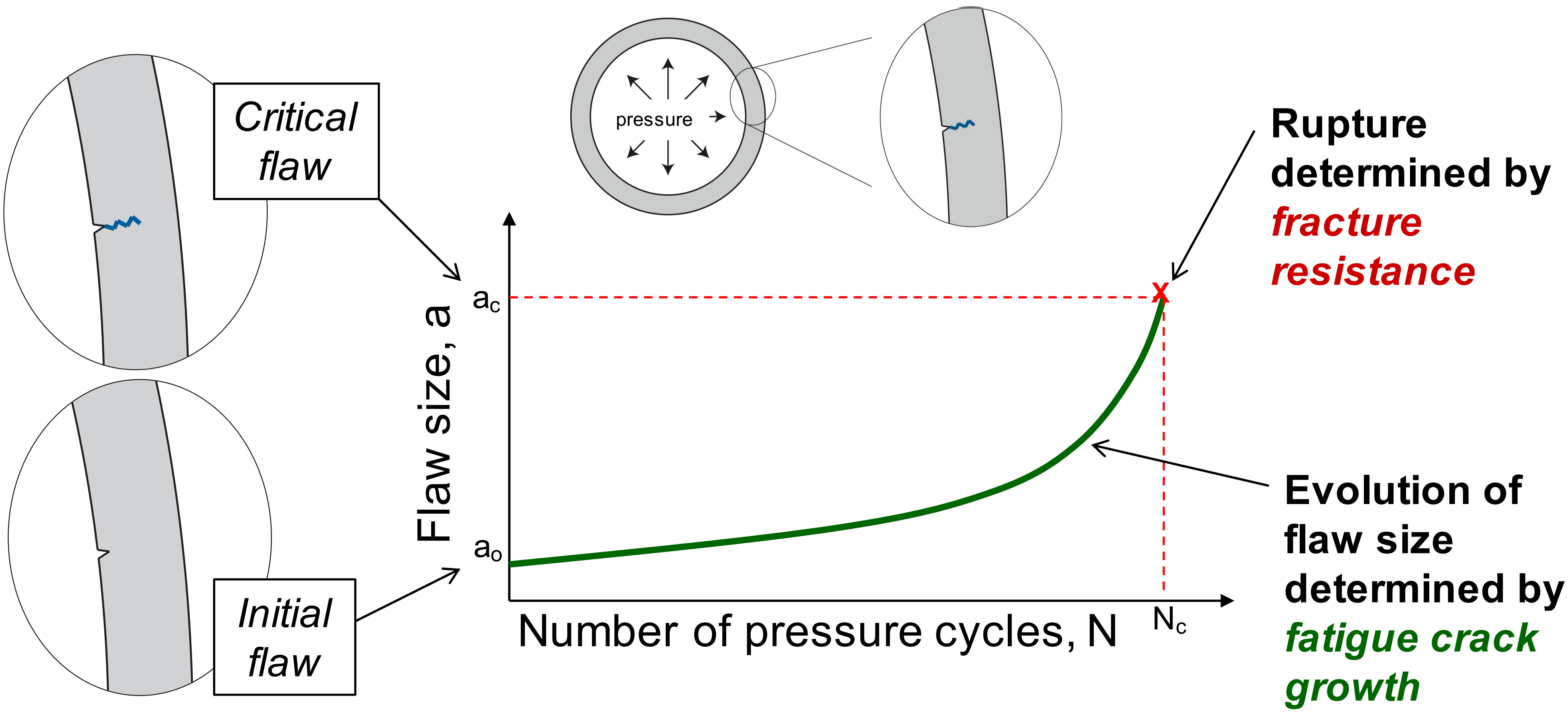
- Hydrogen is a convenient way to store electrical energy.
- The advantages of hydrogen are multiplied when existing infrastructure can be put to use for storing and distribution of the hydrogen.
- Natural gas pipelines are one example of where opportunity exists in this regard.
- However, hydrogen is known to embrittle pipeline steels, leading to safety concerns.
- Hydrogen embrittlement is somewhat of a misnomer, as many structural metals remain very ductile when exposed to gaseous hydrogen.
- Low-strength steels are used to distribute hydrogen for the oil and gas industry.
- Blending gaseous hydrogen into natural gas infrastructure is a different concern as the natural gas infrastructure is operated differently from pipelines dedicated to distribution of pure hydrogen.

Background

- This work is motivated by the desire to demonstrate a fracture mechanics approach to fitness-for-service for pipelines distributing blended hydrogen and natural gases.
- This effort does not seek a comprehensive fitness-for-service analysis, rather we seek to analyze the fatigue growth of small defects based on data generated in relevant gaseous hydrogen environments.

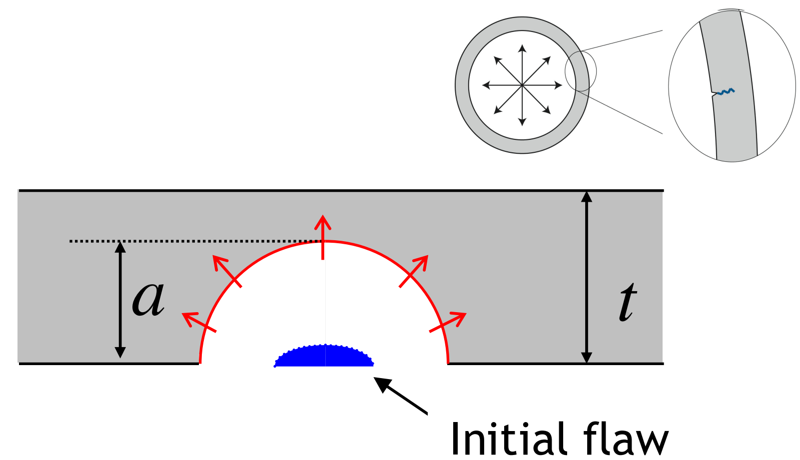


Fracture mechanics-based assessment of fatigue and fracture hydrogen pipelines



ASME B31.12 describes rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Division 3, Article KD-10

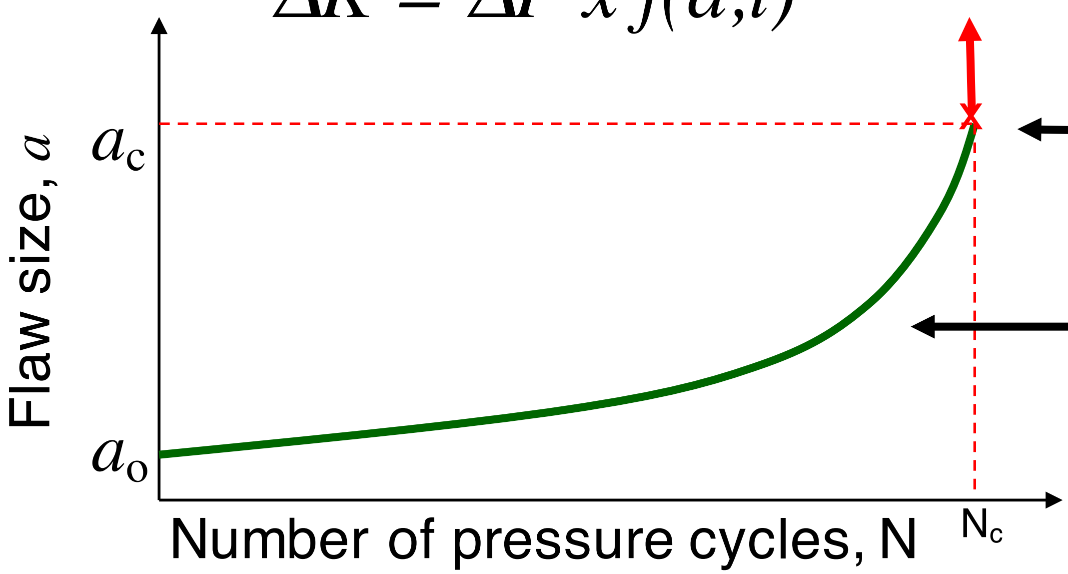
- Initial flaw grows due to pressure cycle
- Driving force is characterized by ΔK



a = depth of crack

t = wall thickness

$$\Delta K = \Delta P \; x \; f(a,t)$$



$$K_{IH} = P \; x \; f(a_c,t)$$

$$a = a_i + \left(\frac{da}{dN} \right)^{a=a_i} \Delta N$$

$$\frac{da}{dN} = C \Delta K^m$$

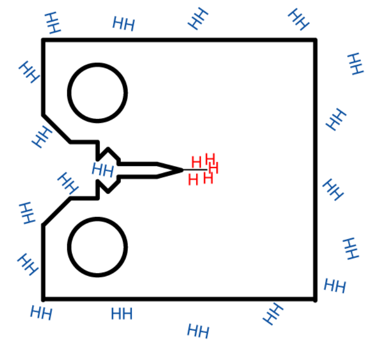
Fracture mechanics parameters must be measured in relevant hydrogen environments

KRISS

Fatigue crack growth

Characterized by $da/dN = f(\Delta K)$

Typical fatigue crack growth methodology described in ASTM E647



Fracture resistance

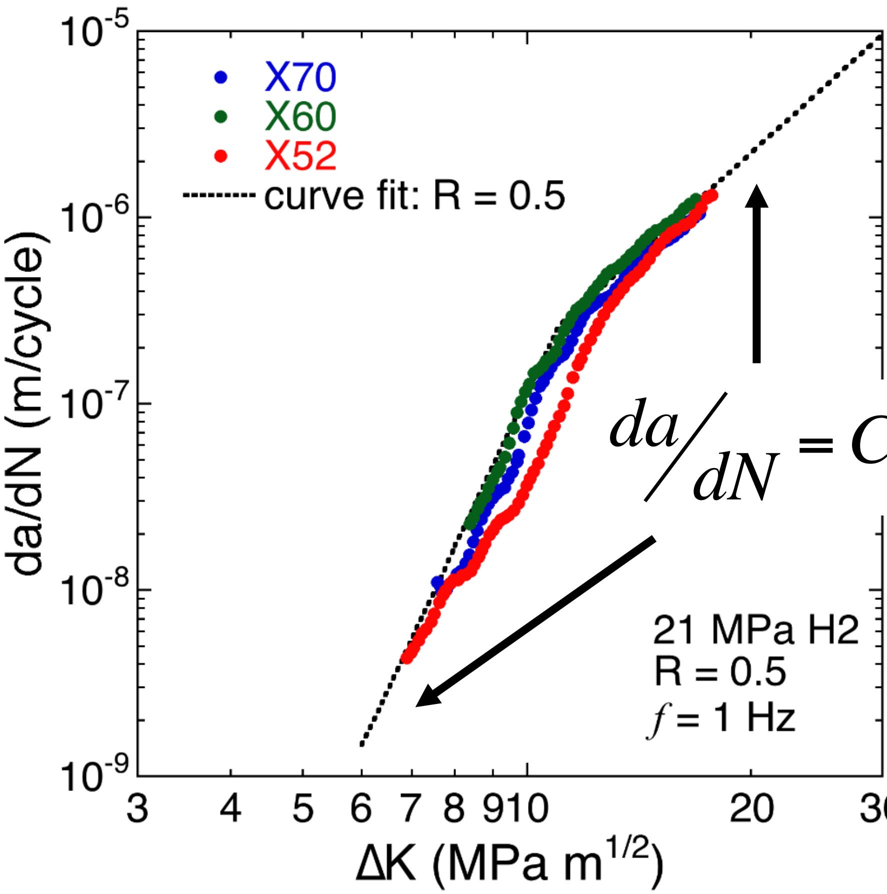
Characterized by K_{IC} or in hydrogen K_{IH}

Elastic-plastic methods are generally needed (ASTM E1820), K_{IH} is calculated from these methods

CSA CHMC1 describes requirements for mechanical testing in high-pressure gaseous hydrogen environments, referencing standard fatigue and fracture methods (e.g., ASTM)

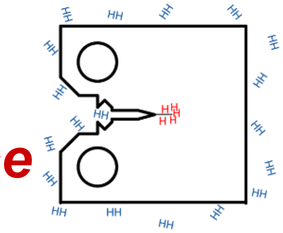
Fracture mechanics measurements can be made in gaseous hydrogen

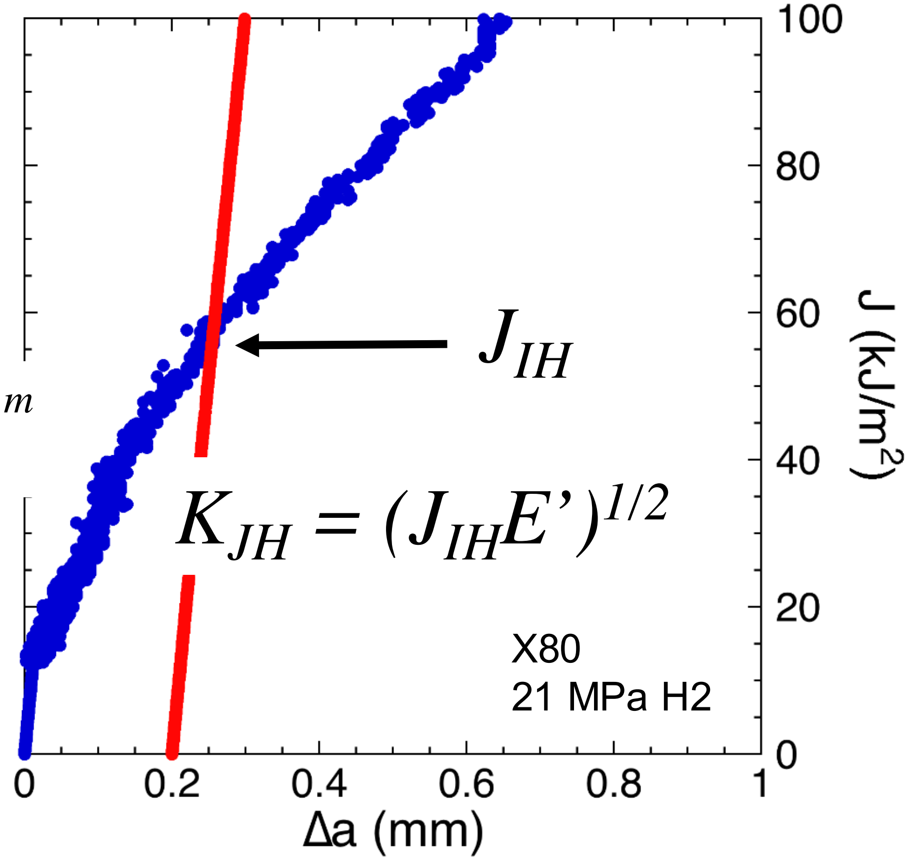
Fatigue crack growth



$$da/dN = C\,\Delta K^m$$

Fracture resistance

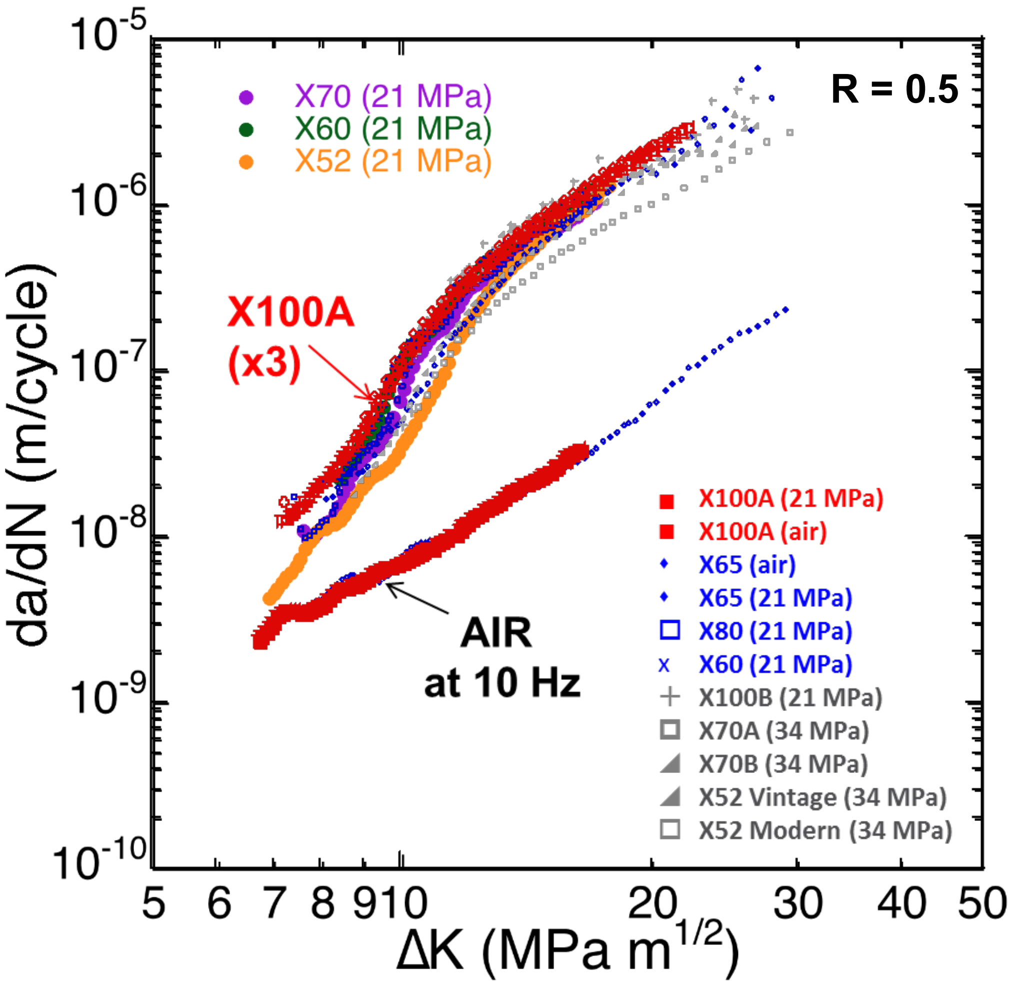




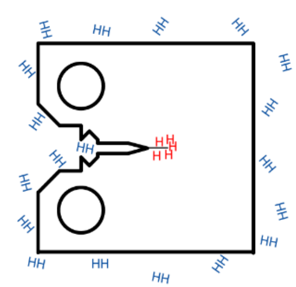
$$J_{IH}$$

$$K_{JH} = (J_{IH}E')^{1/2}$$

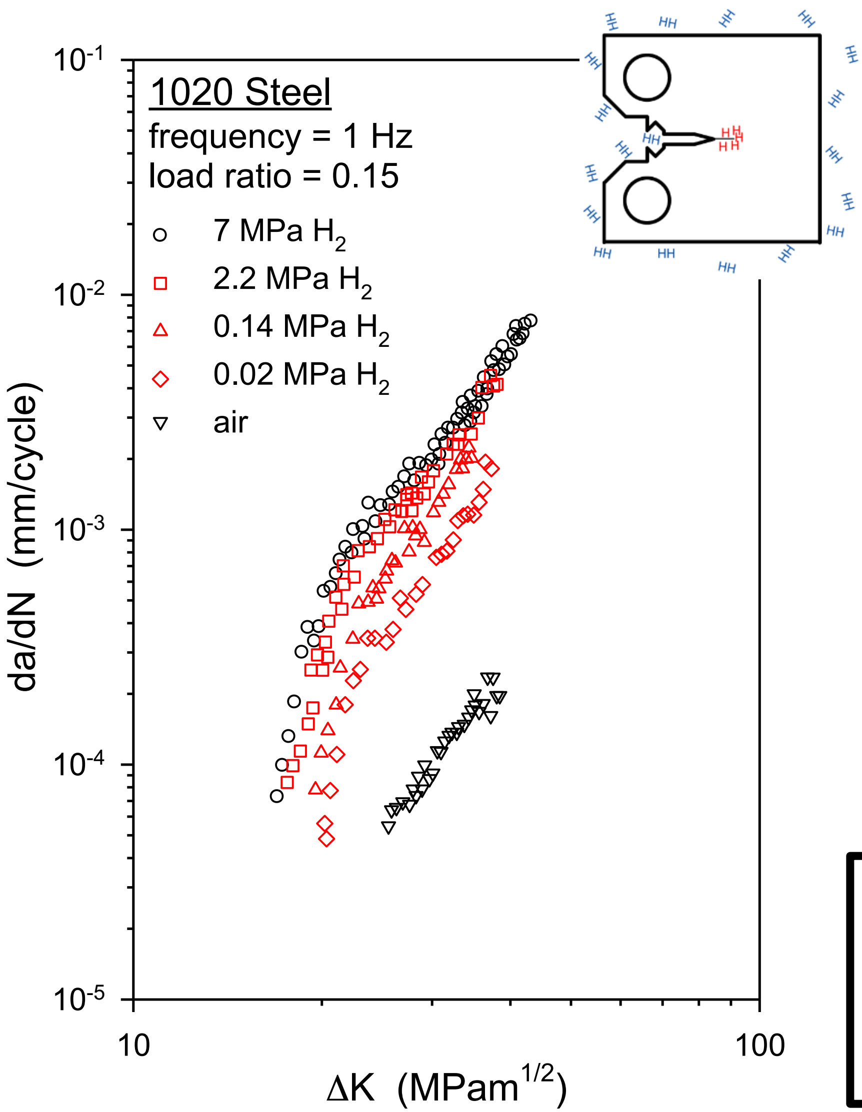
Low strength steels tend to show very similar fatigue crack growth rates in gaseous hydrogen



- 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



Low pressure hydrogen can have significant effects on fatigue crack growth rates



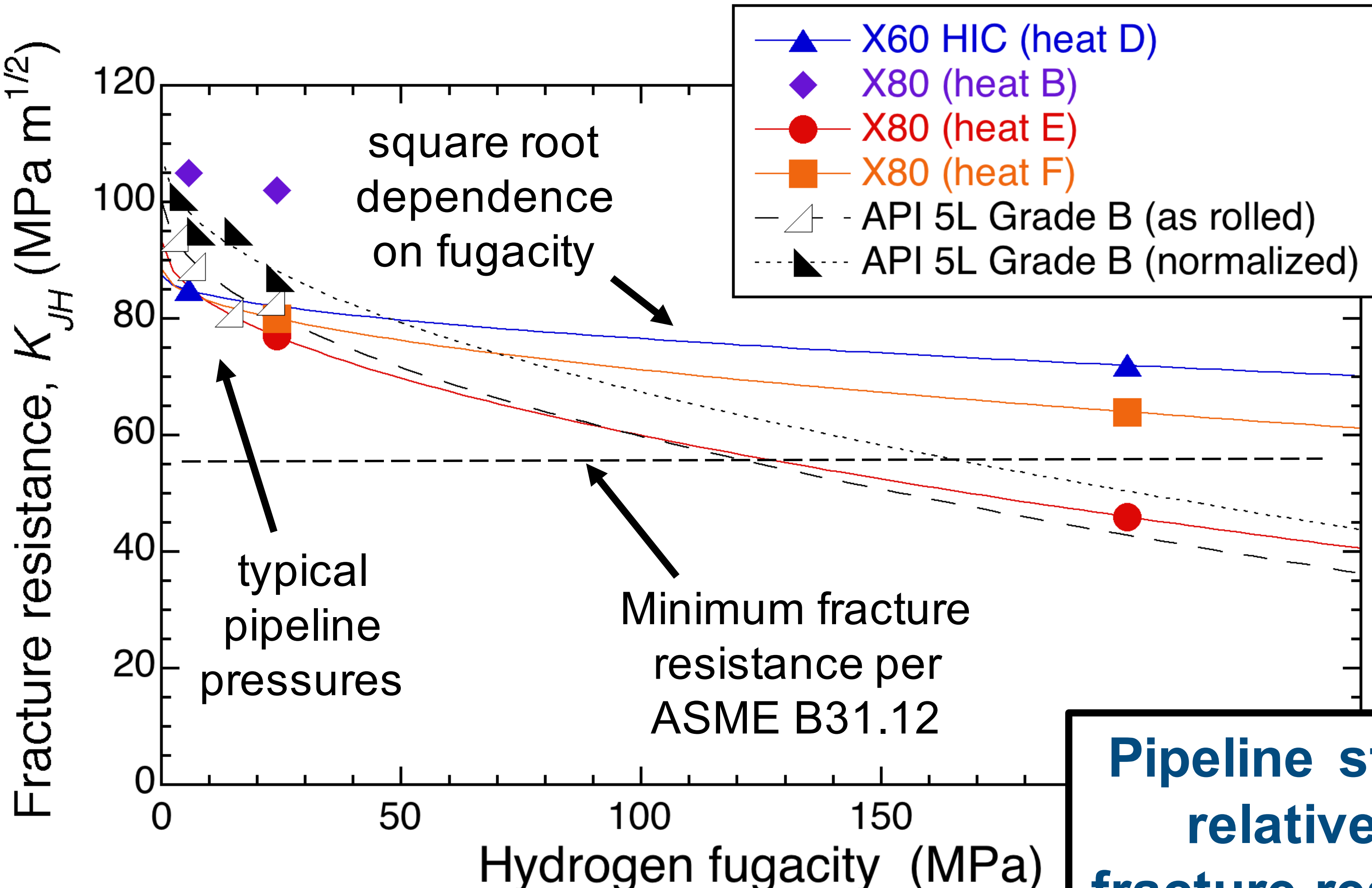
- **Sub-atmospheric pressure of hydrogen (<0.1MPa) can have substantial effect on fatigue crack growth rates for carbon steels**
- **The effect of pressure on fatigue is generally within the scatter for pressure greater than about 2 MPa**

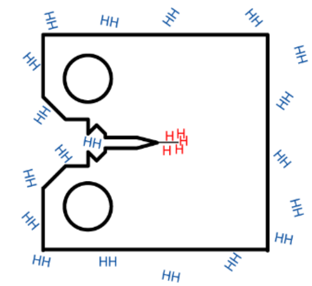
Low partial pressure of hydrogen has nominally same effect as pure hydrogen on pipeline steels

Data from : Technical Reference on Hydrogen Compatibility of Materials, Sandia, 2008

Fracture resistance in gaseous hydrogen depends on pressure (unlike fatigue)

KRISS

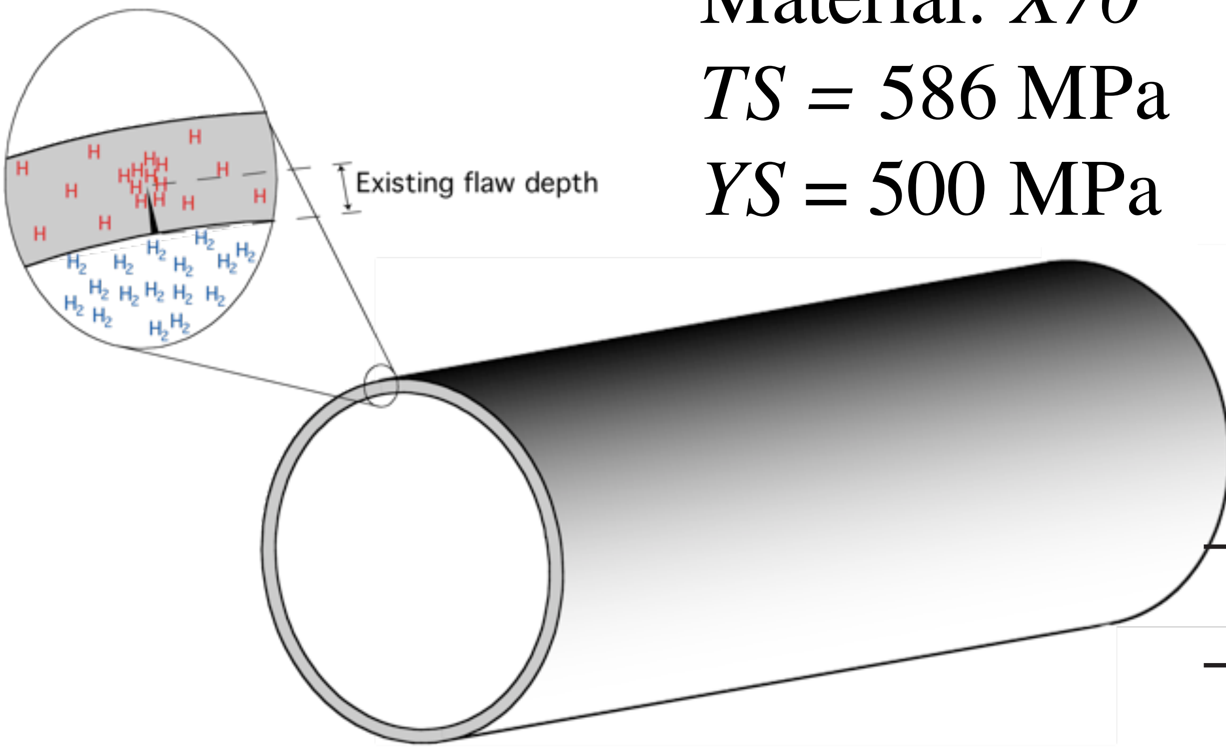




Pipeline steels have relatively high fracture resistance in gaseous hydrogen

Data from : Technical Reference on Hydrogen Compatibility of Materials, Sandia, 2008

Consider a typical "high-pressure" pipeline



Material: *X70*

TS = 586 MPa

YS = 500 MPa

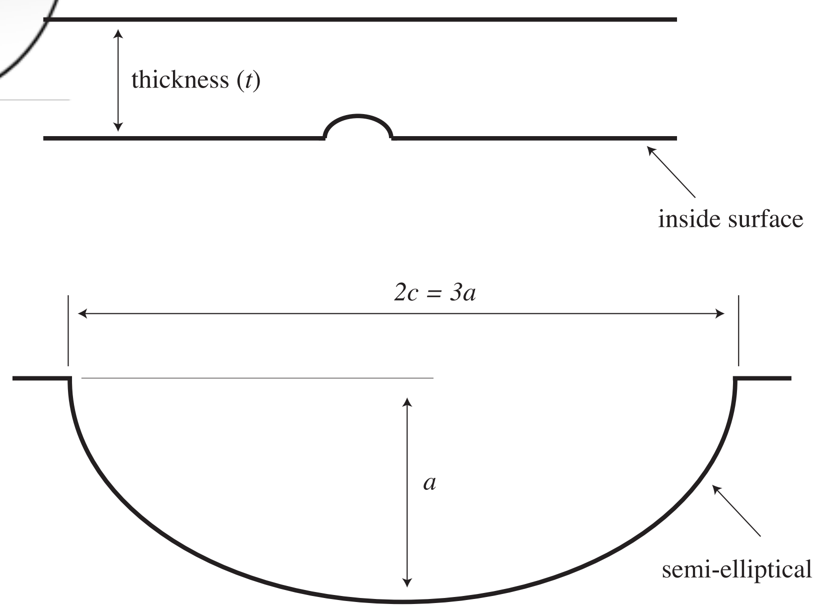
OD = 762 mm

t = 15.9 mm

P_{max} = 7 MPa

P_{min} = 4 MPa

Semi-elliptical crack



a/t = crack depth

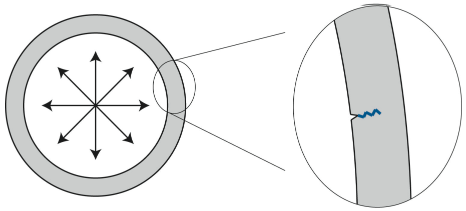
$a/2c$ = depth to length ratio

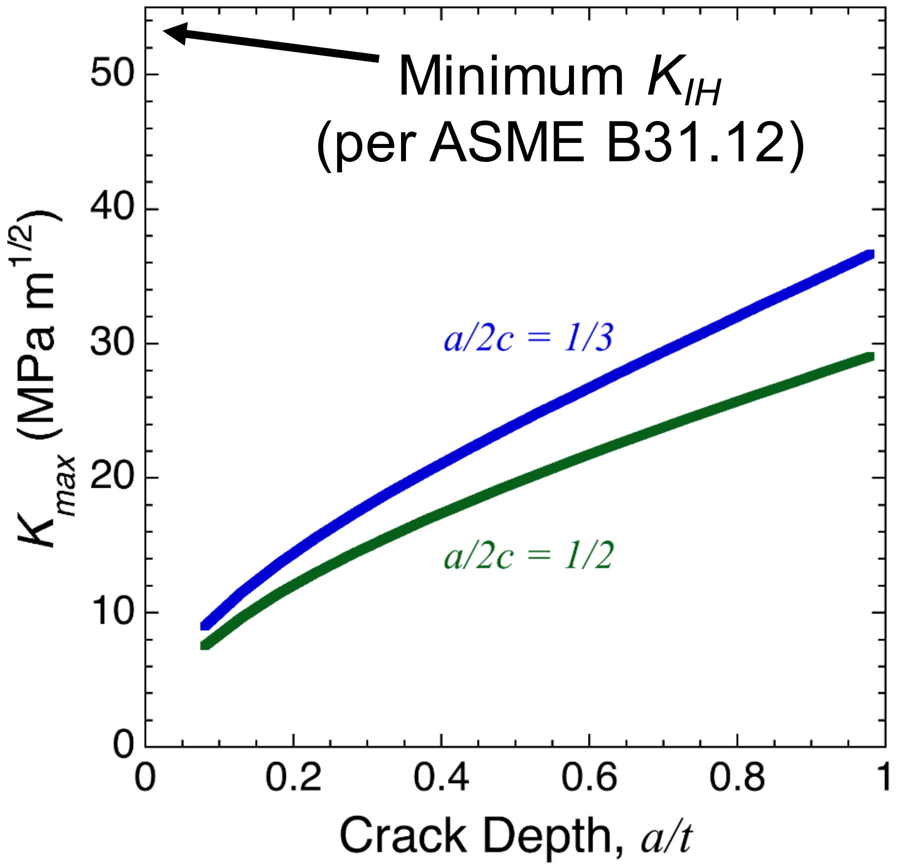
natural crack shape: $a/2c = 1/2$

ASME crack shape: $a/2c = 1/3$

Stress intensity associated with semi-elliptical crack in "high-pressure" pipeline

KRISS

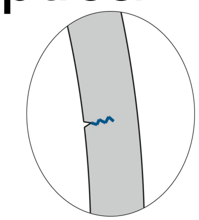




Hoop stress at $P_{max} = 162$ MPa
stress ratio: hoop/TS = 28%

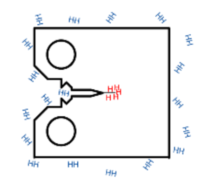
Driving force on semi-elliptical through-wall crack:

$K_{max} < 40$ MPa m$^{1/2}$



Typical pipeline material fracture resistance:

$K_{JH} > 75$ MPa m$^{1/2}$



Fracture resistance of pipeline steels in H2 is greater than driving force on semi-elliptical cracks

Fatigue crack growth relationships for pipeline materials in gaseous hydrogen

$P_{max} = 7$ MPa & $P_{min} = 4$ MPa

$R = 0.57$

For $a/t = 30\%$ & $a/2c = 1/3$

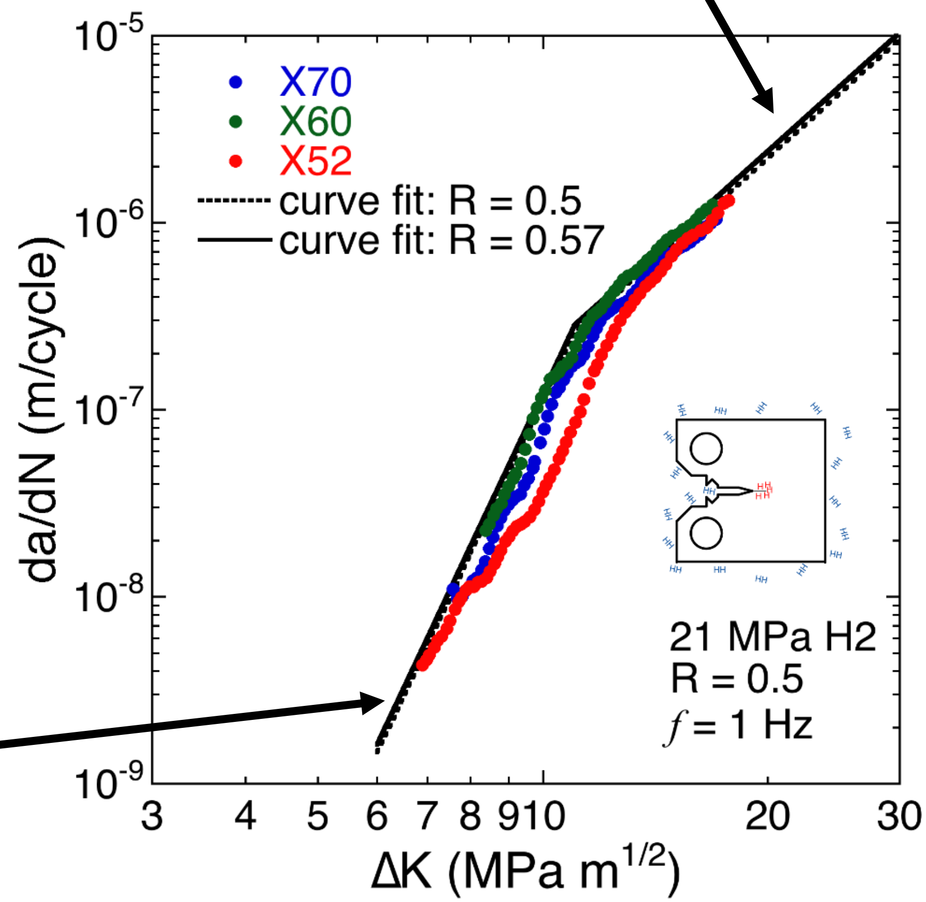
$\Delta K \sim 7.7$ MPa $m^{1/2}$

For $a/t = 40\%$ & $a/2c = 1/2$

$\Delta K \sim 7.5$ MPa $m^{1/2}$

For $\Delta K \geq 11$ MPa $m^{1/2}$

da/dN (m/cycle) $= 5 \times 10^{-11} \Delta K^{3.6}$

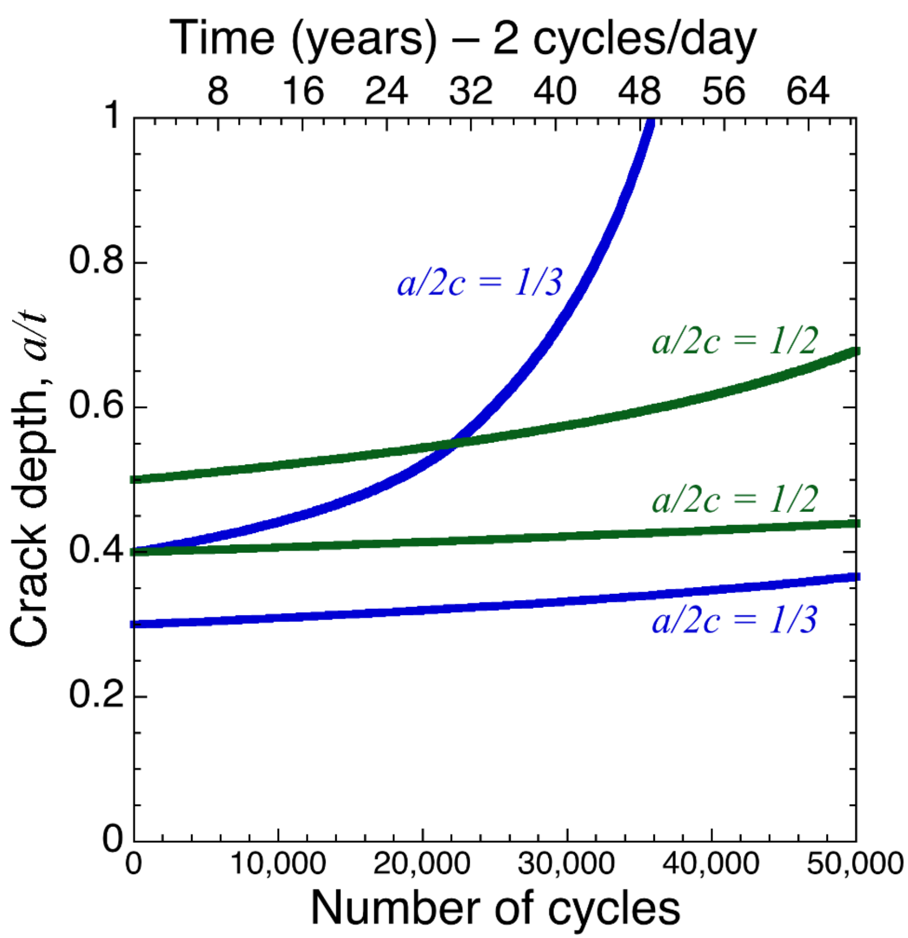


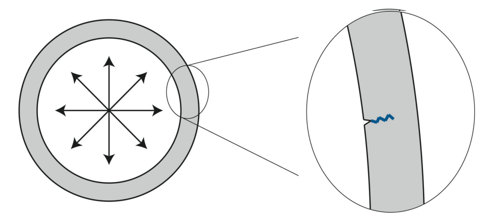
For $6 < \Delta K < 11$ MPa $m^{1/2}$

da/dN (m/cycle) $= 3.9 \times 10^{-16} \Delta K^{8.5}$

Predicted lifetime of pipeline with growing fatigue cracks in hydrogen

KRISS





Assuming

- Pressure cycles between 4 & 7 MPa
- Constant crack shape ($a/2c$)
- Large initial defects
- Fatigue crack growth rates in pure H2 (at higher pressure)

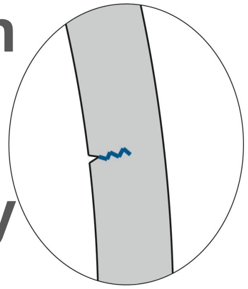
Using:

$$a = a_i + \left({da}/{dN} \right)^{a=a_i} \Delta N$$

- **10,000s of cycles are needed to extend the crack significantly**
- **At 2 cycles per day, decades are needed to advance the crack**

Summary

- Fatigue crack growth rates of pipeline steels are independent of hydrogen partial pressure to first order
  - *H2-NG mixtures have same effect as pure hydrogen*
- Fracture resistance, on the other hand, is sensitive to pressure – but remains relatively high at high pressure
- For conditions of typical pipeline operating with large daily pressure swings (P_{max} = 7 MPa; P_{min} = 4 MPa):
  - Large defects (30-40% wall thickness) show only modest fatigue-induced extension on time scale of decade
  - Stress intensity factor for through wall cracks can be less than fracture resistance measured in hydrogen
    - *Hydrogen does not induce rupture of pipeline*
  - Details, of course, depend on specifics of geometry



Thank you for your attention !!

Sandia National Laboratories

KRISS 한국표준과학연구원