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

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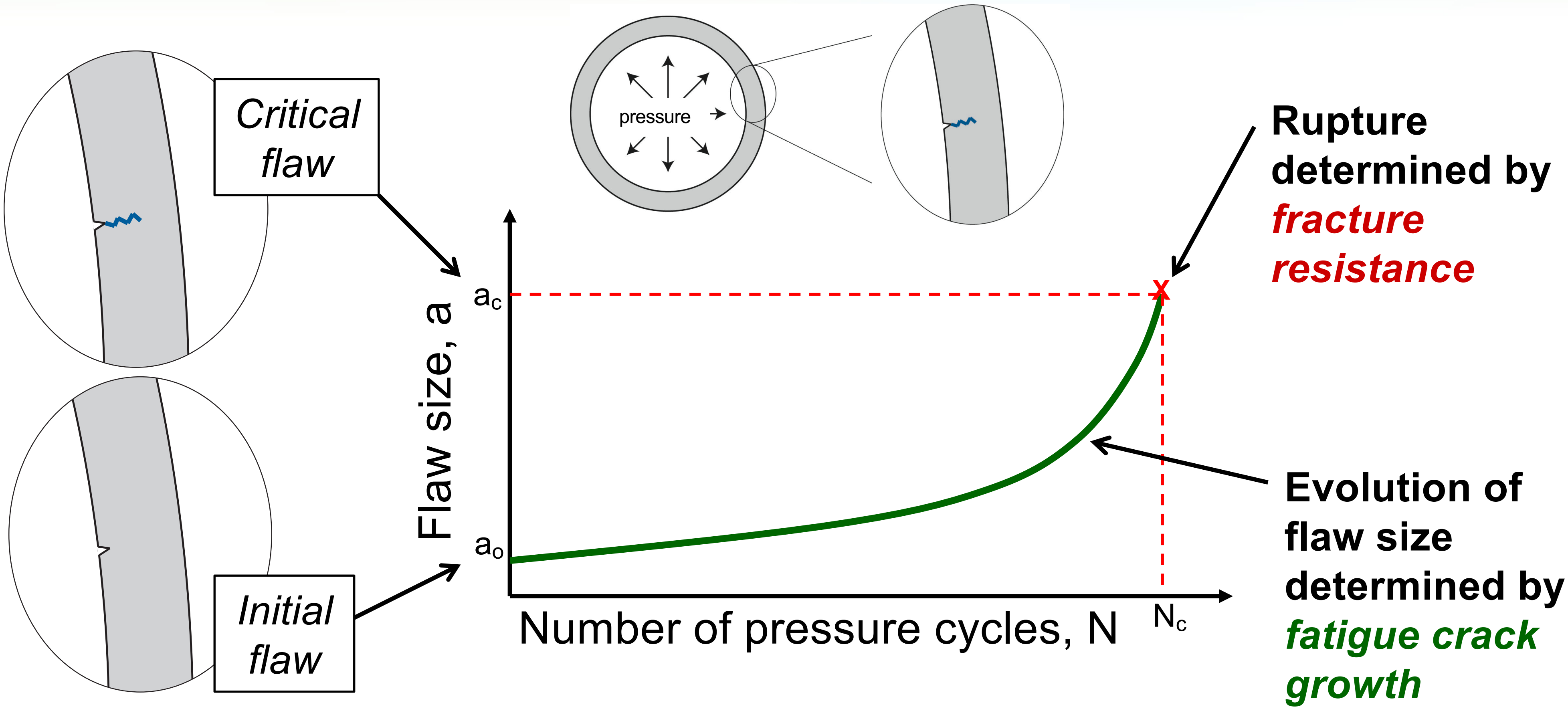
Outline

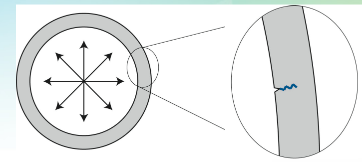
- Overview of fracture mechanics based assessment
- Representative fatigue and fracture data measured in hydrogen
- Example life calculations based on idealized cracks

Fracture mechanics-based assessment of fatigue and fracture hydrogen pipelines

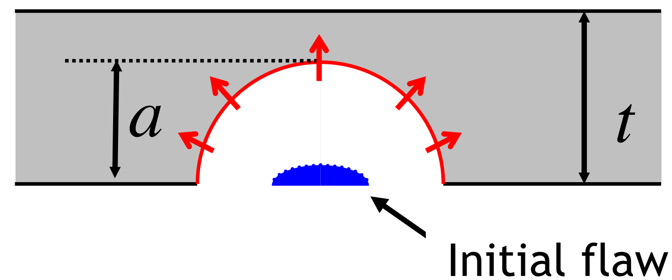


ASME B31.12 describes rules for hydrogen pipelines with reference to ASME BPVC Section VIII, Division 3, Article KD-10

Crack growth through the thickness of the pipeline driven by hoop stress



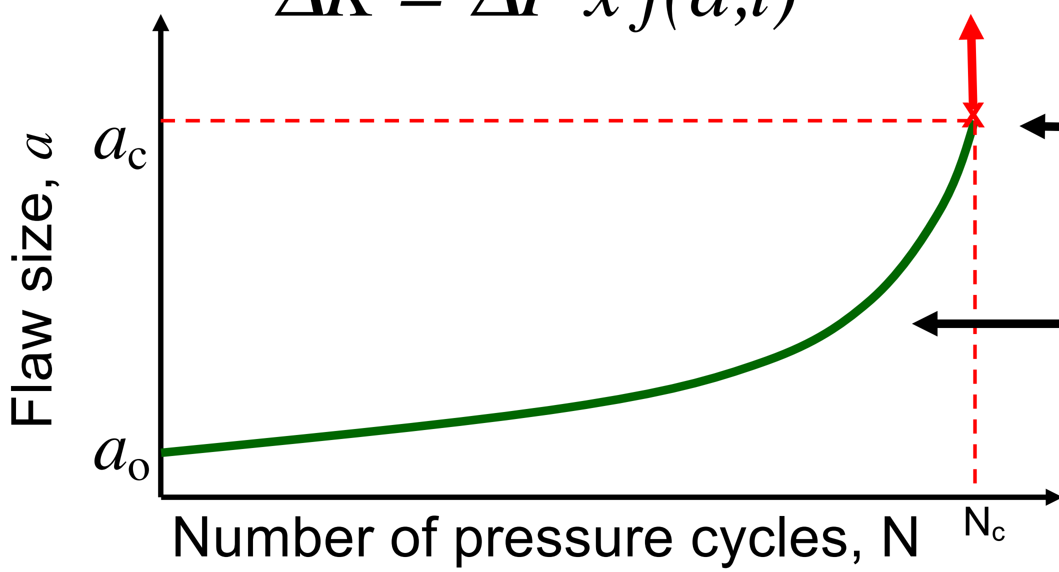
- **Initial flaw grows due to pressure cycle**
- **Driving force is characterized by ΔK**



a = depth of crack

t = wall thickness

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



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

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

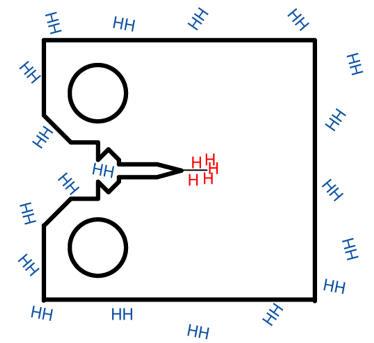
$$da/dN = C \Delta K^m$$

Fracture mechanics parameters must be measured in relevant hydrogen environments

Fatigue crack growth

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

- Typical fatigue crack growth methodology described in ASTM E647



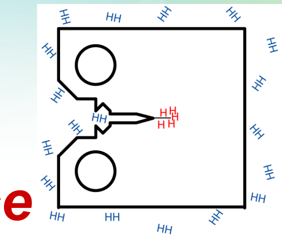
Fracture resistance

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

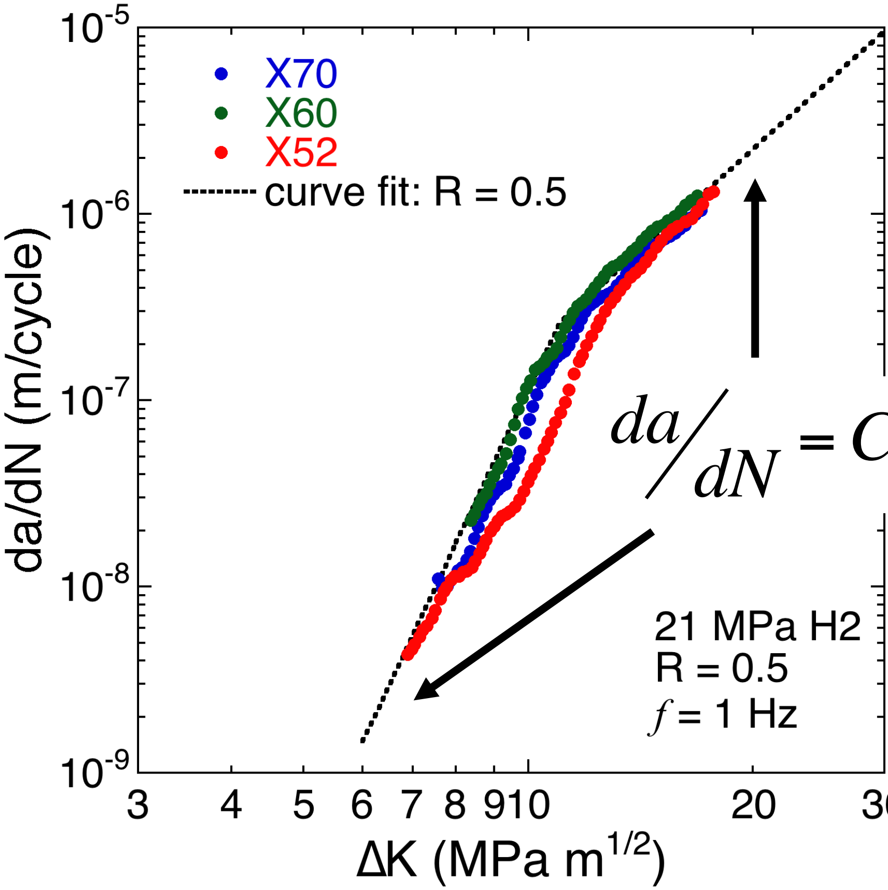
- Elastic-plastic methods are generally needed (ASTM E1820), K_{IH} is calculated from these methods

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

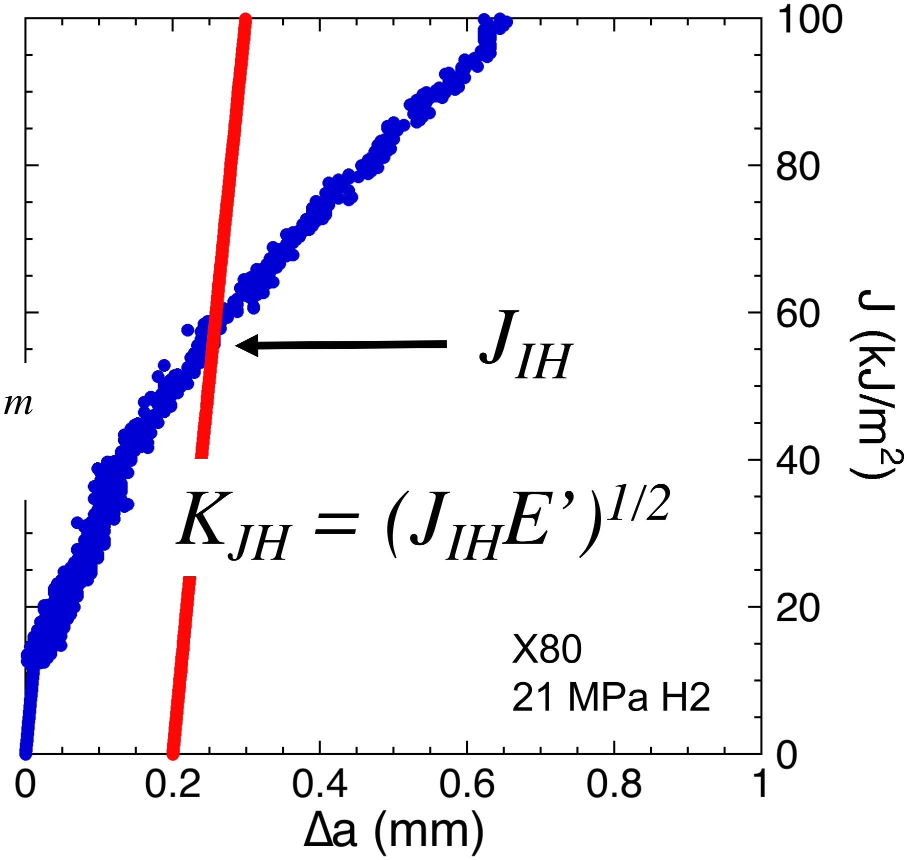


Fatigue crack growth



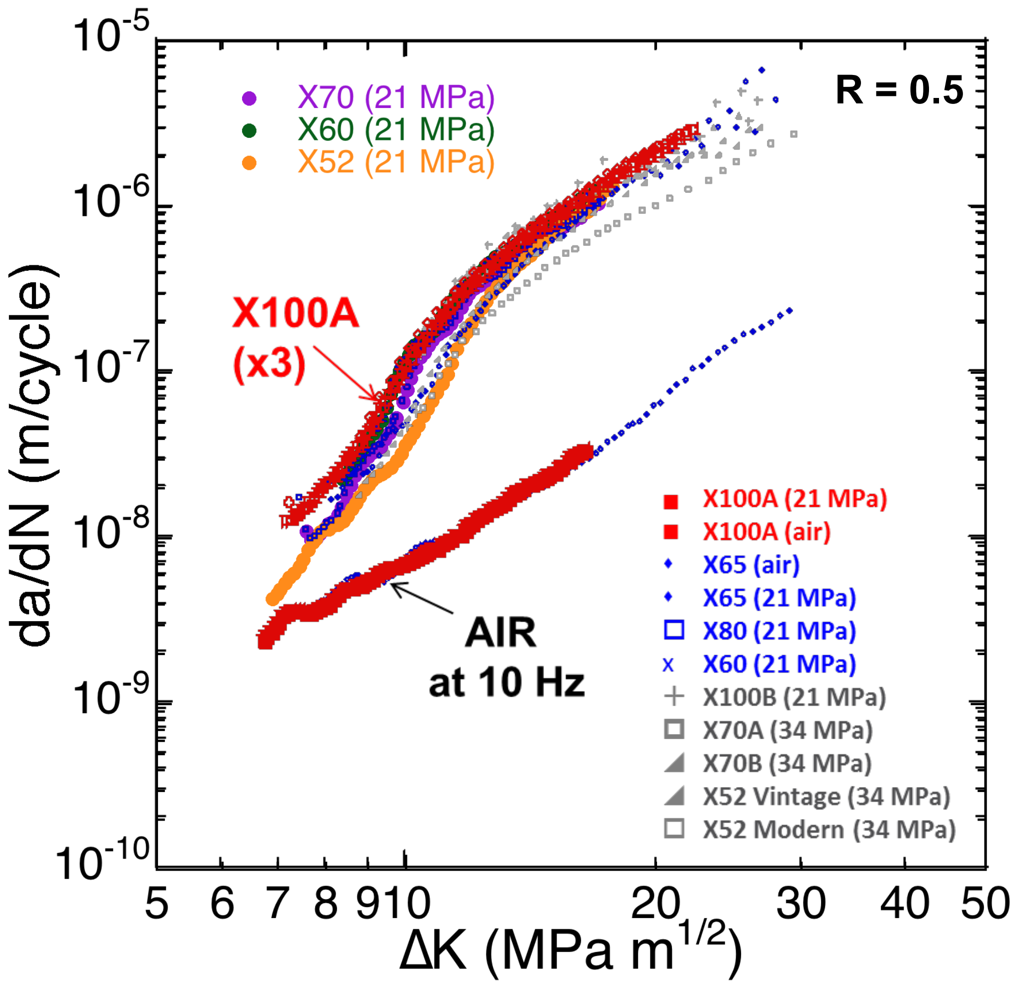
$$da/dN = C \Delta K^m$$

Fracture resistance

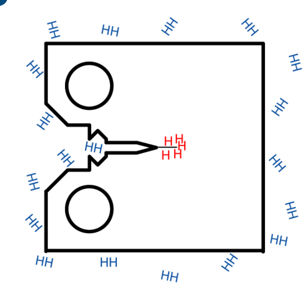


$$K_{JH} = (J_{IH} E')^{1/2}$$

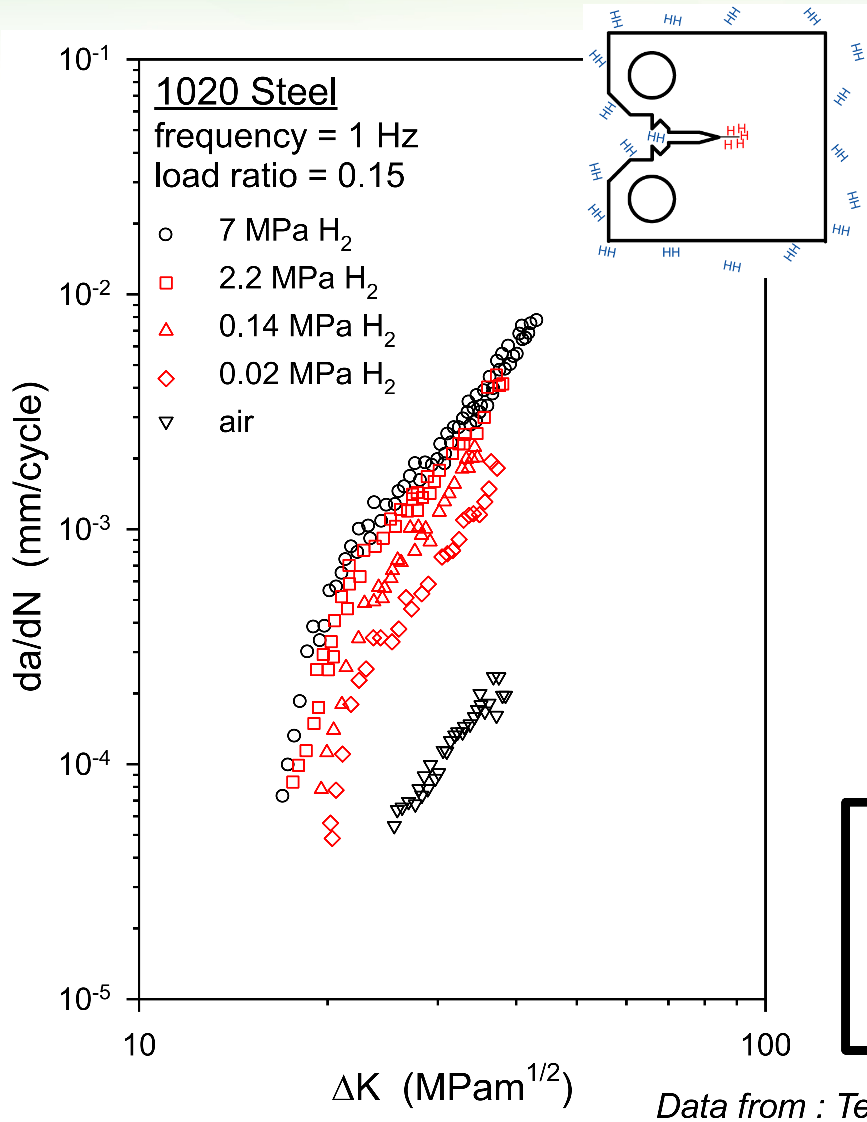
Low strength steels tend to show very similar fatigue crack growth rates in gaseous hydrogen



- 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 : <u>Technical Reference on Hydrogen Compatibility of Materials</u>, Sandia, 2008

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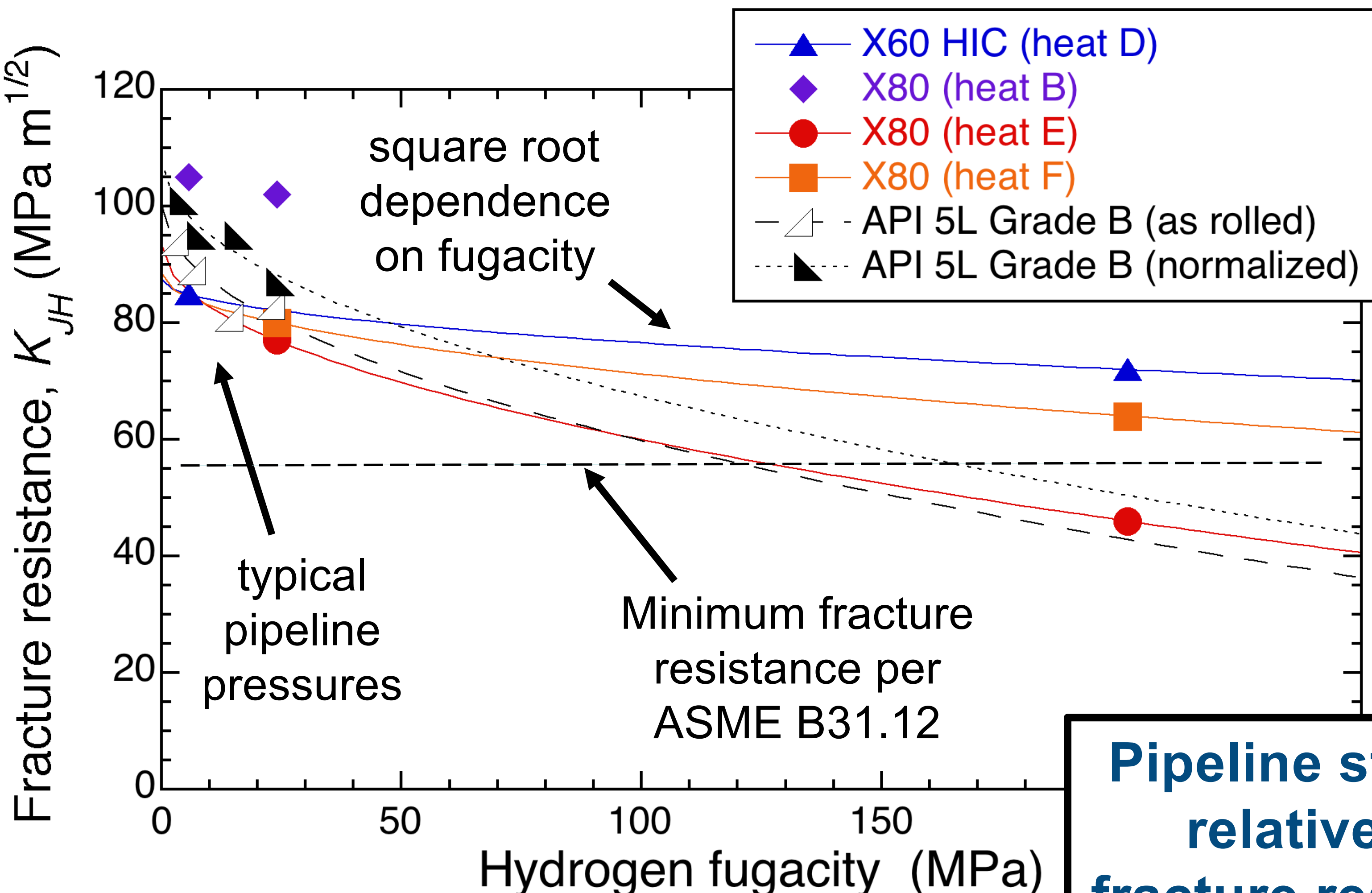
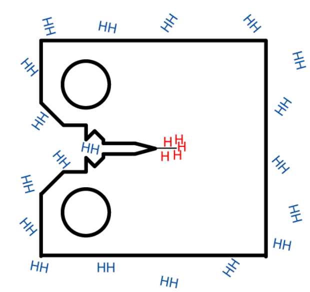
H_2FC Hydrogen and Fuel Cells Program

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

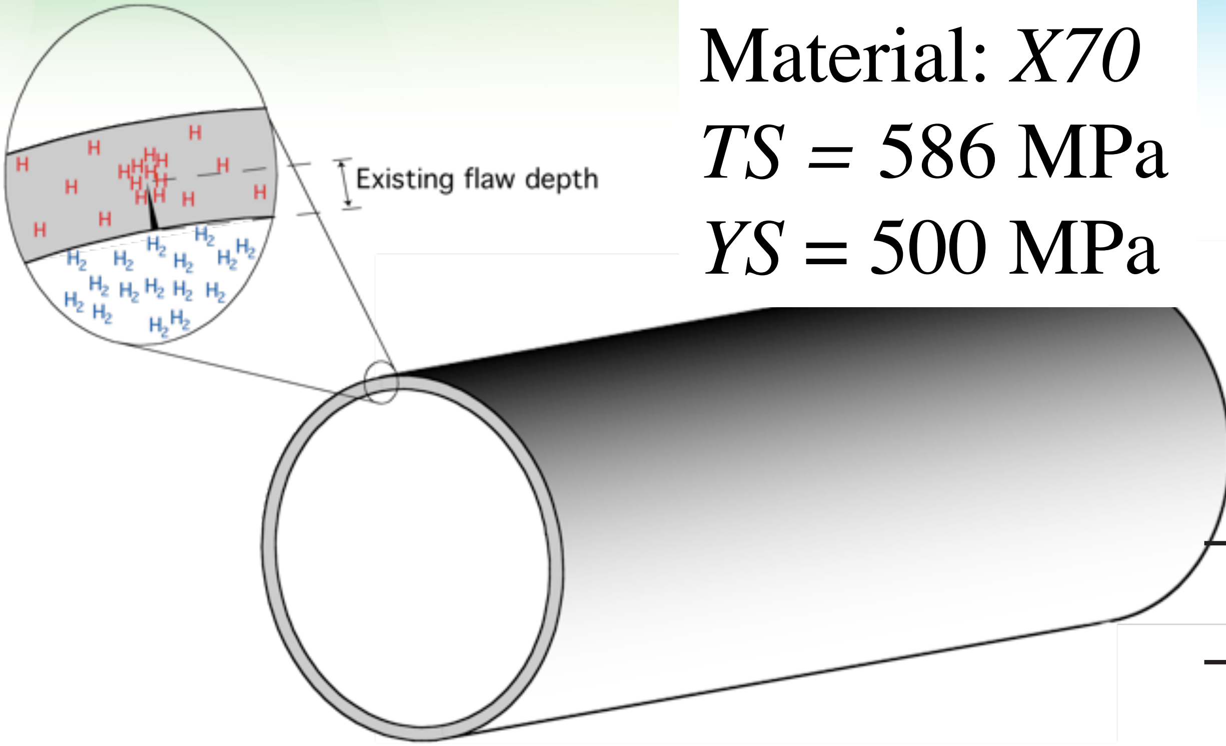




Pipeline steels have relatively high fracture resistance in gaseous hydrogen

Data from : <u>Technical Reference on Hydrogen Compatibility of Materials</u>, Sandia, 2008

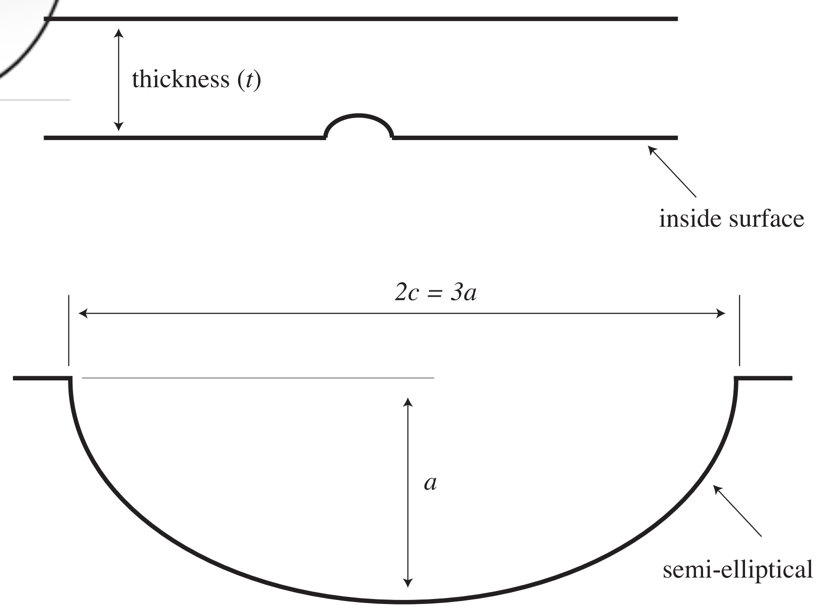
Consider a typical "high-pressure" pipeline



Material: *X70*
TS = 586 MPa
YS = 500 MPa

OD = 762 mm
t = 15.9 mm
P_{max} = 7 MPa
P_{min} = 4 MPa

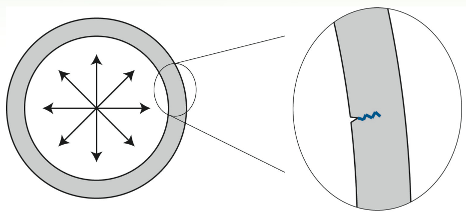
Semi-elliptical crack



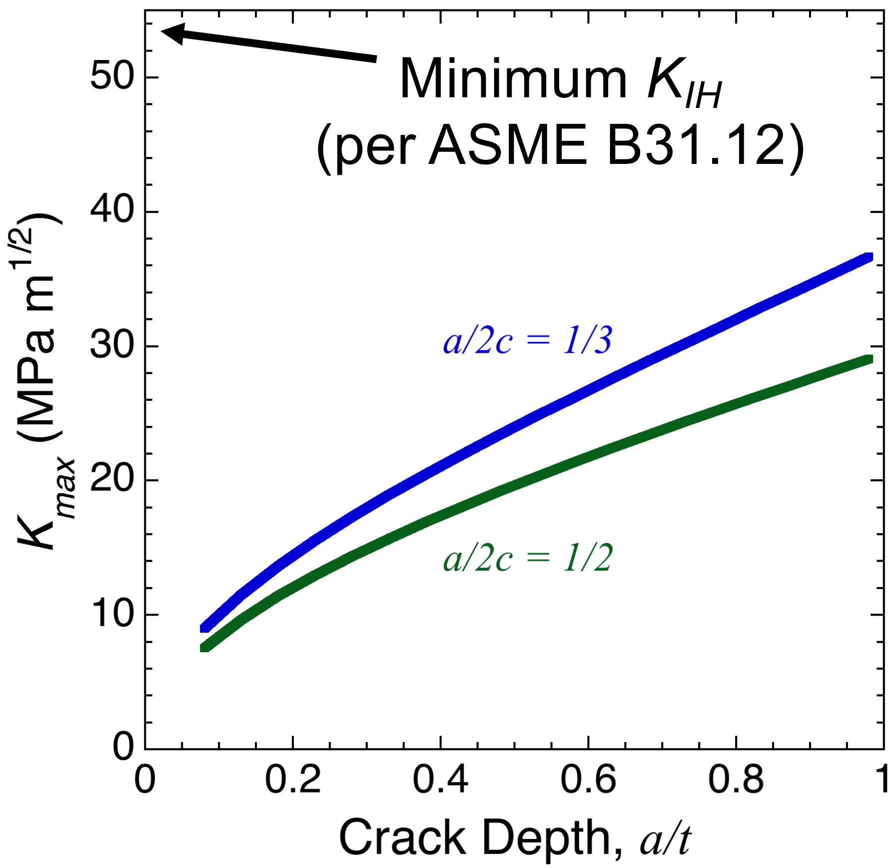
a/t = crack depth
$a/2c$ = depth to length ratio

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

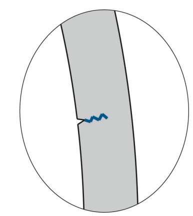


Hoop stress at $P_{max} = 162$ MPa
stress ratio: hoop/TS = 28%



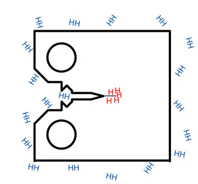
Driving force on semi-elliptical crack:

$K_{max} < 40$ 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

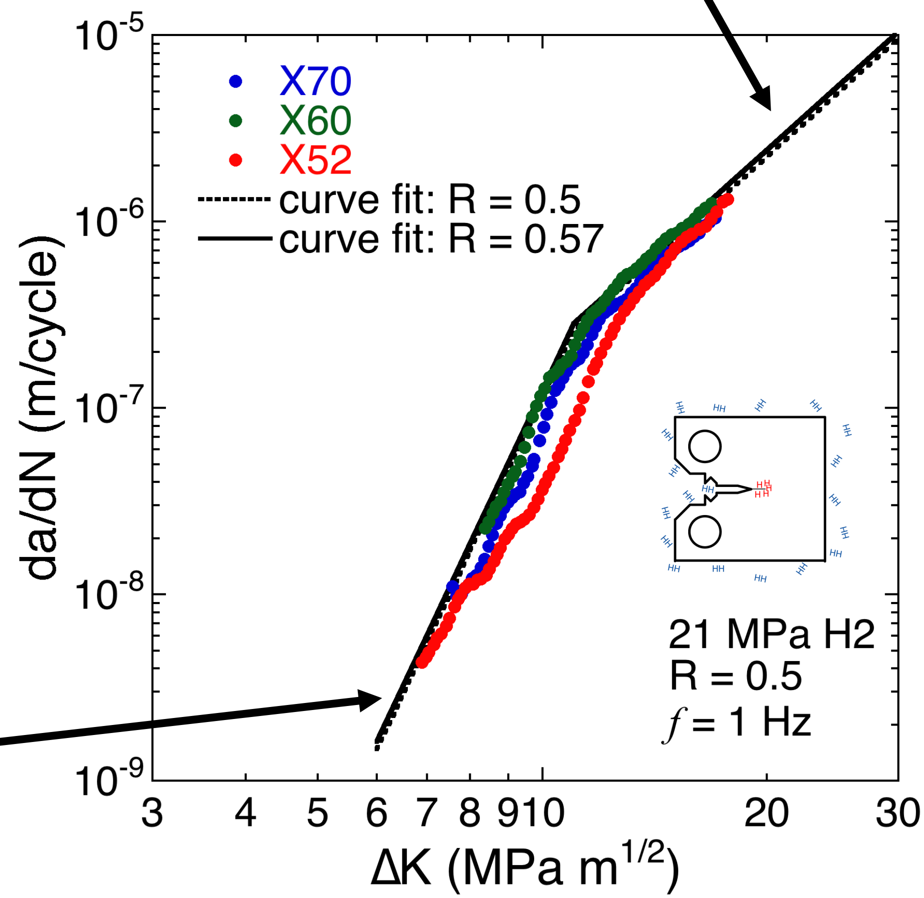
$\Delta K \sim 7.7$ MPa m$^{1/2}$

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

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

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

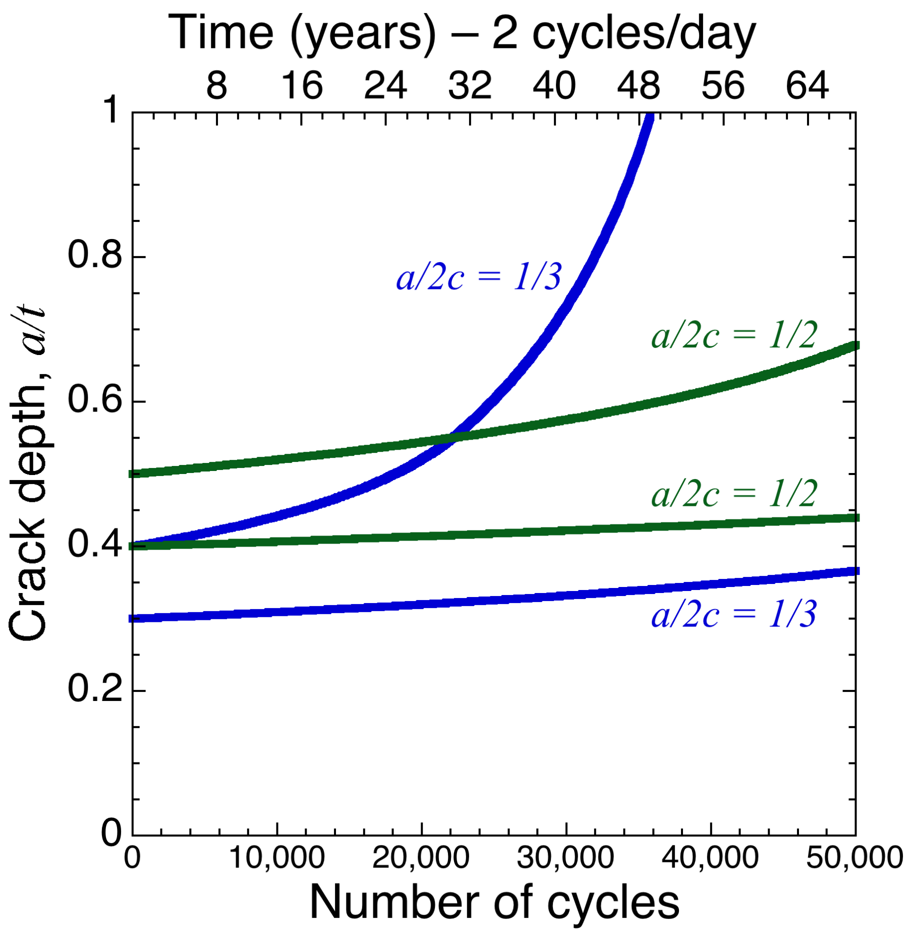
da/dN (m/cycle) = $5\text{x}10^{-11}\ \Delta K^{3.6}$

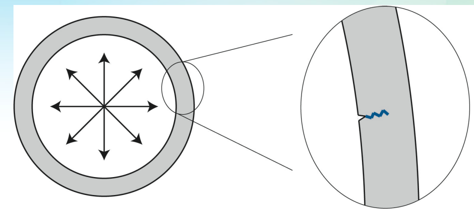


For $6 < \Delta K < 11$ MPa m$^{1/2}$

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

Predicted lifetime of pipeline with growing fatigue cracks in hydrogen





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 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**