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Mechanical Properties of Structural Steels in Hydrogen

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Livermore, CA

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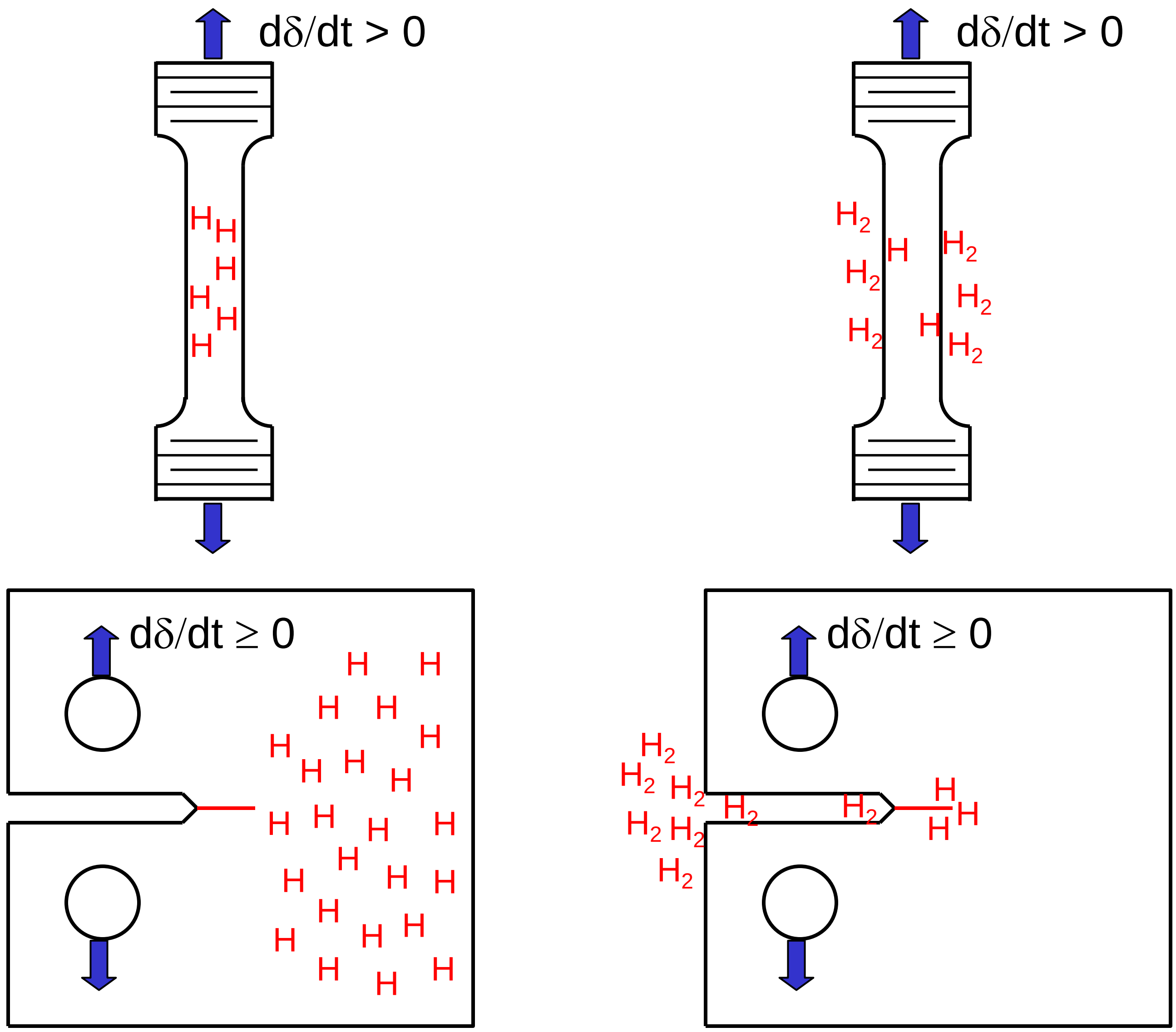
Array of methods for measuring mechanical properties of structural steels in hydrogen

strength of materials:

σ_{UTS}, σ_{YS}, ε_f, RA

fracture mechanics:

K_{IH}, K_{TH}

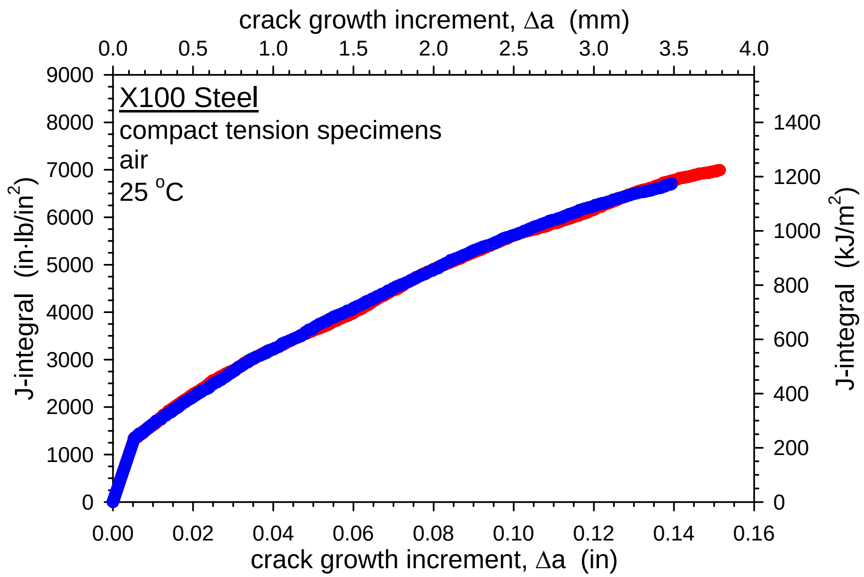


Crack propagation resistance of X100 steel

- Alloy composition

C	Mn	Si	P	S	Ti	V	Ni	Cu	Mo	Cr
0.073	1.86	0.11	0.009	<0.002	0.01	<0.005	0.48	0.27	0.17	0.02

- Yield strength
  - 96 ksi (662 MPa) in longitudinal orientation
  - 114 ksi (787 MPa) circumferential orientation
- Crack growth resistance curves in air



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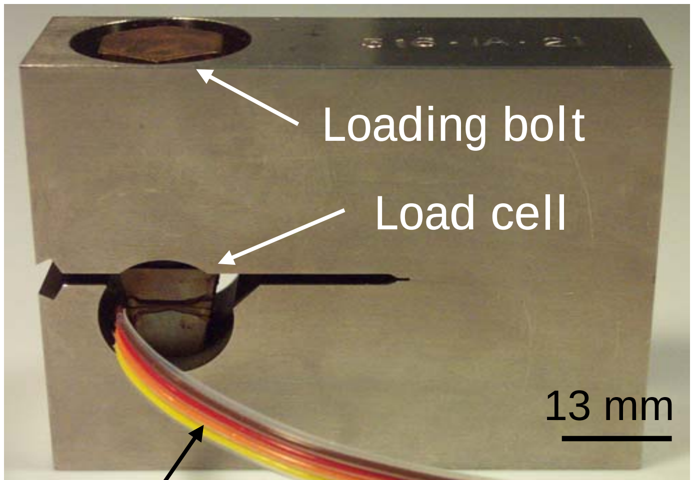
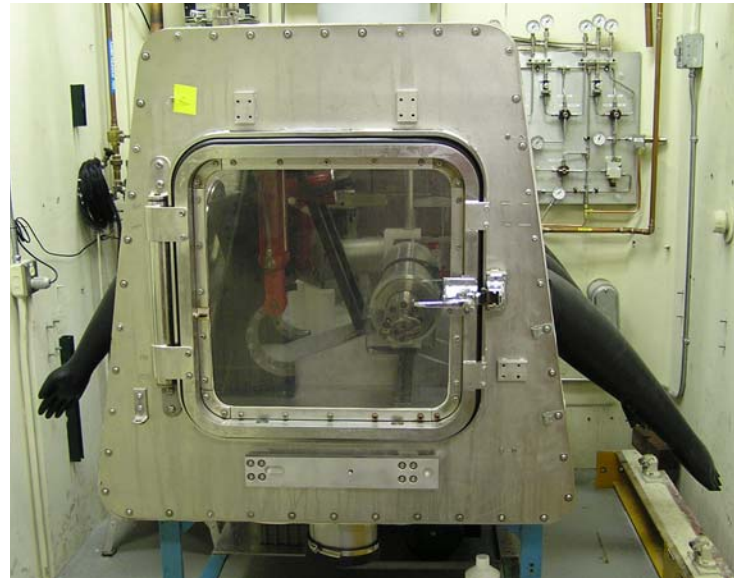
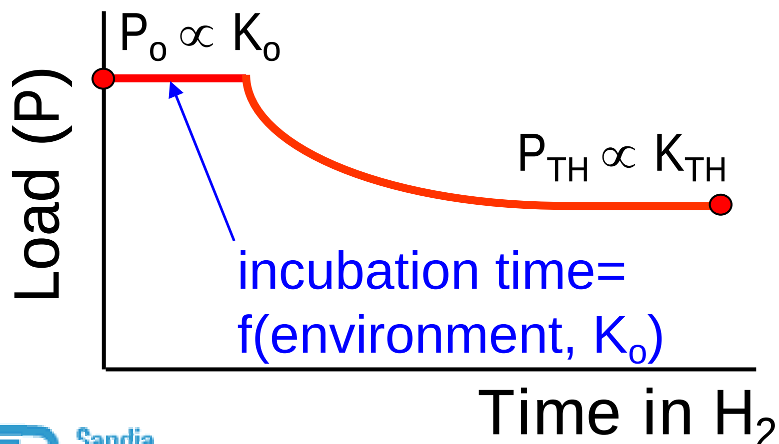
Measurement of sustained-load cracking thresholds

wedge opening load (WOL)
cracking threshold specimen



strain gage leads (Excitation and DAQ)





- Specimen loaded to $K_o > K_{TH}$ using bolt while contained in glove box (Ar with ~1 ppm O_2)
- Loaded specimen exposed to H_2, crack extends after incubation time
- Crack arrests at $K = K_{TH}$

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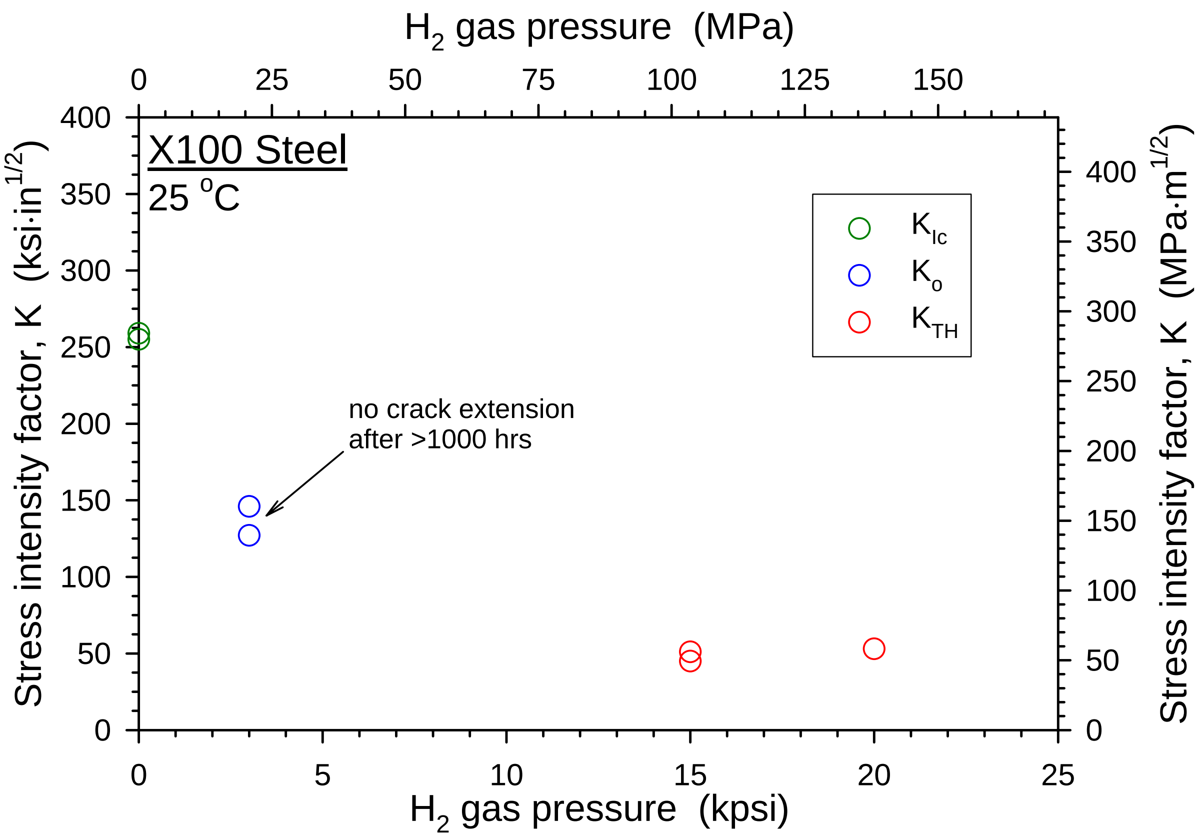
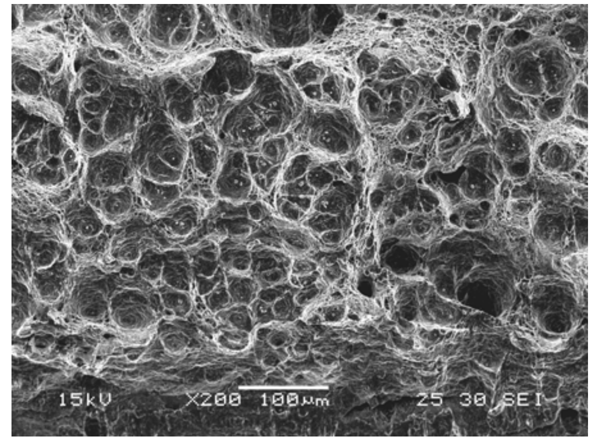
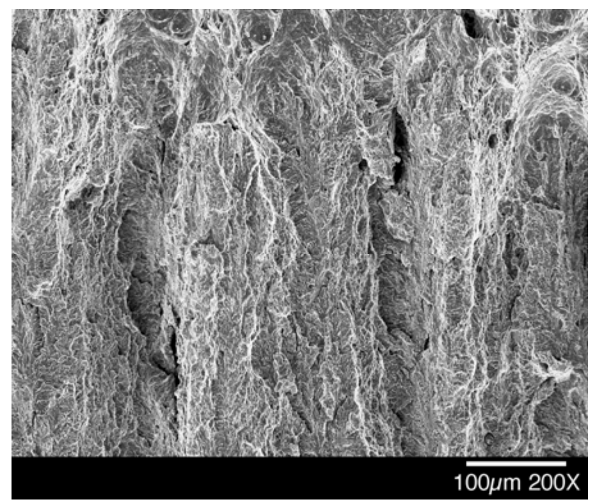
High-pressure H_2 gas severely degrades crack propagation resistance of X100 steel



X100 in air



X100 in 15 kpsi H_2 gas



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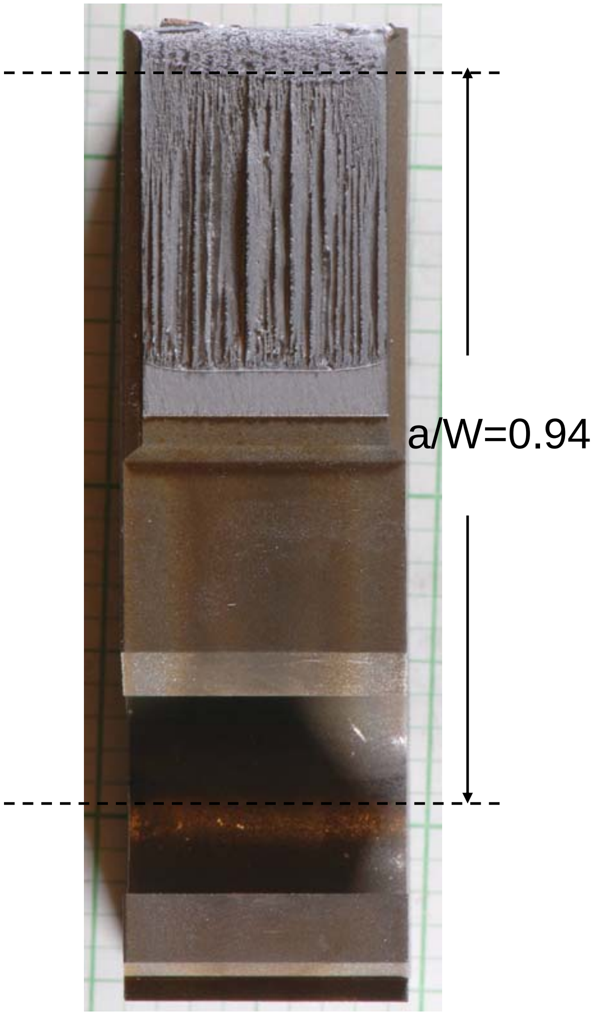
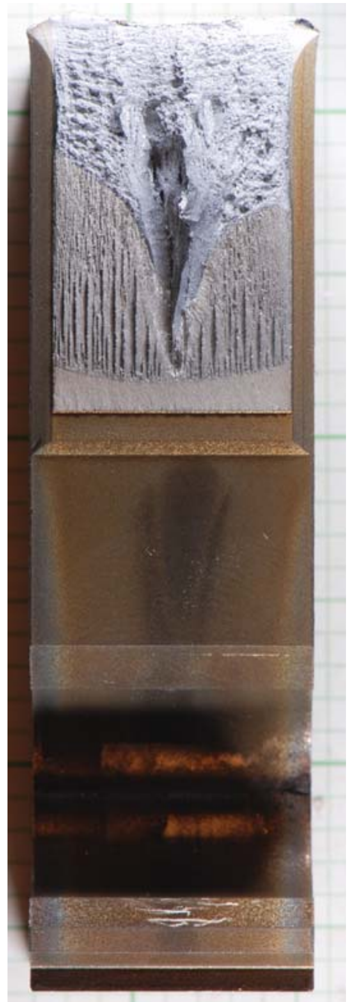
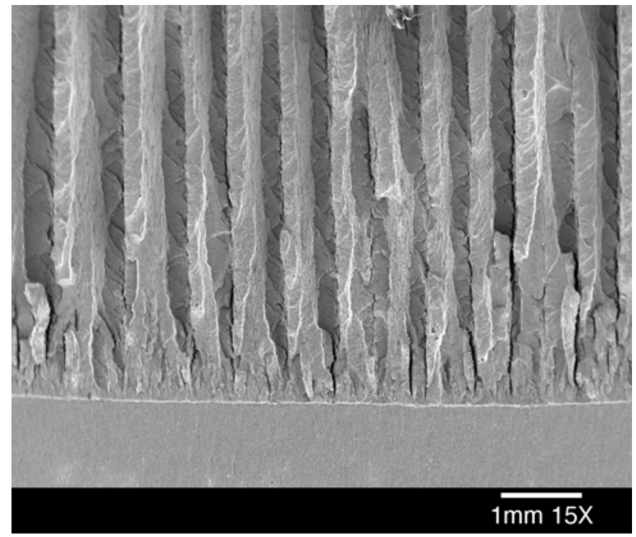
Images of fracture surfaces from X100 tested in H_2 show long crack lengths and delaminations

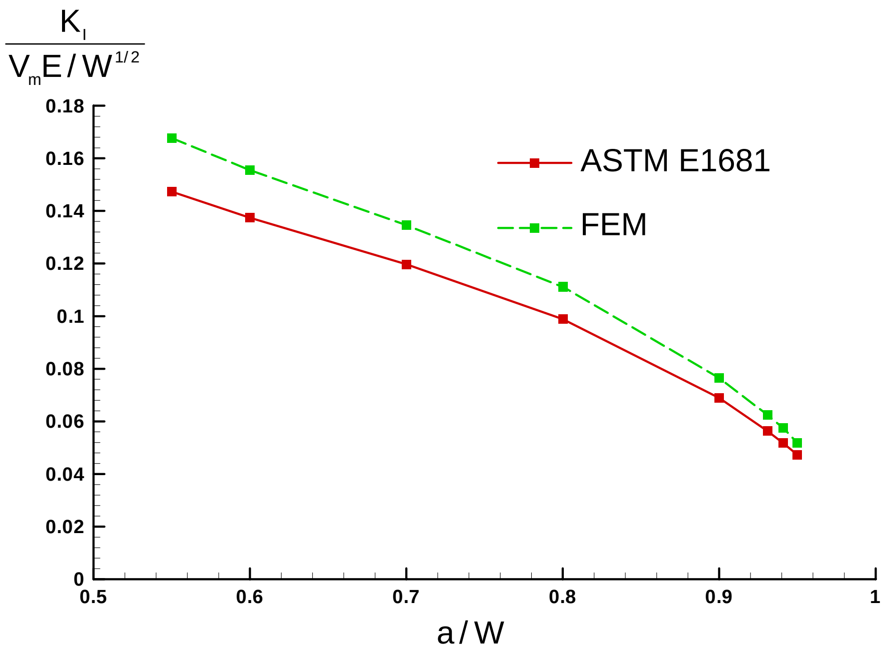




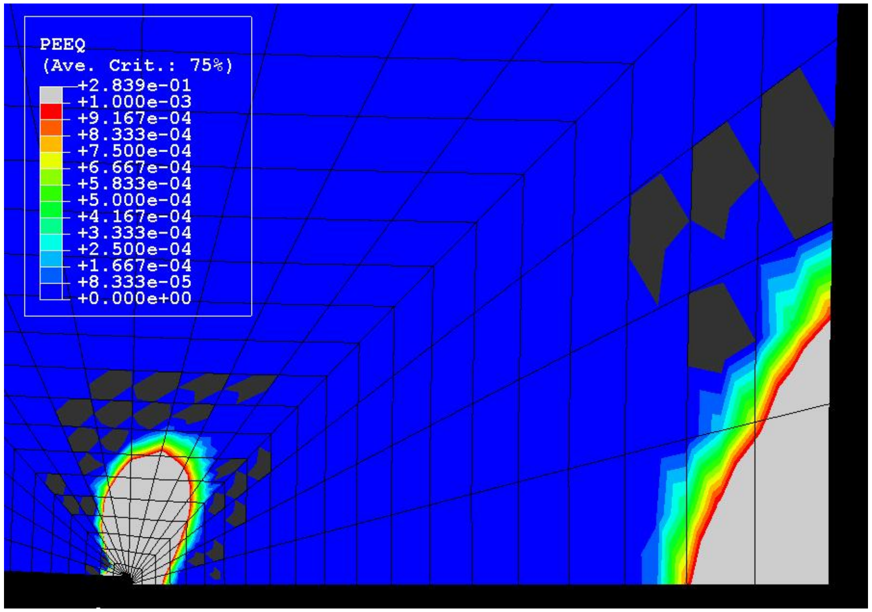
H_2-assisted crack extension from precrack



FEM calculations verify K solution and demonstrate K dominance for long cracks in WOL specimen



$a/W = 0.9408$



ASTM E1681: $K_I = 57.5 \text{ MPa}\sqrt{\text{m}}$

FEM elastic: $K_I = 63.8 \text{ MPa}\sqrt{\text{m}}$

FEM plastic: $J = 16008 \text{ N/m}$

$$K_I = \sqrt{\frac{JE}{1-\nu^2}} \qquad K_I = 62.2 \text{ MPa}\sqrt{\text{m}}$$

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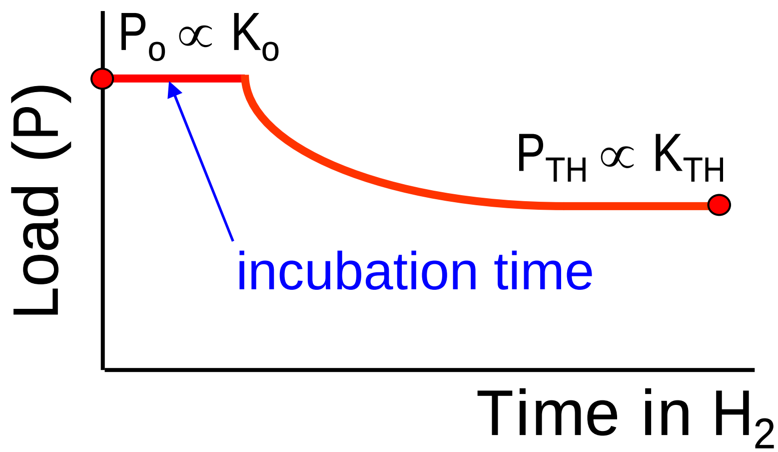
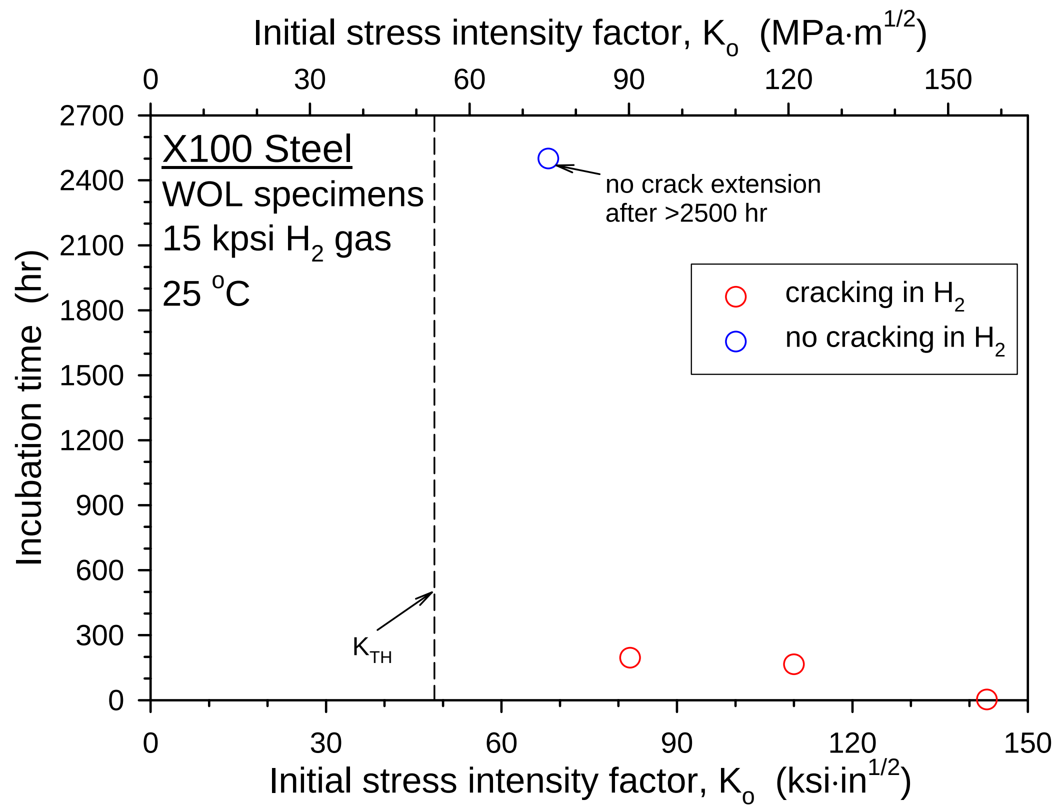
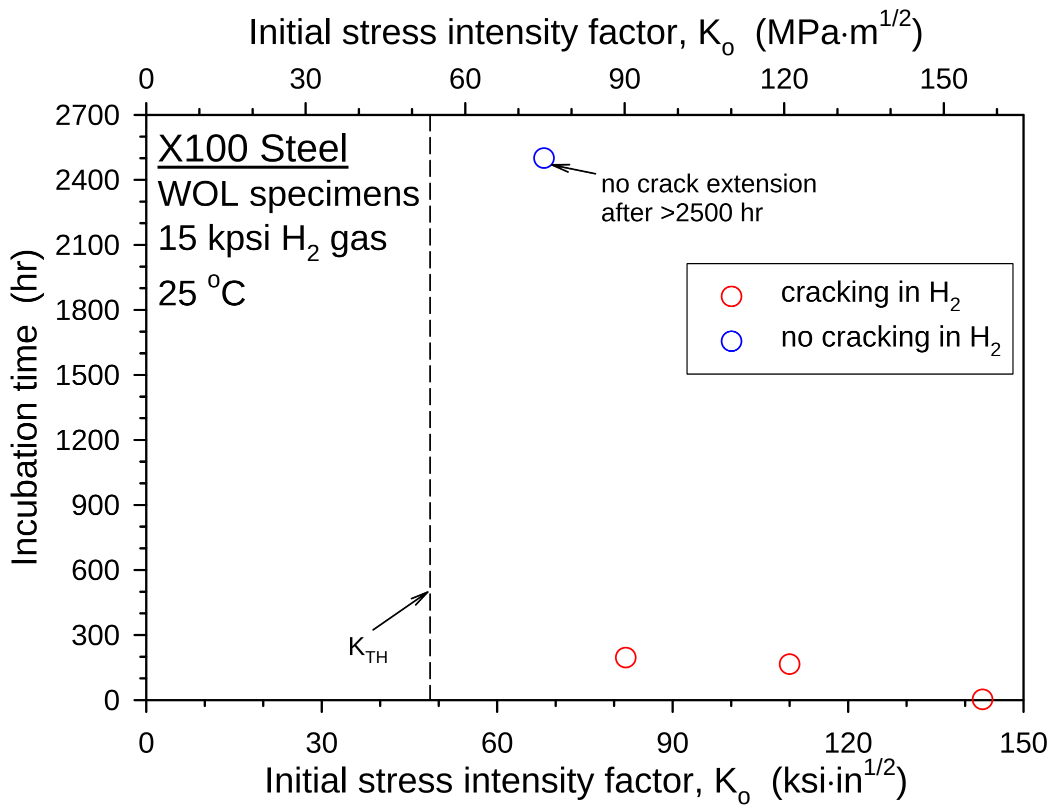
Incubation time for crack extension depends on K_o

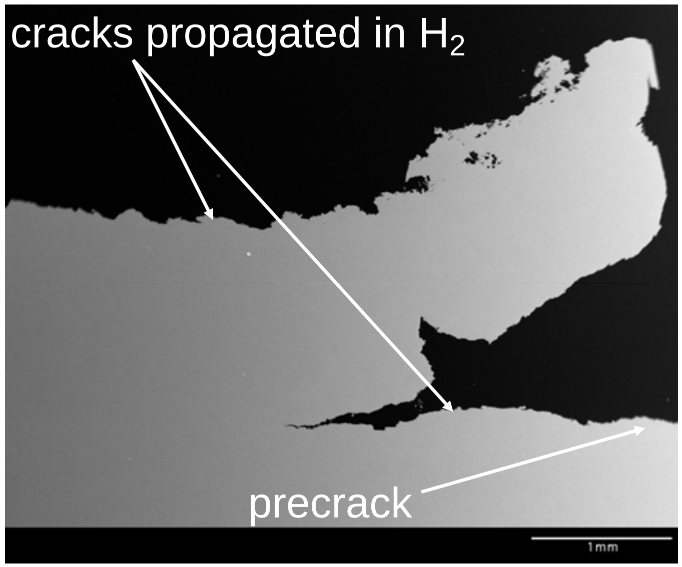




Measurement of sustained-load cracking threshold in H_2 cannot be assured unless crack propagates

Crack branching may account for no crack extension in specimens with $K_o > K_{TH}$





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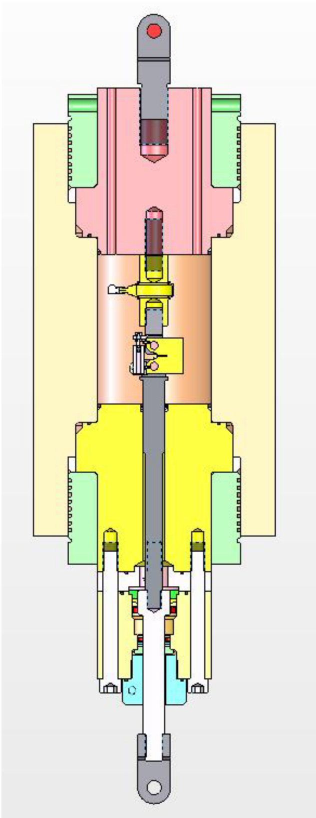
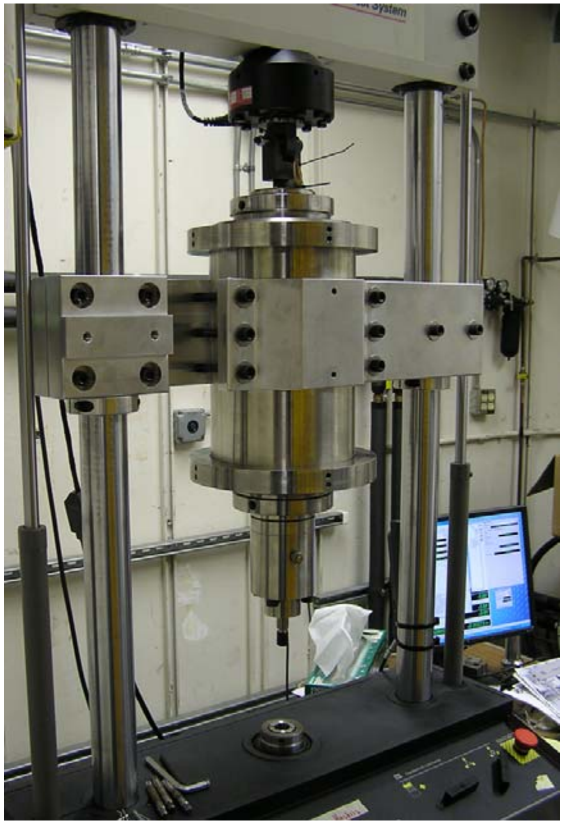
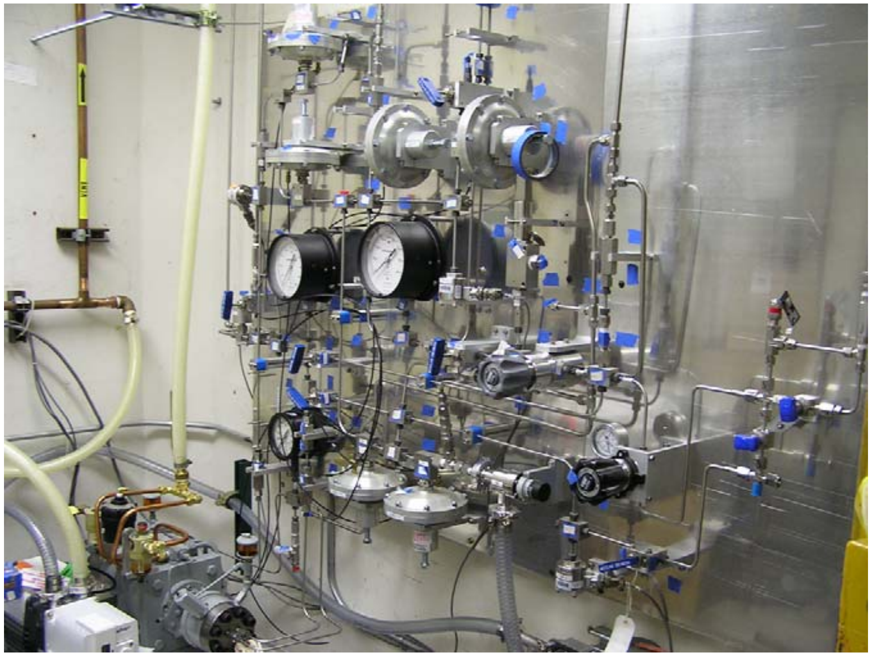
System for measuring fatigue crack growth in high-pressure H_2 nearly complete

vessel on mechanical test frame





gas manifold



- Pressure vessel can contain H_2 gas up to 20 kpsi (138 MPa)

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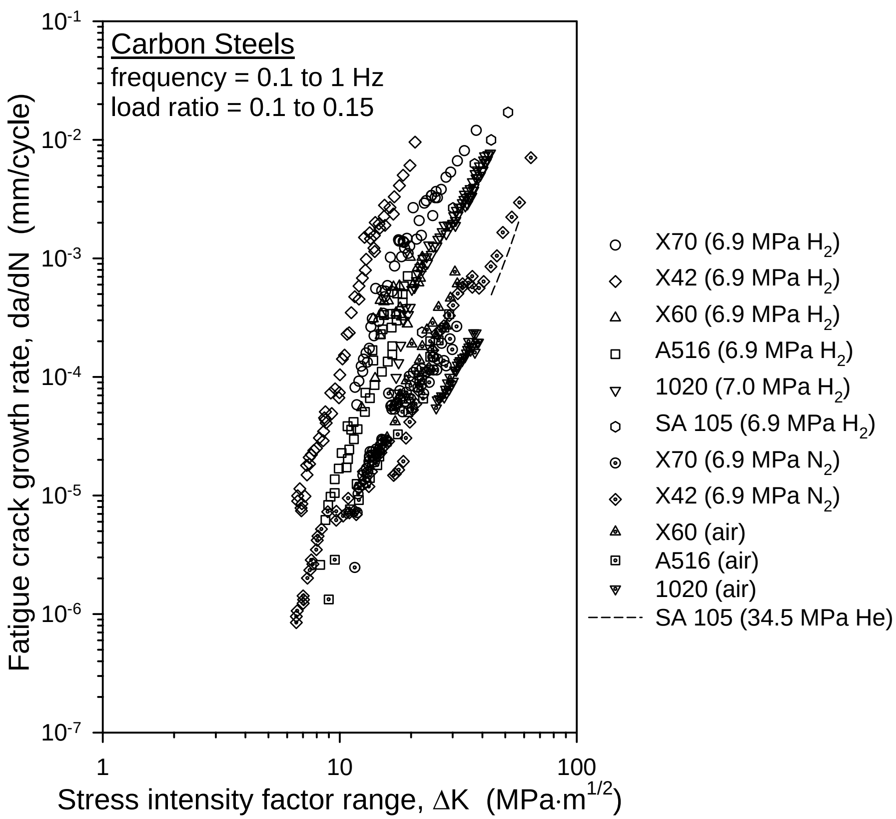
What is metric for qualifying steels for H_2 pipelines?

Tech. Ref. Hydrogen Compatibility of Materials, www.ca.sandia.gov/matlsTechRef



- Fatigue crack growth rates in H_2 greater than growth rates in air or inert gas
- Fatigue crack growth rates in H_2 vary by factor of 10

What is acceptable fatigue crack growth rate?

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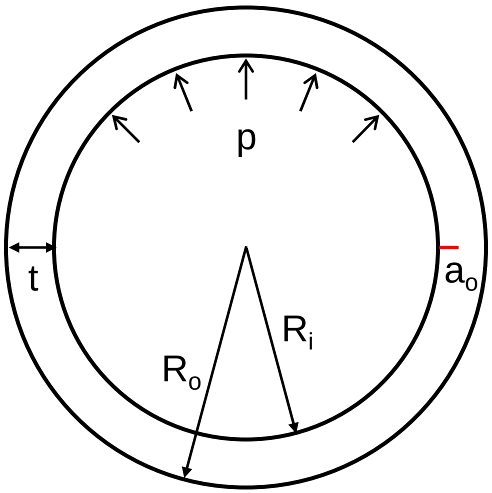
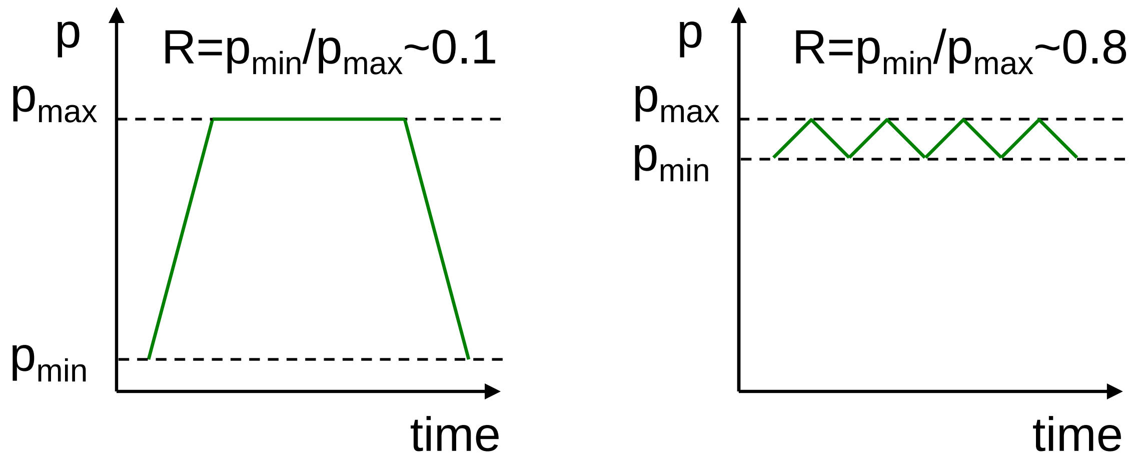
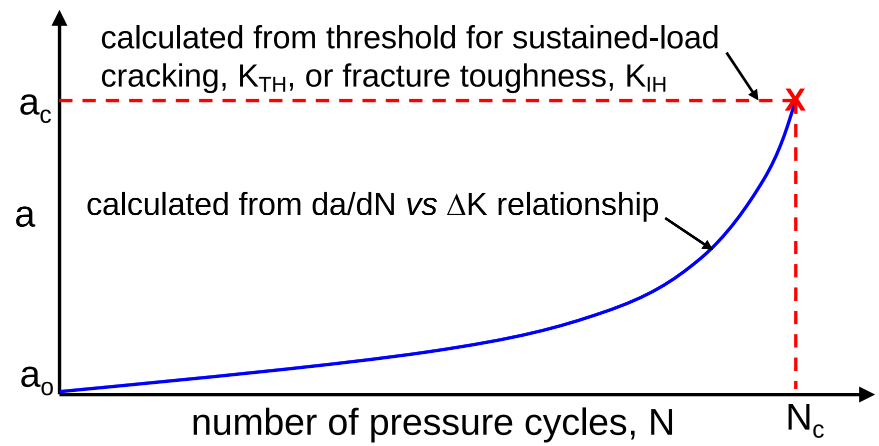
Assess fatigue crack growth data by conducting fracture mechanics analysis of pipeline



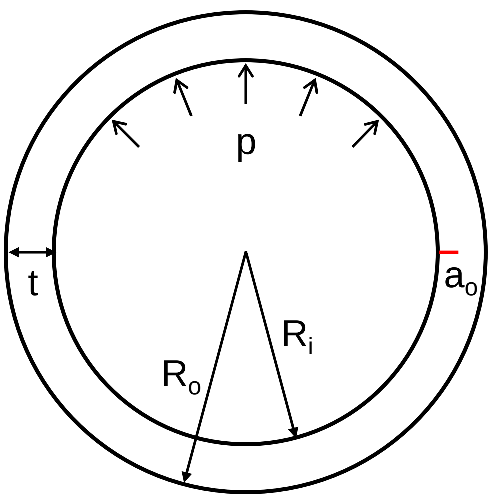
- Assume pipeline subjected to pressure cycling



- Calculate number of pressure cycles for crack to reach critical depth



Assume steel, dimensions, and maximum pressure are similar to current H_2 pipelines



- Data for Air Products H_2 pipelines
  (ASME, *Interim Standardization Report*, 2005)
  - API 5L X42 steel, manufactured with ERW
  - Inner radius, R_i = 6.0 in
  - Wall thickness, t, from 0.219 to 0.500 in

- Maximum operating pressure, p = 1500 psi

- Assume existing defect with depth a_o and length parallel to pipeline axis
  - Simulates defect along manufacturing (seam) weld

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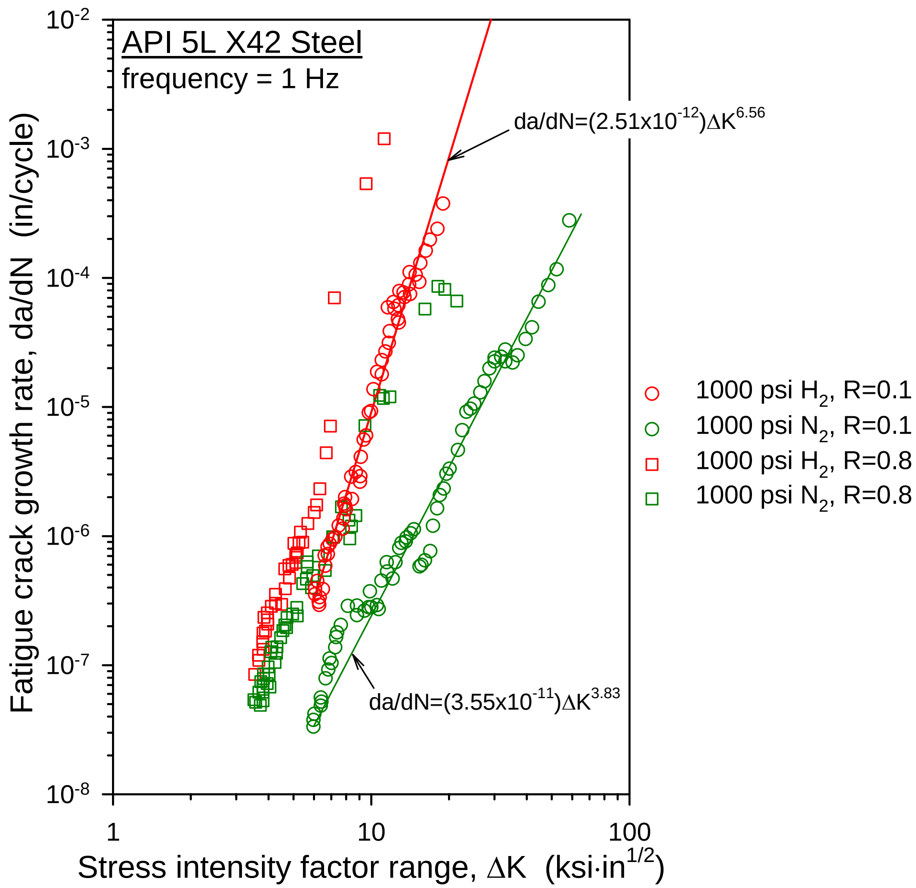
Select appropriate material property data

Cialone et al., *Met Trans A*, 1985



- Need da/dN *vs* ΔK for X42 ERW in 1500 psi H_2 gas
  - assume data for 1000 psi H_2 gas representative
  - assume data for weld and base metal are similar
- Need da/dN *vs* ΔK at relevant R ratio and frequency
  - pressure cycling parameters for pipeline unknown
  - use data at R=0.1 and frequency=1 Hz
- Need fracture toughness for X42 ERW in 1500 psi H_2 gas
  - K_{IH}=44 ksi·in$^{1/2}$ in 1000 psi H_2
    (Cialone et al., *ASTM STP 962*, 1988)

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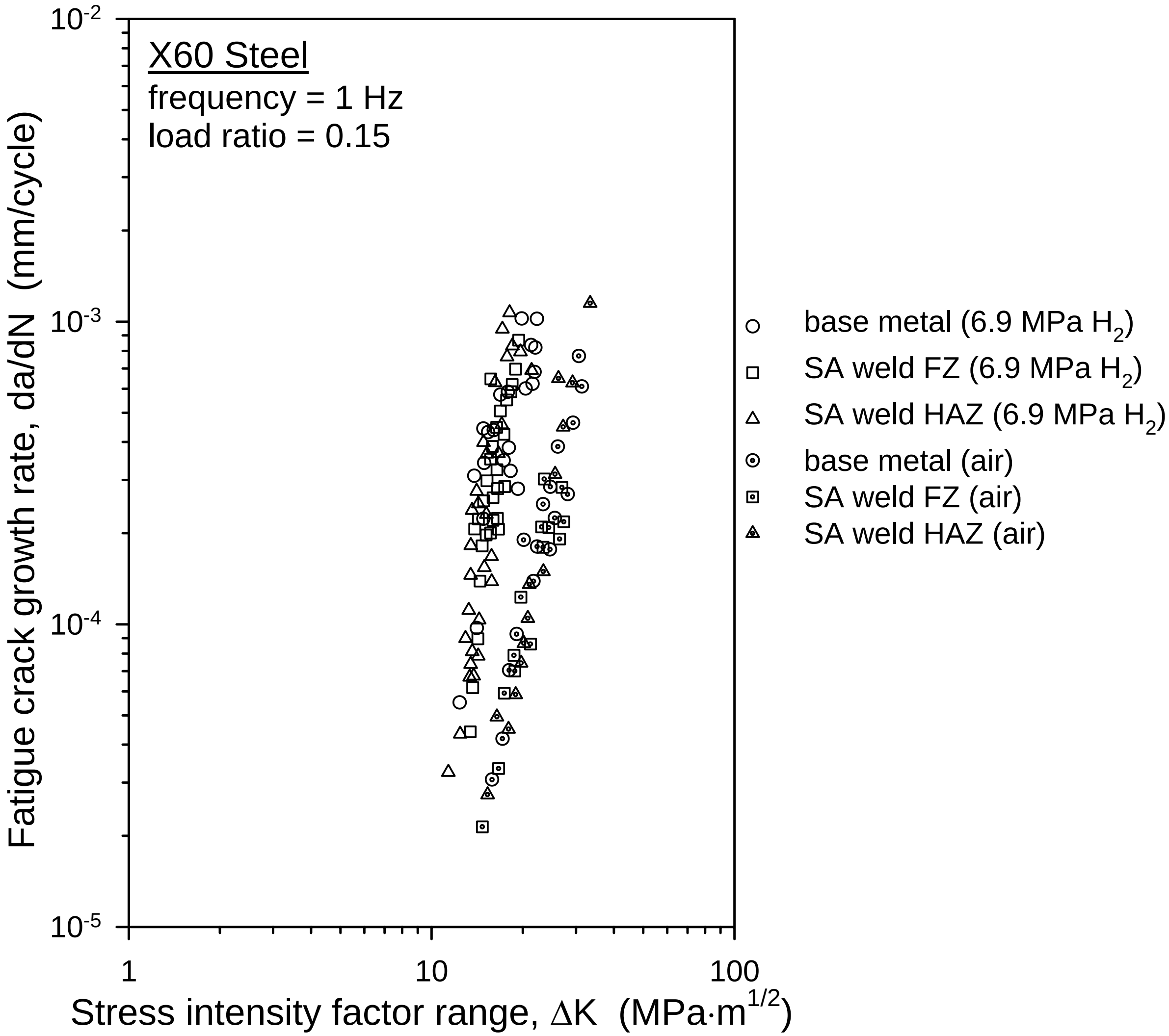
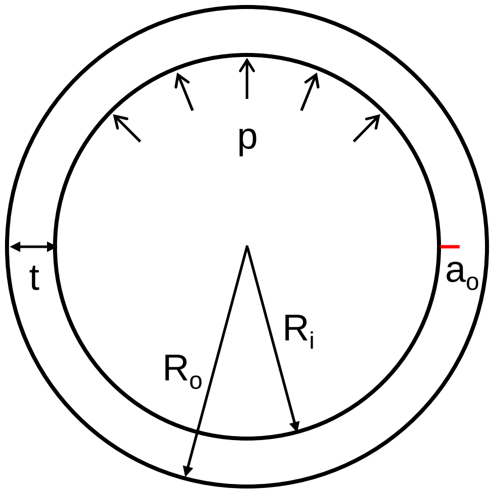
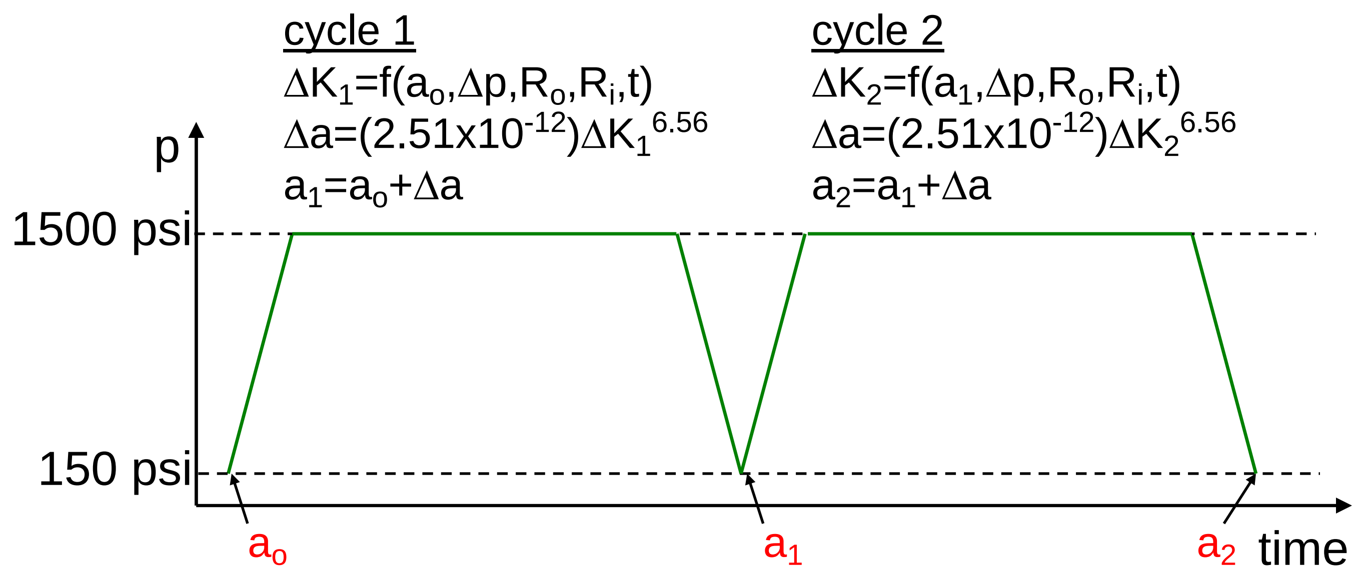
Fatigue crack growth rates similar in base metal, fusion zone, and HAZ for X60 steel

Wachob, NASA-CR-166334, 1981



Calculate number of pressure cycles to reach critical crack depth for three cases





- Case 1: t=0.330 in (σ_h=65% SMYS) and a_o/t=0.10
- Case 2: t=0.500 in (σ_h=43% SMYS) and a_o/t=0.10
- Case 3: t=0.500 in (σ_h=43% SMYS) and a_o/t=0.05

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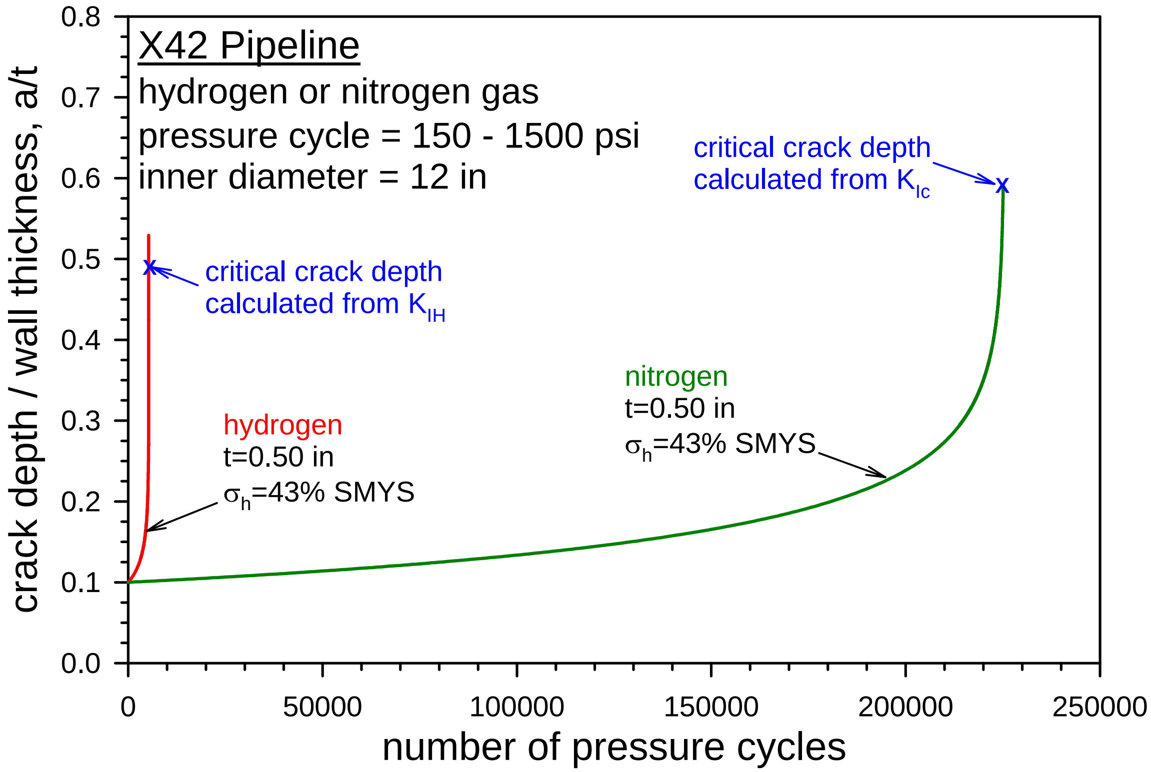
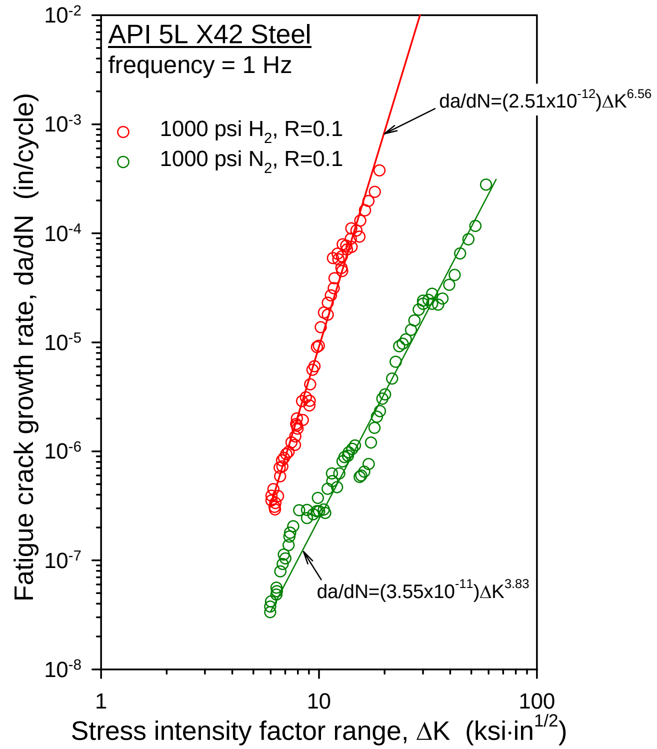
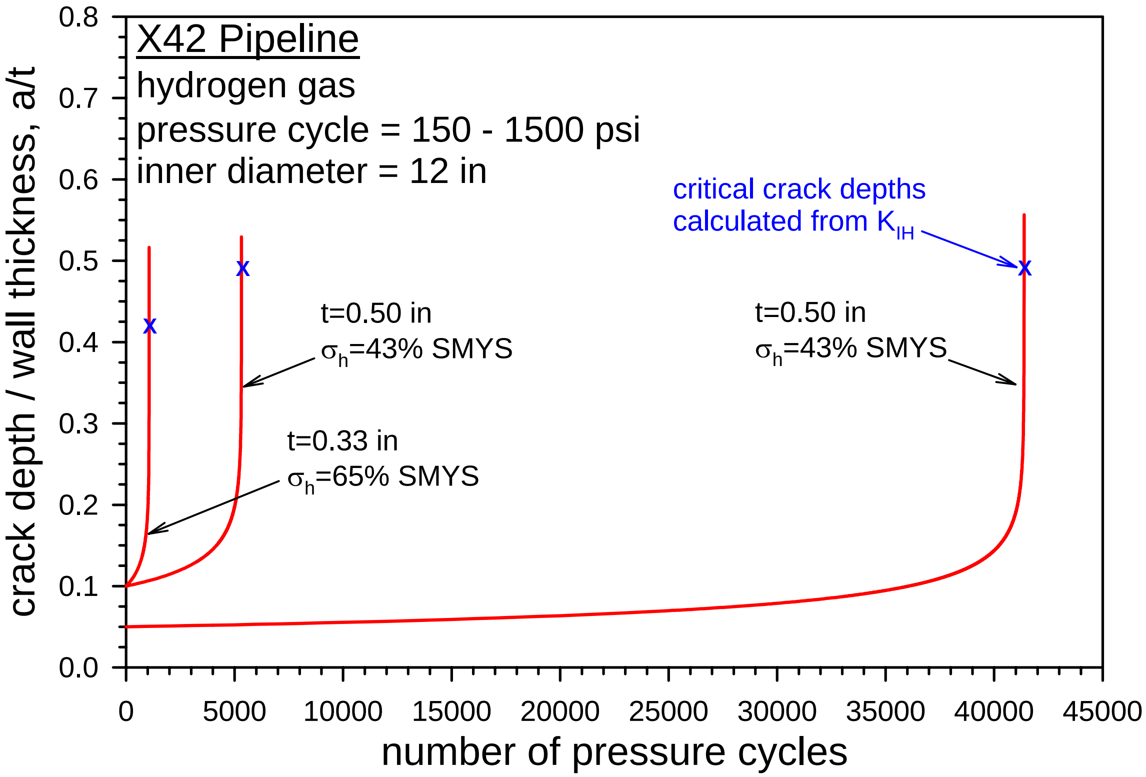
Number of pressure cycles *vs* crack depth relationships: H_2 compared to inert gas

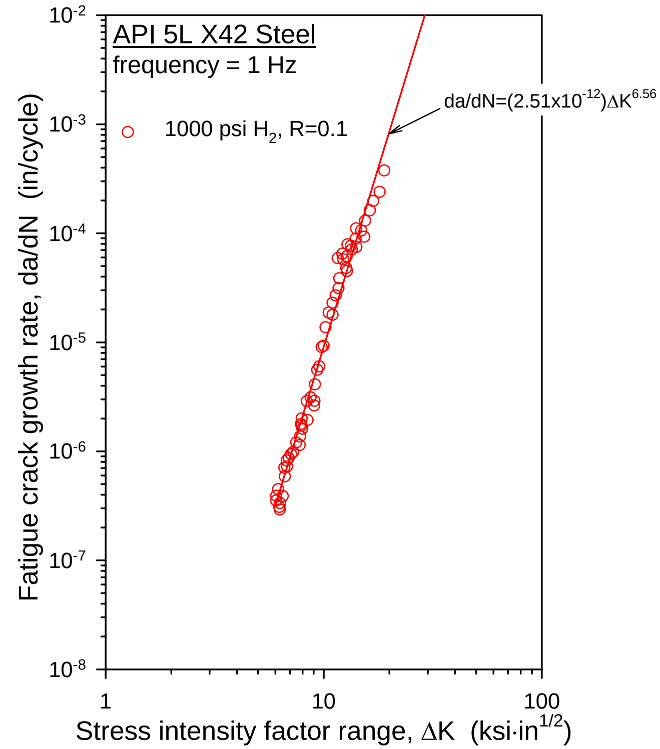




Number of cycles to critical crack depth reduced by about factor of 40 in H_2 compared to inert gas

Number of pressure cycles *vs* crack depth relationships in H_2 for varying dimensions





Number of cycles to critical crack depth is sensitive to applied stress and initial crack depth

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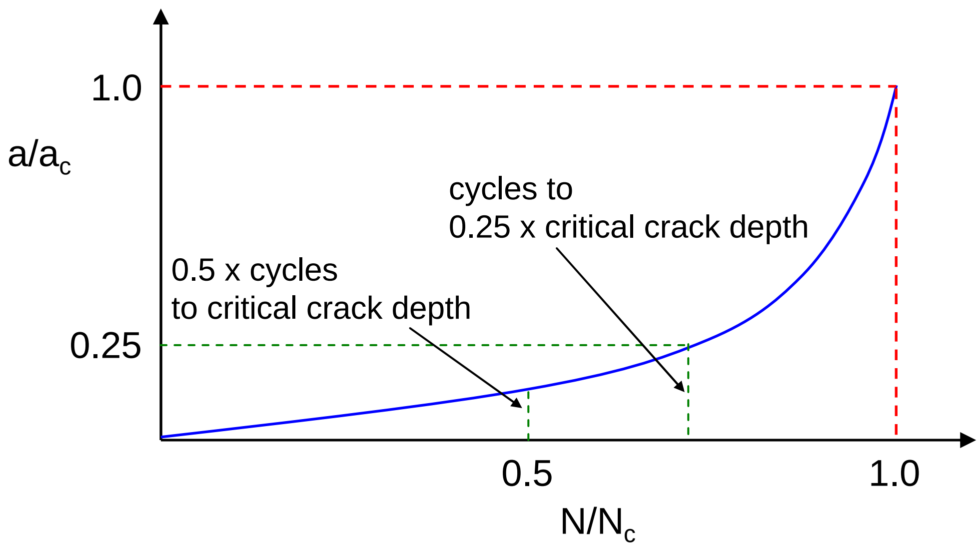
ASME applies safety factors on critical crack depth and number of cycles to critical crack depth



Environment	t (in)	σ_h	a_o/t	cycles to 0.25 x a_c	0.5 x N_c
H_2	0.330	65% SMYS	0.10	170	535
H_2	0.500	43% SMYS	0.10	2,735	2,660
H_2	0.500	43% SMYS	0.05	38,790	20,690
inert	0.500	43% SMYS	0.10	125,260	112,545

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Lifetime of steel hydrogen pipeline depends on both material properties and structural design

- Fatigue crack growth law
  - $da/dN = C\Delta K^n$ in stage II
- Fracture toughness or threshold for sustained-load cracking
  - does not significantly affect cycles to critical crack depth
- Wall thickness
  - affects stress (ΔK)
- Initial crack depth
  - depends on detection limit of NDE
- Operating pressure
  - affects stress (ΔK) and material properties