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Enhancing Safety of Hydrogen Containment Components Through Materials Testing Under In-Service Conditions

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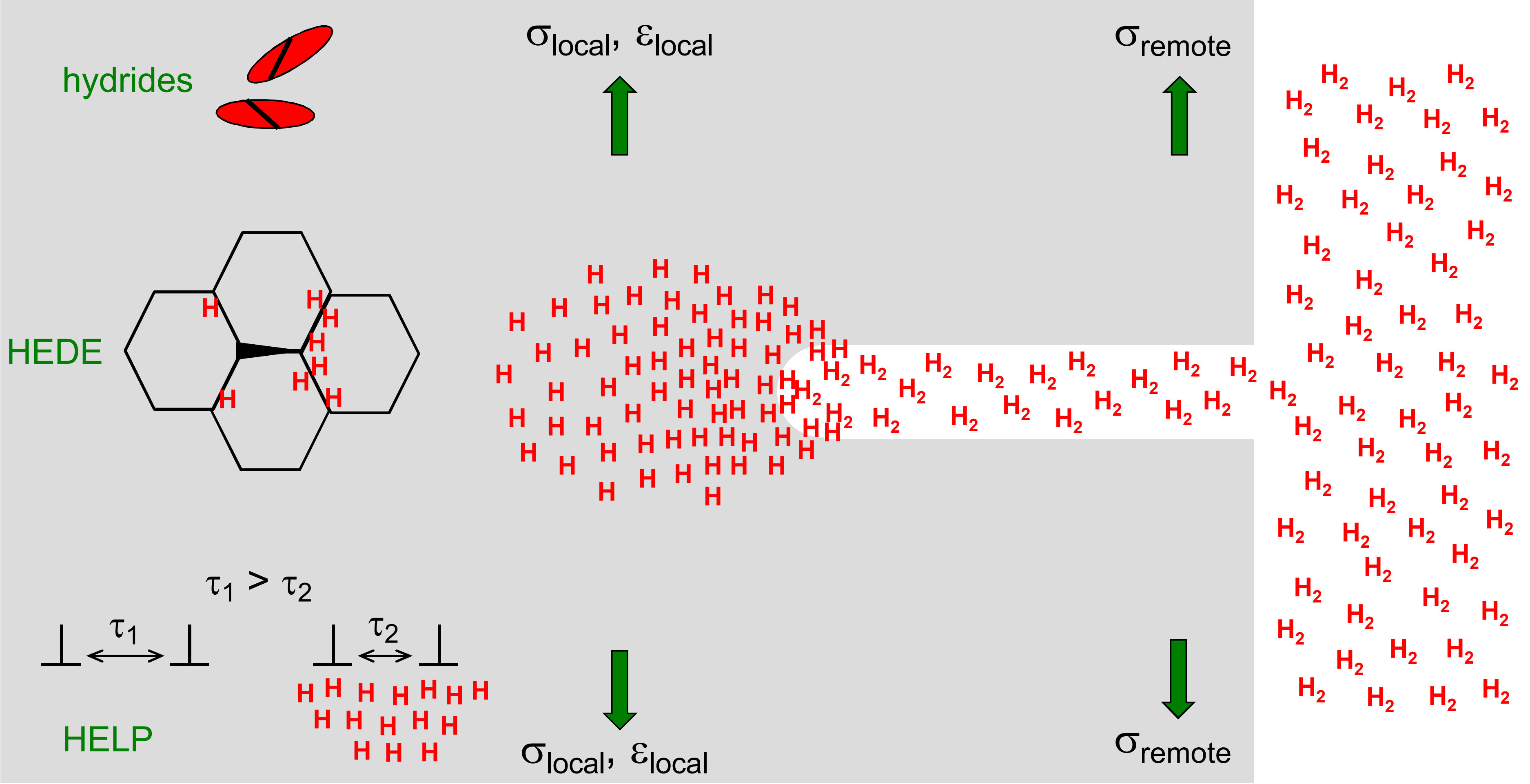
Hydrogen can permeate into containment materials and activate hydrogen embrittlement

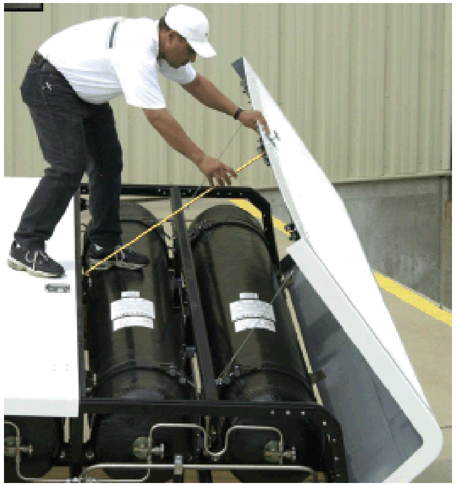


Mobility of H at ambient temperature distinguishes it from other embrittlement species (e.g. S, P)

Materials in range of H_2 containment components can be susceptible to hydrogen embrittlement

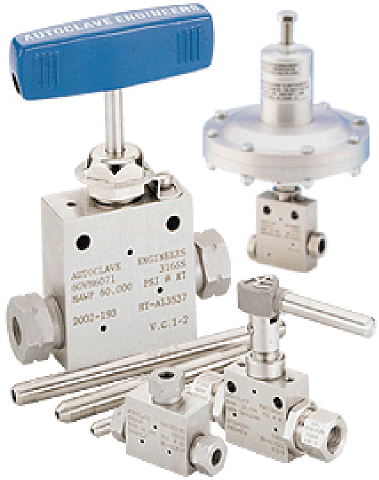
stationary and transport vessels
(martensitic steels)

on-board tanks
(stainless steel boss)

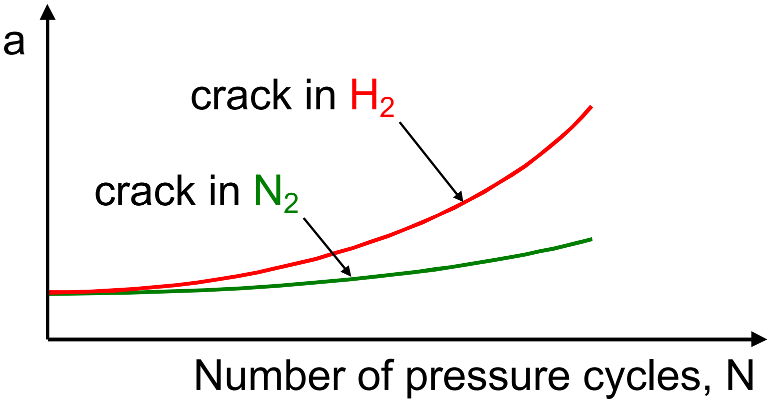


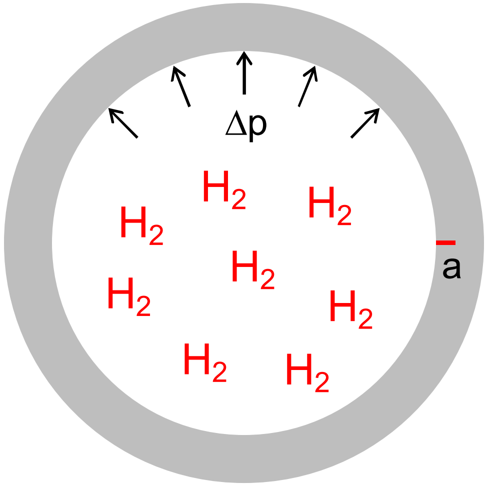
pipelines
(ferritic steels)

manifold components
(stainless steels)



Hydrogen embrittlement accelerates crack extension, potentially compromising component safety

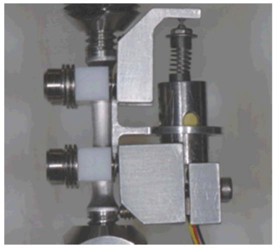


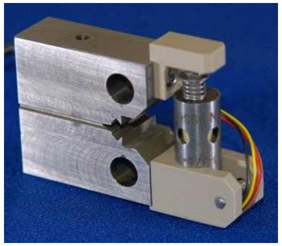


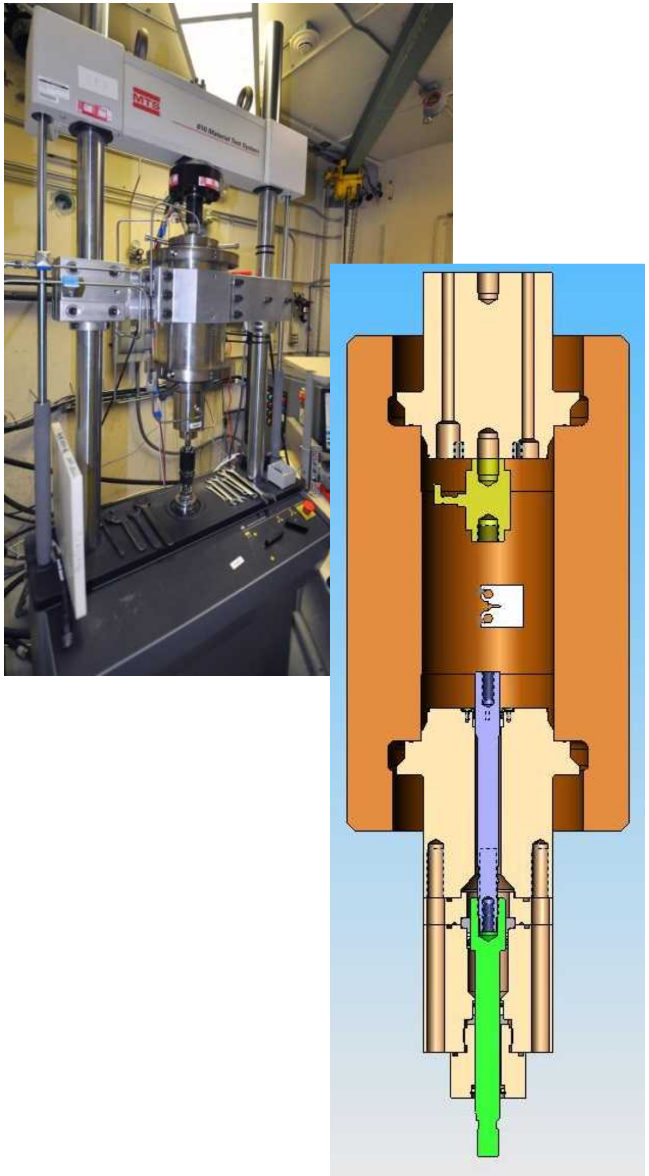
Barthélémy, 1st ESSHS, 2006

Hydrogen embrittlement accounted for in design and safety qualification through materials testing

Dynamic-Load Testing in High-Pressure H_2 Gas: concurrent mechanical loading and H_2 exposure



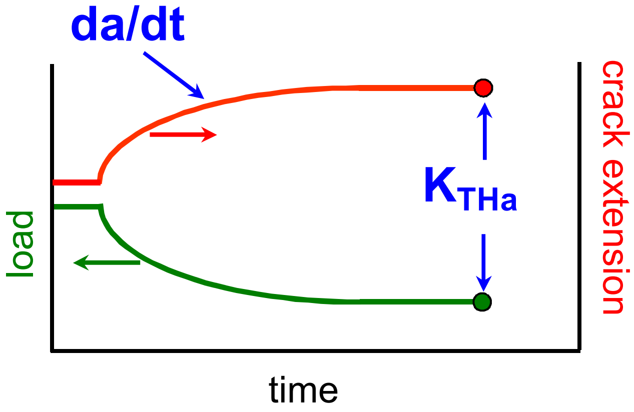


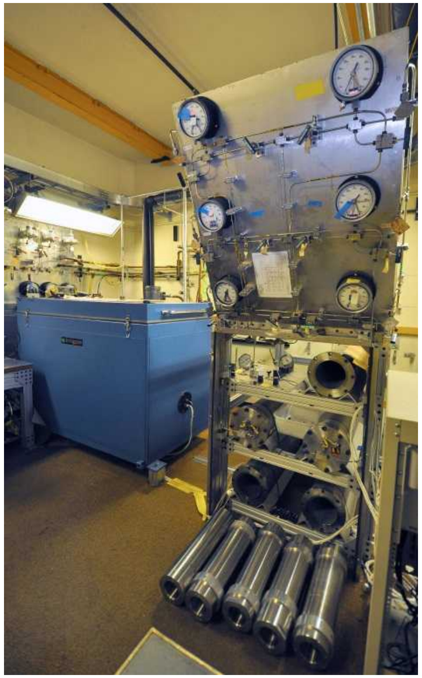


- Dynamic mechanical loading
  - Monotonic or cyclic
- Operating envelope
  - H_2 gas pressure up to 138 MPa
  - Load-cycle frequency from 10^{-3} to 10 Hz
  - Room temperature
- Instrumentation
  - Internal load cell
  - LVDT-based displacement gauges
  - Direct-current potential difference crack measurement system

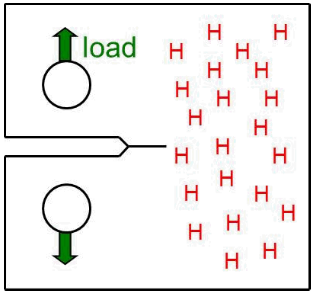
Static-Load Crack Growth Testing in H_2 Gas: concurrent mechanical loading and H_2 exposure

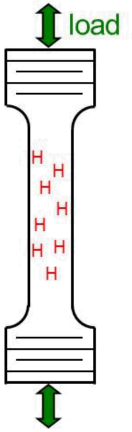
- Static mechanical loading
  - Constant displacement imposed by bolt reacting against pin
- Operating envelope
  - H_2 gas pressure up to 200 MPa
  - Temperature chamber: -70 to 170 °C
- Instrumentation
  - Reaction pins with strain gauges serve as load cells





Thermal Precharging in H_2 Gas: mechanical loading follows H_2 exposure





- Operating envelope
  - H_2 gas pressure up to 138 MPa
  - Furnace temperature up to 300 °C
- Dynamic or static mechanical loading
  - Subsequent to H_2 gas exposure
- Instrumentation
  - Load cells and displacement gauges on mechanical test frames

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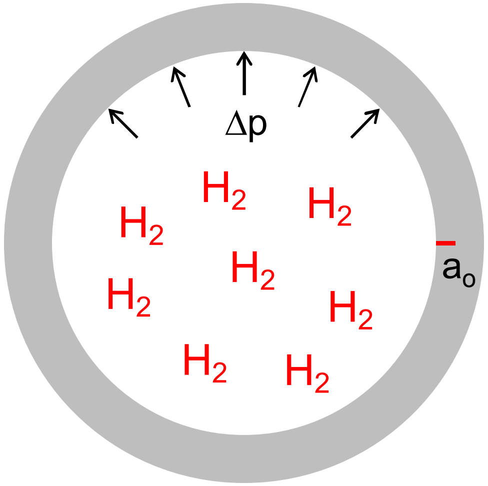
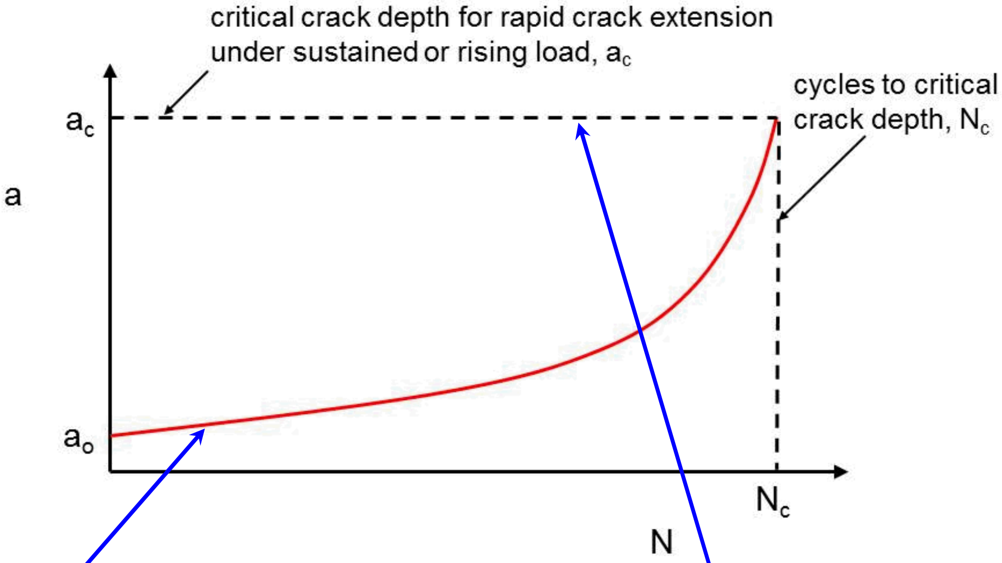
Steel pressure vessels store high-pressure compressed hydrogen at refueling stations

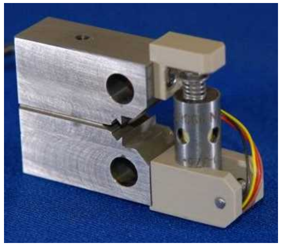
- ASME developed Article KD-10 in Section VIII-3 of Boiler and Pressure Vessel code for high-pressure H_2 vessel design
  - “Special Requirements for Vessels in High Pressure Gaseous Hydrogen Service”
  - Mandatory for seamless vessels with H_2 pressure > 41 MPa and welded vessels with H_2 pressure > 17 MPa (upper limit 100 MPa)

KD-10 requires fracture mechanics measurements on containment materials in high-pressure H_2 gas

Design life analysis in ASME Article KD-10 requires data from materials testing in H_2 gas

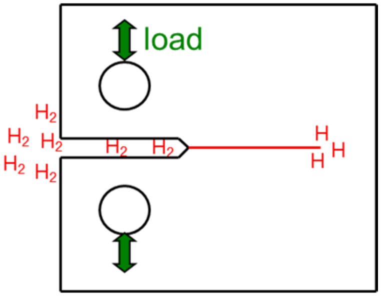


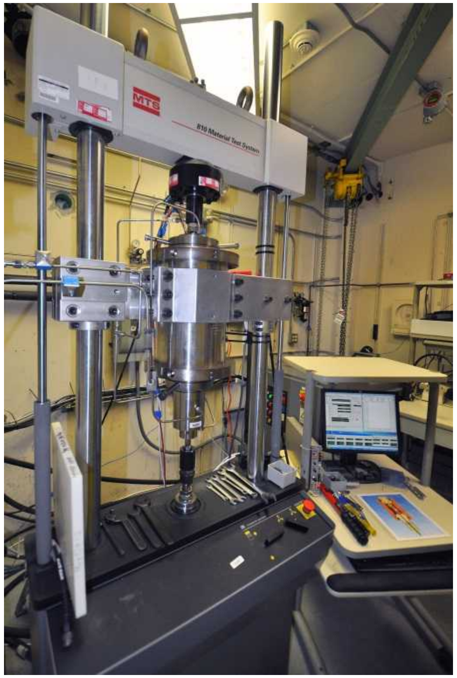




Materials testing must be performed in the service environment: high-pressure H_2 gas

Fatigue crack growth relationships measured for Cr-Mo pressure vessel steel in high-pressure H_2 gas





- Materials
  - Three different heats of SA-372 Grade J
- Instrumentation
  - Internal load cell in feedback loop
  - Crack-opening displacement measured internally using LVDT
  - Crack length calculated from compliance
- Mechanical loading
  - Triangular load-cycle waveform
  - Constant load amplitude
  - Load-cycle frequency = 0.1 Hz
- Environment
  - 99.9999% H_2 supply gas
  - Pressure = 100 MPa
  - Room temperature

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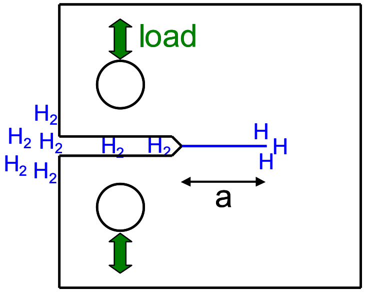
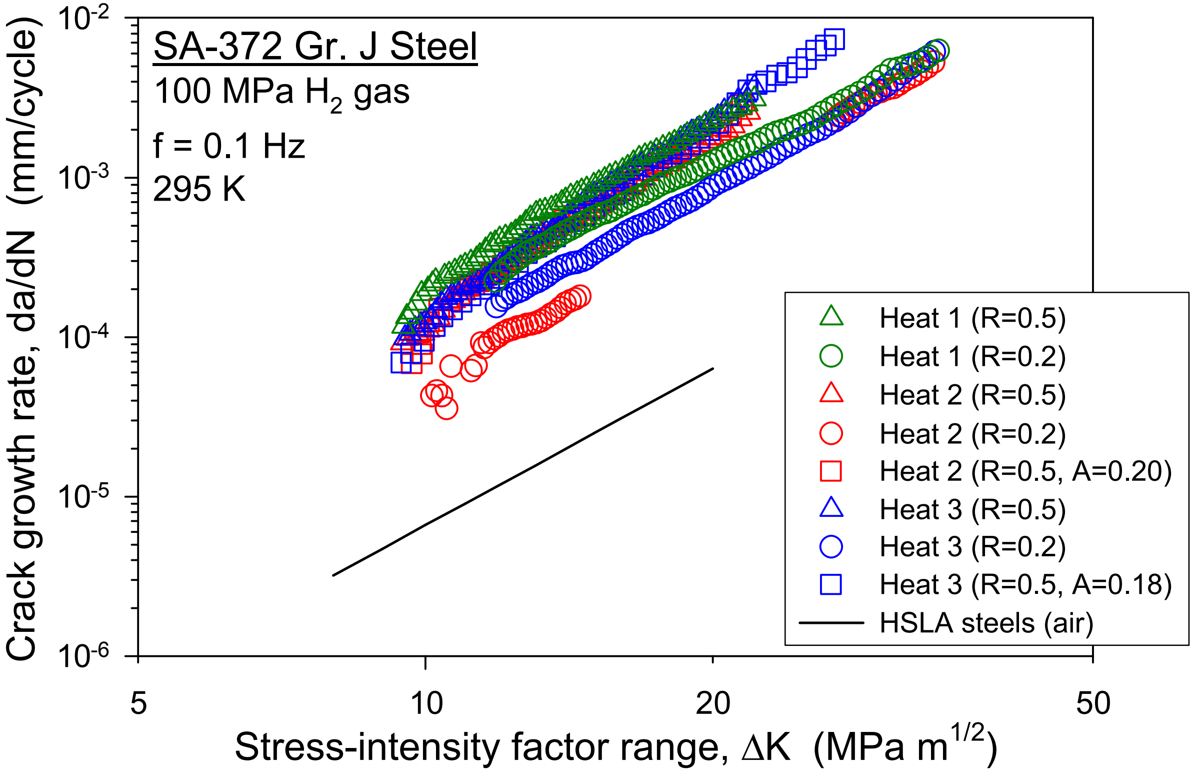
Measurements reveal significant effect of H_2 gas on fatigue crack growth rates for SA-372 Gr. J steel

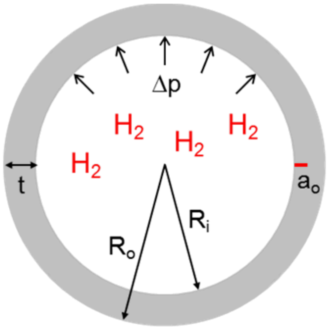


B. Somerday, C. San Marchi, K. Nibur, *ASME PVP*, 2013

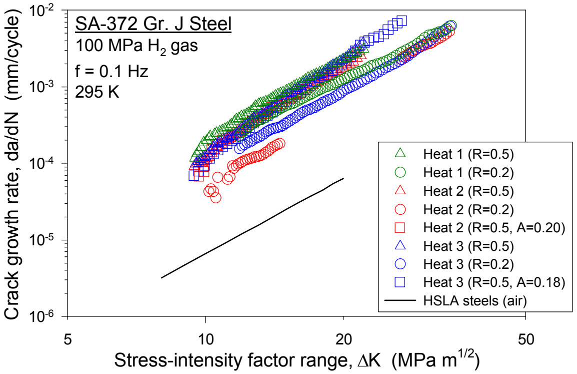


Accelerated crack growth rates in H_2 gas can be accounted for in pressure vessel design through analysis

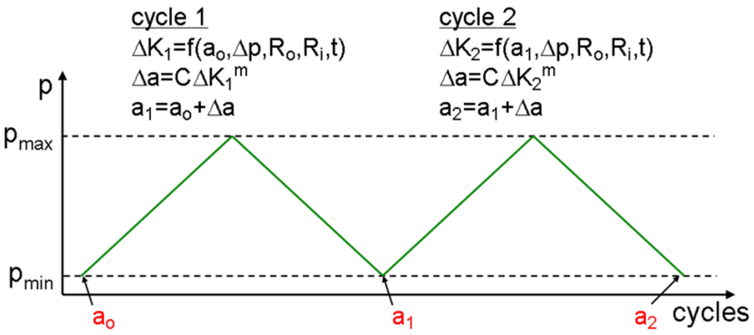
Design life analysis in ASME Article KD-10 accounts for effect of H_2 gas on fatigue crack growth rates

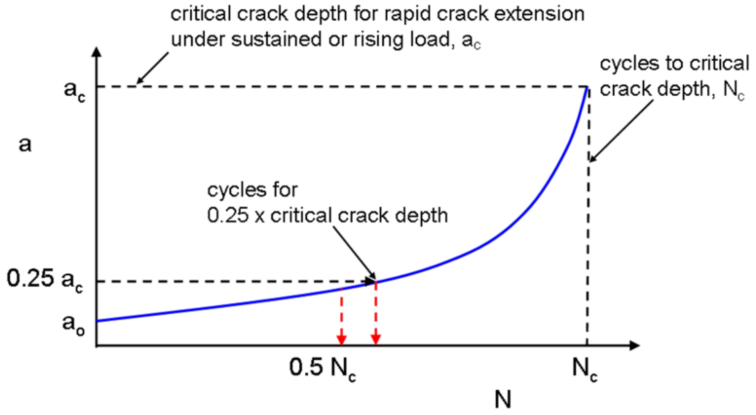


$\Delta K = \Delta p[f(a, t, R_o, R_i)]$



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





Analysis determines number of pressure cycles for safe operation of pressure vessel

Summary

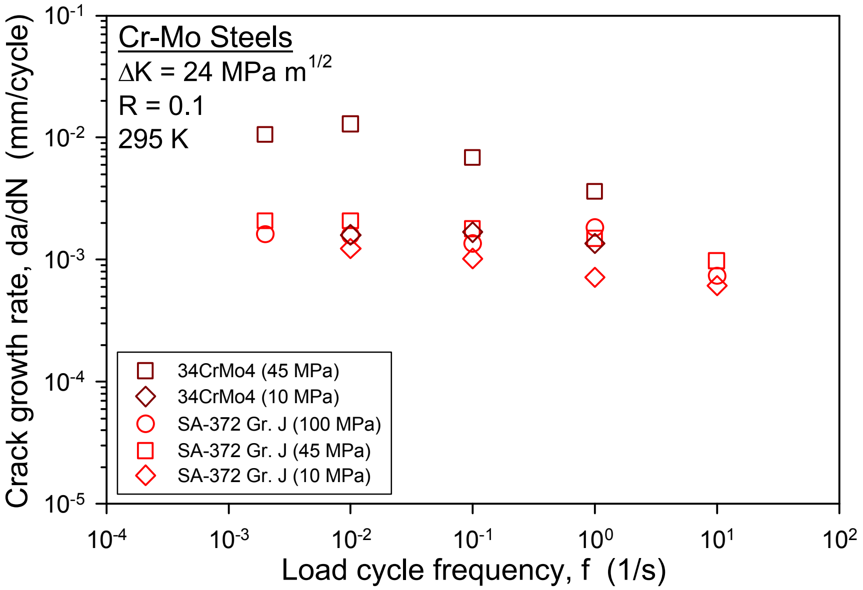
- Hydrogen embrittlement accounted for in design and safety qualification of components through materials testing

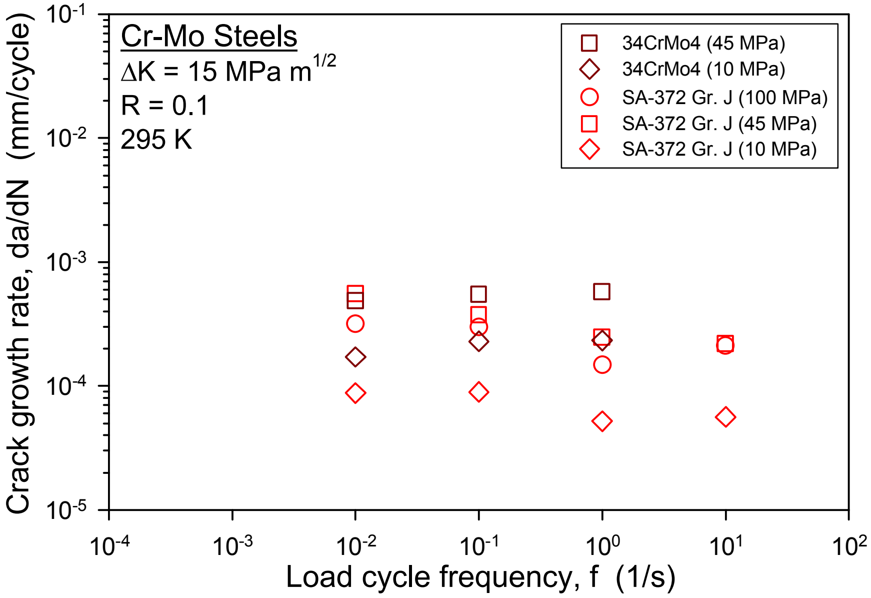
- Sandia National Laboratories features three systems for materials testing in H_2 gas:
  - Dynamic-Load Testing in High-Pressure H_2 Gas
  - Static-Load Crack Growth Testing in H_2 Gas
  - Thermal Precharging in H_2 Gas
  - ***Distinguishing feature: high-pressure (>138 MPa) H_2 gas***

- Materials testing at Sandia National Laboratories motivated by developing and exercising standards
  - Fatigue crack growth testing of pressure vessel steel in H_2 gas supported design-life calculation prescribed in ASME code

Back-up Slides

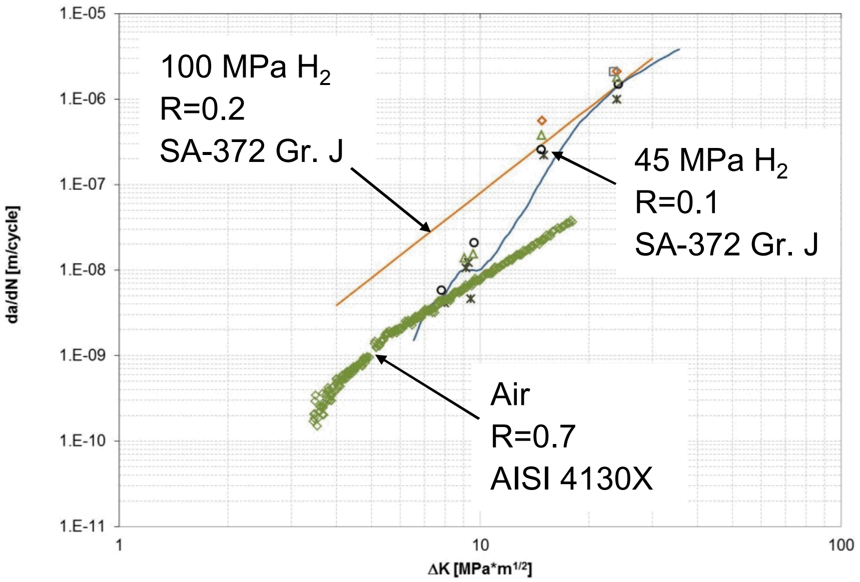
Measurement of da/dN vs. frequency indicates that crack growth rates at 10 Hz are not upper bounds

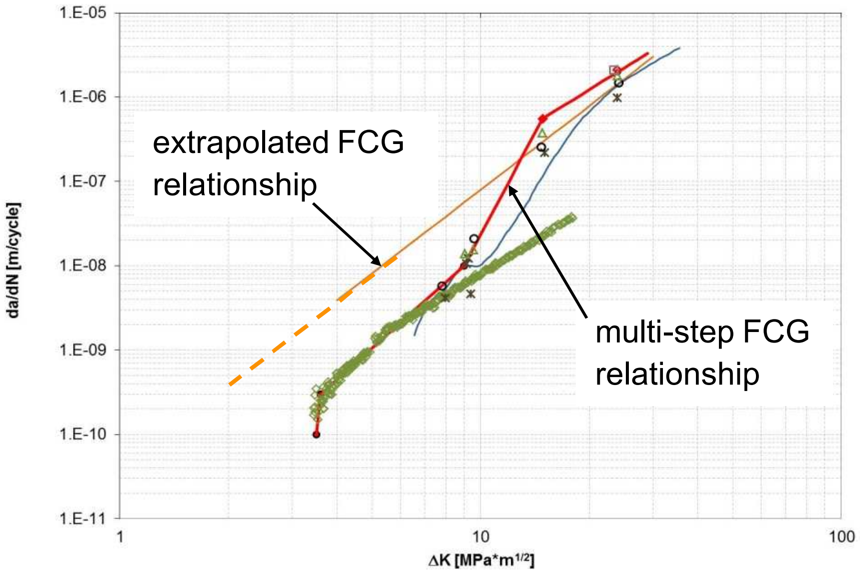




- *General trend: da/dN increases as frequency decreases, then reaches plateau value*
  - Most pronounced for 34CrMo4 steel in 45 MPa H_2 gas at $\Delta K = 24$ MPa $m^{1/2}$
- da/dN vs. f data reveal effects of material and environmental variables
  - Higher-strength 34CrMo4 steel generally more susceptible to hydrogen-accelerated fatigue crack growth than lower-strength SA-372 Gr. J steel
  - Crack growth rates for SA-372 Gr. J steel equal at 45 and 100 MPa H_2 pressure

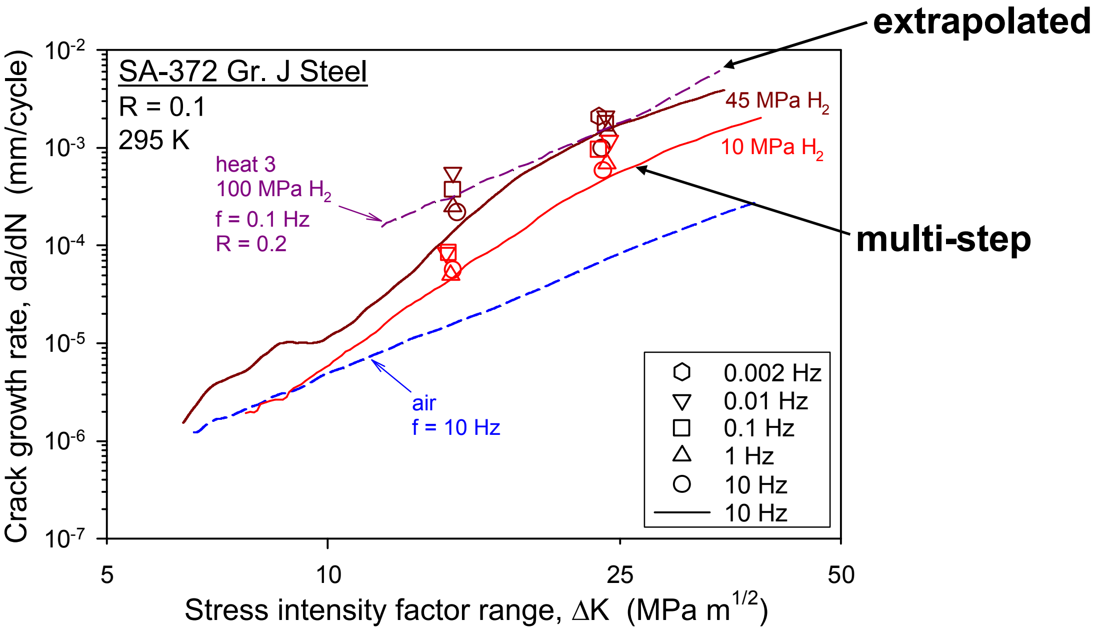
Extrapolated and multi-step FCG relationships formulated from multiple data sets





- Extrapolated FCG relationship: SA-372 Gr. J at 100 MPa H_2 and 0.1 Hz
  - Crack growth rates do not vary with H_2 pressure above 45 MPa
- Multi-step FCG relationship: SA-372 Gr. J at 45 MPa H_2 and 4130X in air
  - At intermediate and high ΔK, curve fit to upper-bound crack growth rates
- Assumption: relative differences between extrapolated and multi-step FCG relationships maintained at higher R ratios (i.e., R = 0.5 and 0.7)

Fatigue-life analysis for manufactured vessel: consider extrapolated and multi-step FCG relationships

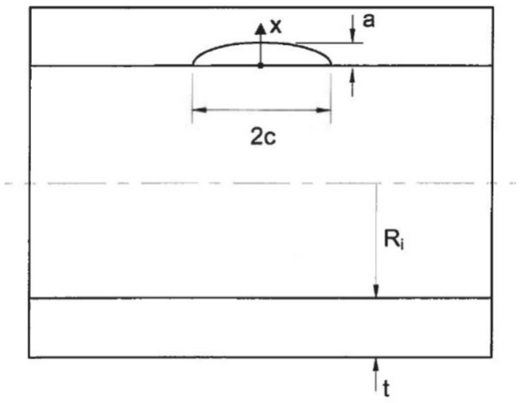


- Double-neck cylinder designed according to EN-1964-1 + 2010/35/EU (TPED qualification)
  - 220 x 9.1 mm (OD x WT min)
  - MAWP = 28 MPa
  - Fabricated from 34CrMo4 steel (S_y min = 600 MPa, 780 < S_u < 890 MPa): not ASME-qualified, but cylinder thickness compliant with Section VIII-2
  - For fatigue-life calculations, assume SA-372 Gr. J steel

Fatigue-life analysis follows fracture mechanics approach using K solutions from API579-1/ASME FFS1

Applied K solution for internally pressurized cylinder with longitudinal-oriented, semi-elliptical surface crack

$$K_I = \frac{pR_0^{\,2}}{R_0^{\,2} - R_i^{\,2}}\left[2G_0 - 2G_1\left(\frac{a}{R_i}\right) + 3G_2\left(\frac{a}{R_i}\right)^2 - 4G_3\left(\frac{a}{R_i}\right)^3 + 5G_4\left(\frac{a}{R_i}\right)^4\right]\cdot\sqrt{\frac{\pi a}{Q}}$$



Semi-elliptical defect size and shape:

- Depth: a = 0.455 mm (5% min WT)
- Length: c = 1.365 mm (a/2c = 1/3, as specified in KD-4)

Crack depth (a) vs. number of cycles (N) calculated from two different fatigue crack growth relationships:

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

Extrapolated: single power-law relationship fit only to high-ΔK data

Multi-step: multiple power-law relationships fit to data in low-, intermediate-, and high-ΔK ranges

Fatigue crack growth relationship has prominent effect on calculated pressure vessel design life

Δp	FCG relationship	Allowable # cycles
14 – 28 MPa (50% MAWP)	extrapolated	36,000
	multi-step	179,000
19.6 – 28 MPa (30% MAWP)	extrapolated	194,000
	multi-step	∞

Developing test procedures that allow construction of reliable multi-step FCG relationship has significant impact