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Structural Design Methods and Materials Testing for H_2 Storage Tanks and Pipelines

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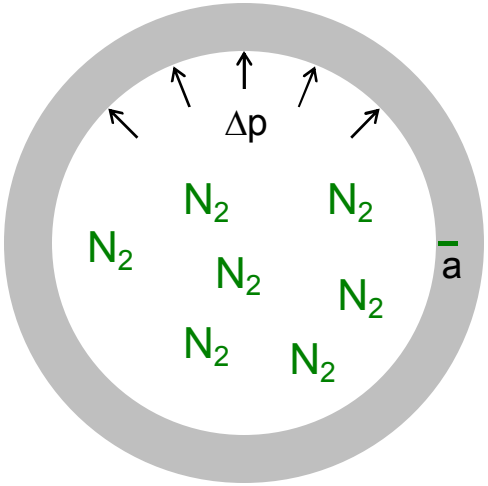
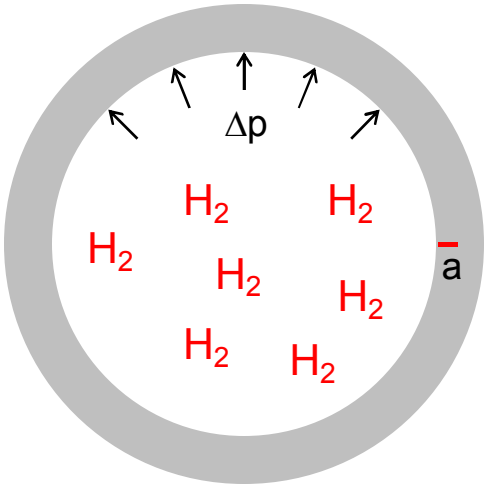
Tanks and pipelines are important components in hydrogen energy infrastructure

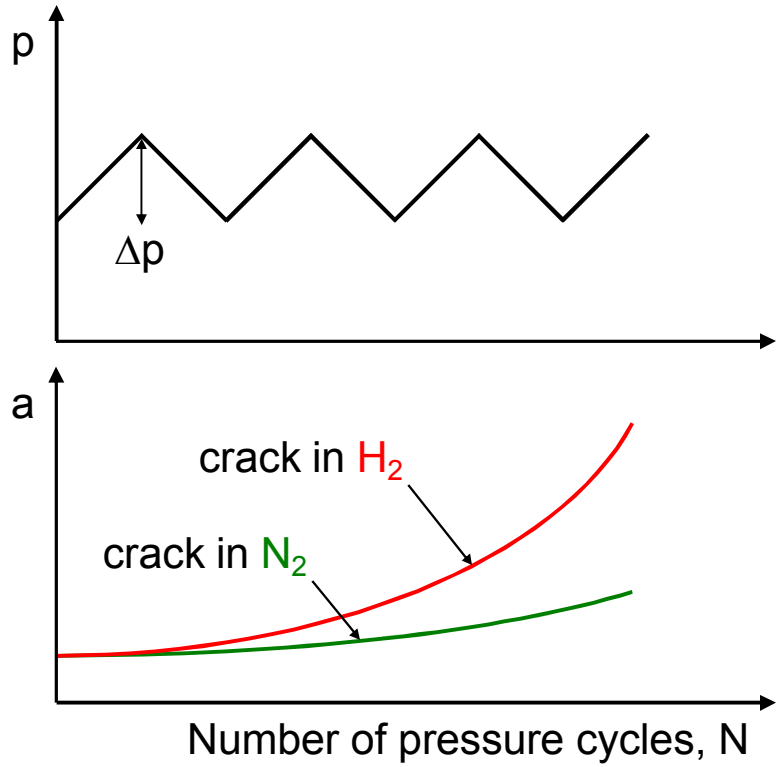
- Cr-Mo (or Ni-Cr-Mo) ferritic steels
- H_2 gas pressure <103 MPa

- C-Mn ferritic steel
- H_2 gas pressure <21 MPa

Hydrogen-induced failure mode in tanks and pipelines: accelerated fatigue crack growth







- Crack growth caused by pressure cycling is faster in hydrogen tanks and pipelines

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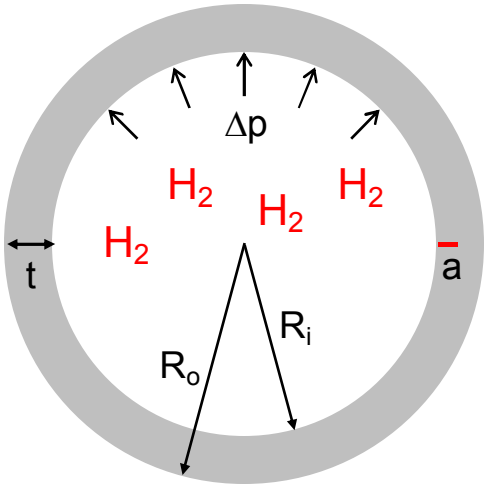
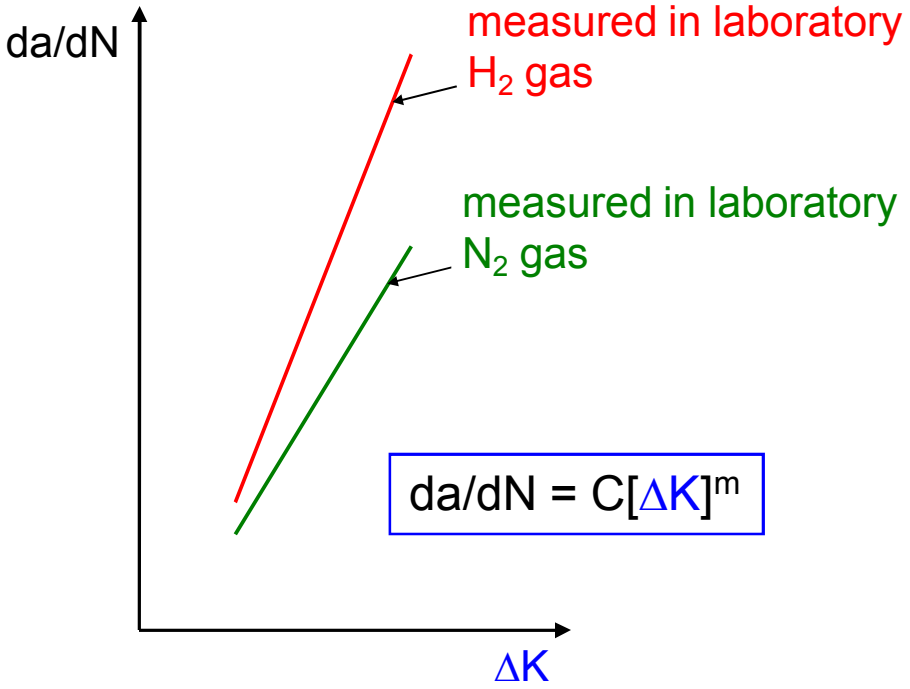
Material resistance quantified by crack growth rate (da/dN) *vs* stress-intensity factor range (ΔK)



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



- Fatigue crack growth rates in tank and pipeline materials depend on ΔK

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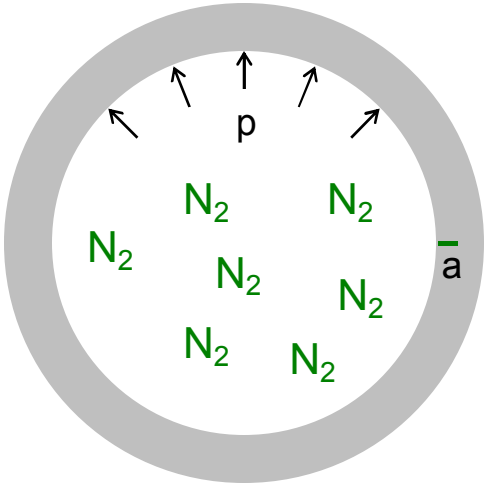
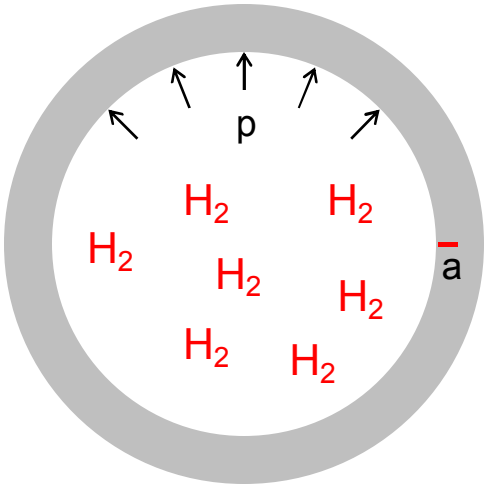
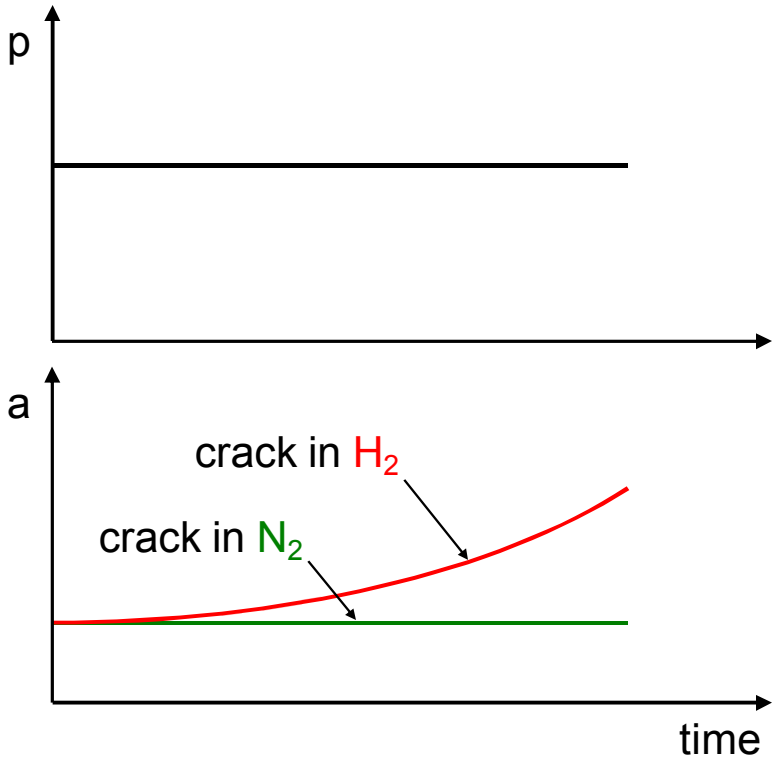
Hydrogen-induced failure mode in tanks and pipelines: sustained-load crack growth







- Time-dependent crack growth can occur under static pressure in hydrogen tanks and pipelines

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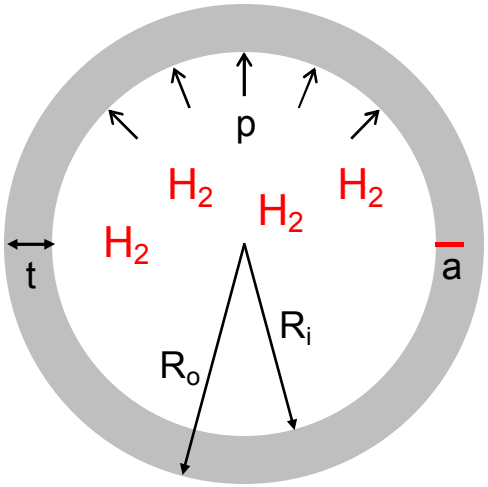
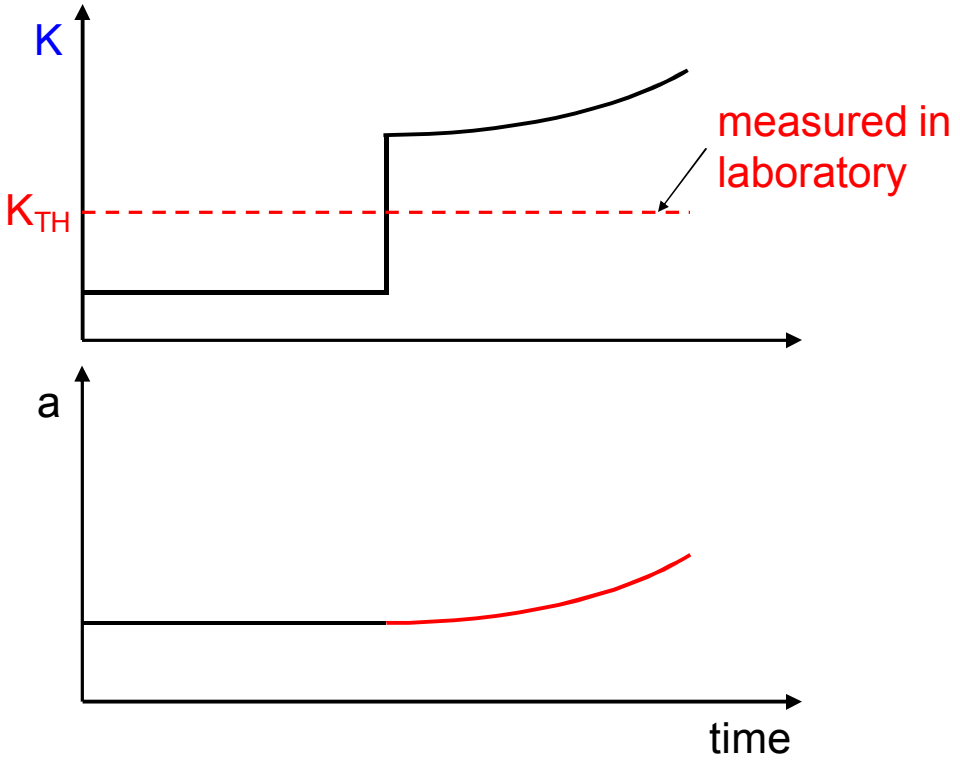
Material resistance quantified by threshold stress-intensity factor, K_{TH}



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



- Sustained-load crack growth in tanks and pipeline materials proceeds when $K > K_{TH}$

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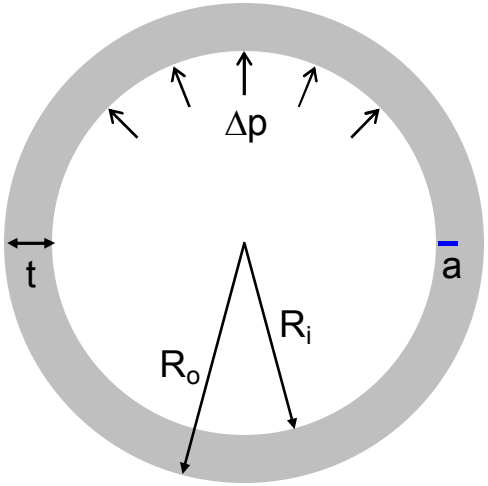
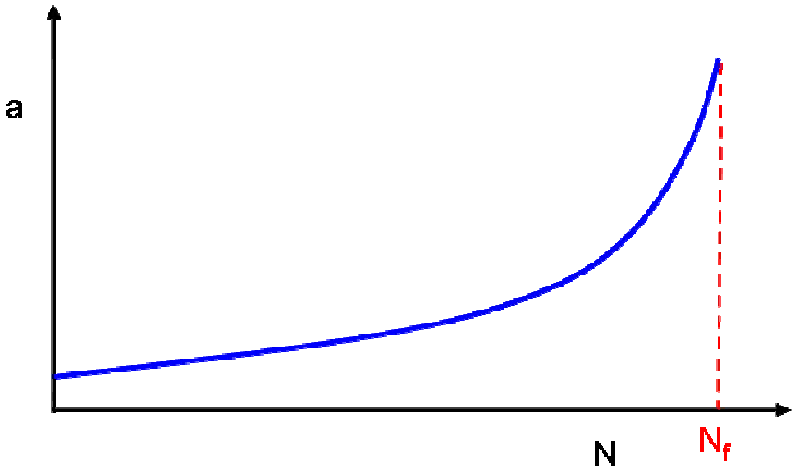
Tank design qualification typically conducted by either engineering analysis or performance testing



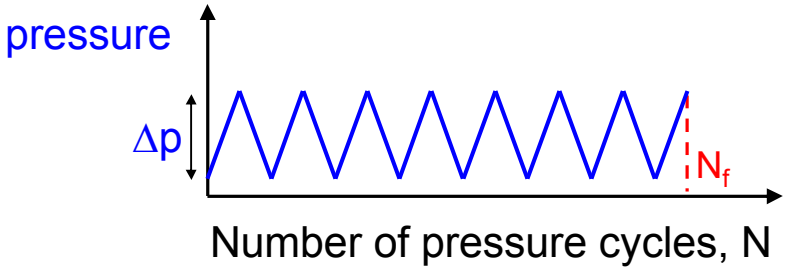
engineering analysis

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

crack growth law: $da/dN = C(\Delta K)^m$



performance testing



- Design qualification in ASME standards based on engineering analysis

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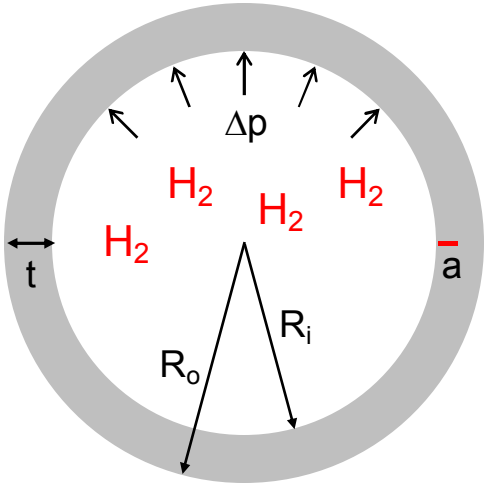
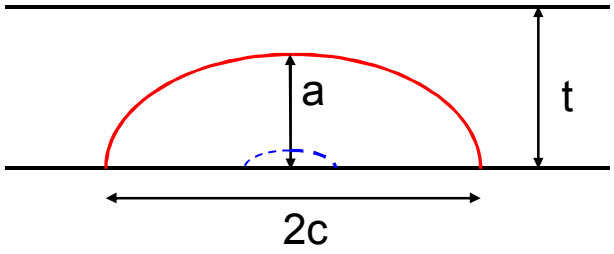
American Society of Mechanical Engineers (ASME) developed design qualification method for H_2 tanks

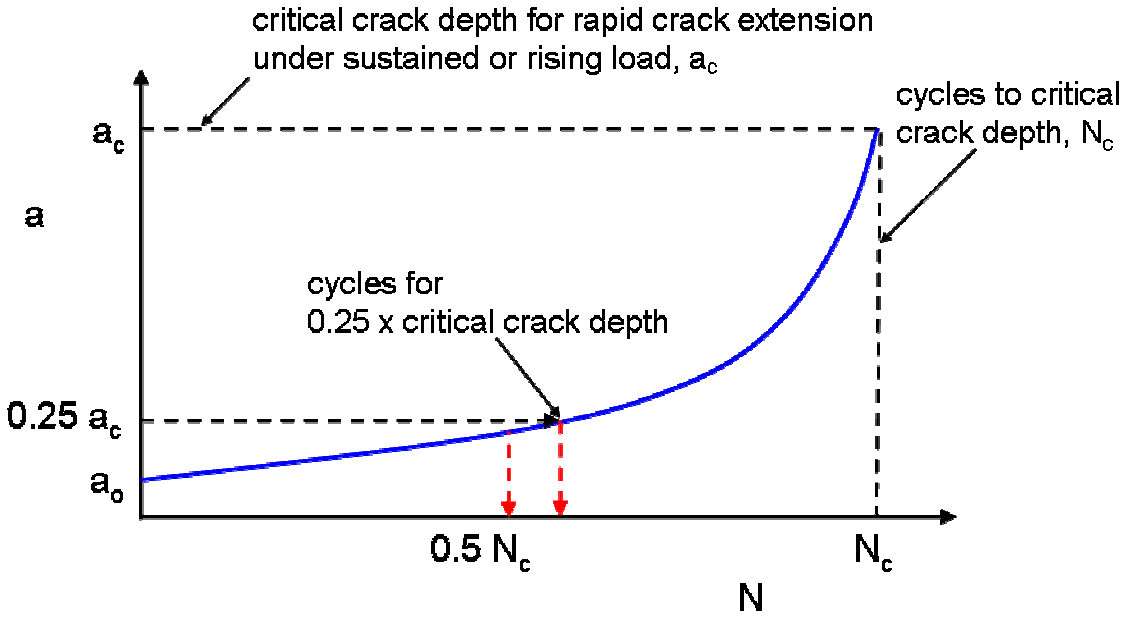
- Article KD-10 in Section VIII, Division 3 of Boiler and Pressure Vessel (BPV) code
  - "Special Requirements for Vessels in High Pressure Gaseous Hydrogen Service"
  - Mandatory for seamless tanks with H_2 pressure > 41 MPa and welded tanks with H_2 pressure > 17 MPa
  - Allows H_2 pressure up to 103 MPa
  - Qualification method also considered for H_2 pipelines
  - Requires sustained-load cracking (K_{TH}) and fatigue crack growth (da/dN vs ΔK) data in high-pressure hydrogen gas for fracture mechanics-based design

ASME Article KD-10 design method addresses fatigue crack growth and sustained-load cracking

- Objective: *calculate number of pressure cycles, N_c, to grow crack to critical depth, a_c*







$K = p * f(a/t, a/c, R_i, R_o)$

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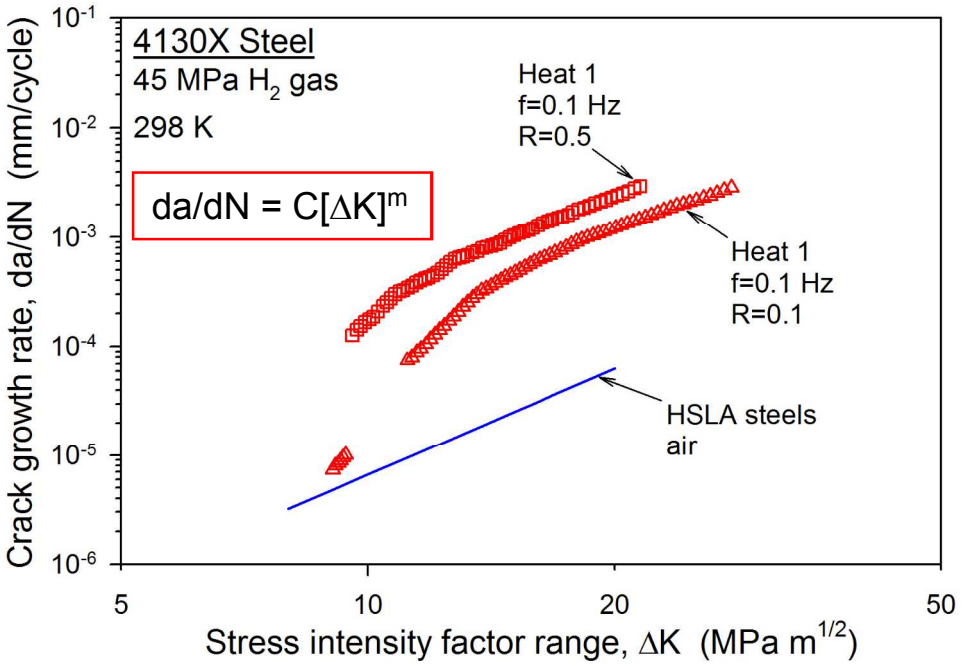
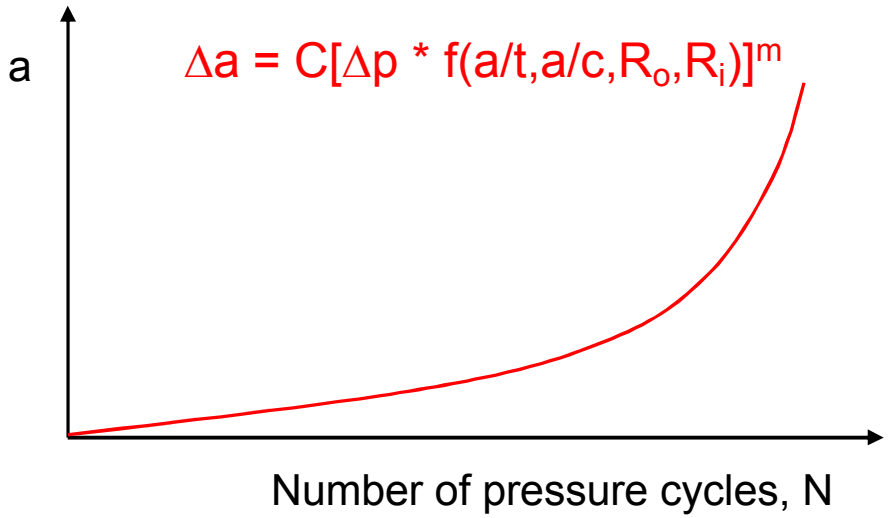
Crack depth, a, *vs* number of cycles, N, calculated from measured da/dN *vs* ΔK relationship

- da/dN *vs* ΔK relationship measured in high-pressure hydrogen gas in laboratory





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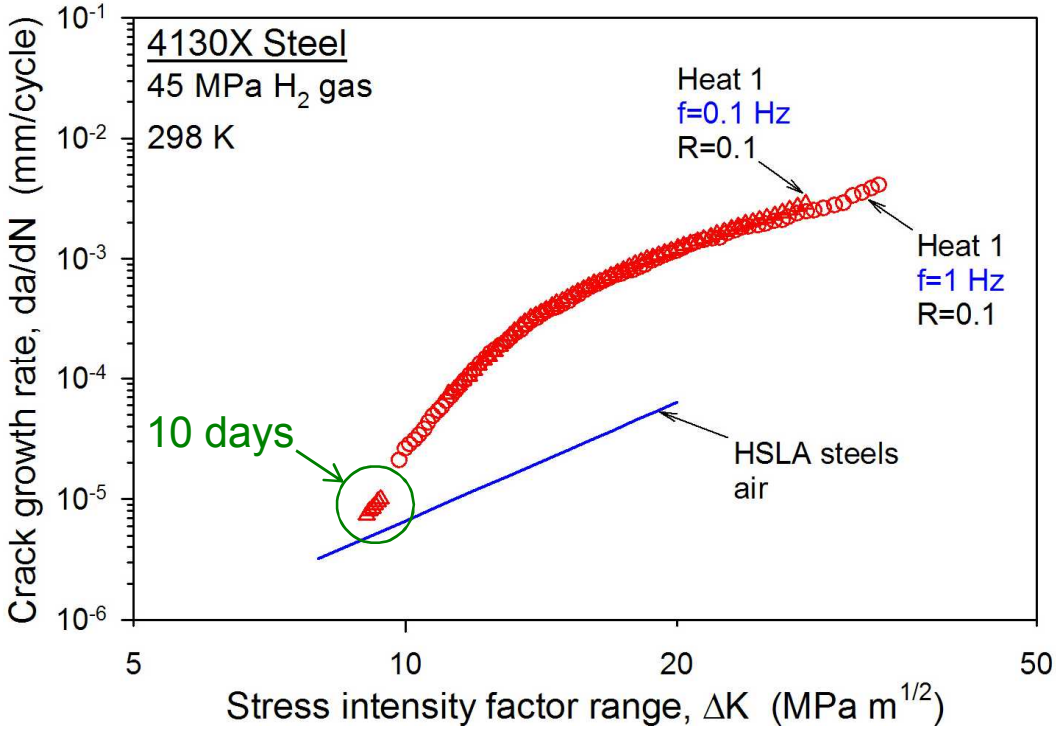
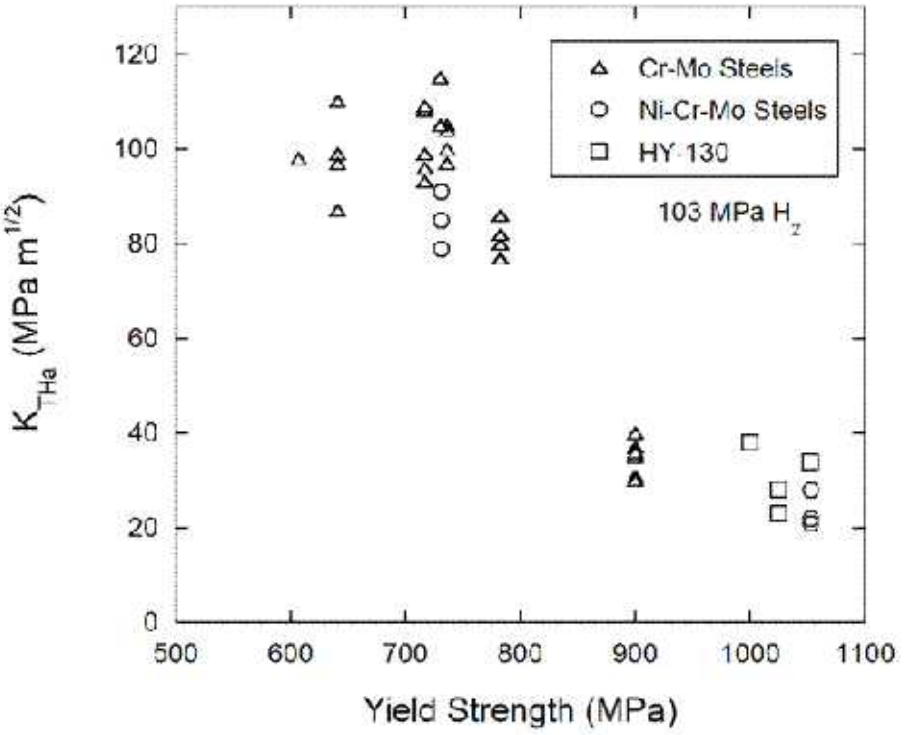
Test method improvements needed to enhance efficiency and reliability of data generation

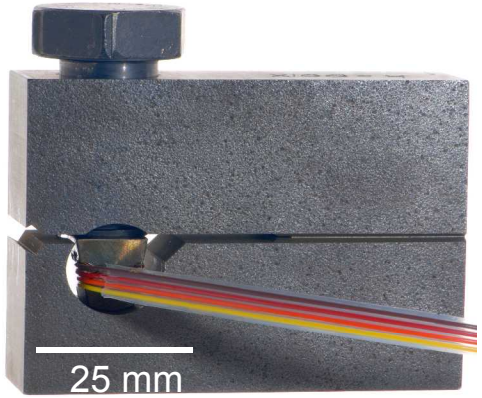


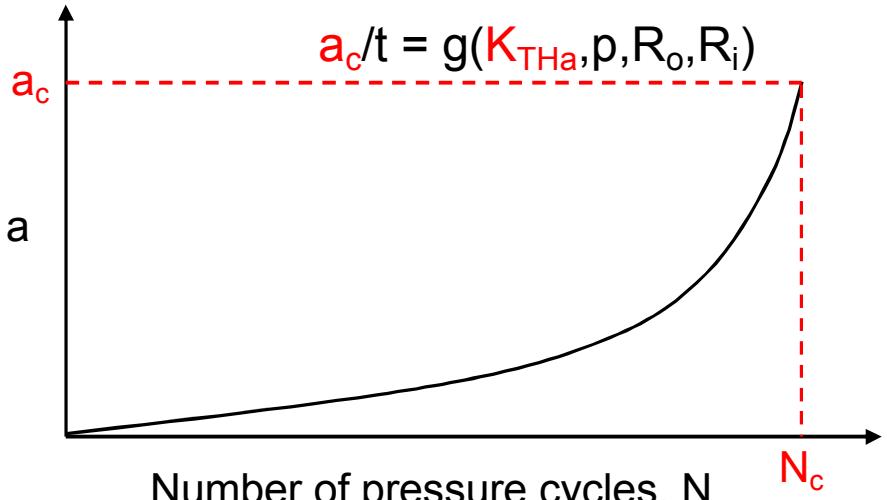
- Test frequency currently in ASME KD-10 (0.1 Hz) leads to impractical test durations
- Goal: *establish test frequencies that shorten test duration without compromising data quality*

Critical crack depth, a_c, calculated from measured threshold for sustained-load cracking, K_{THa}

- Threshold for sustained-load cracking, K_{THa}, measured in high-pressure hydrogen gas in laboratory







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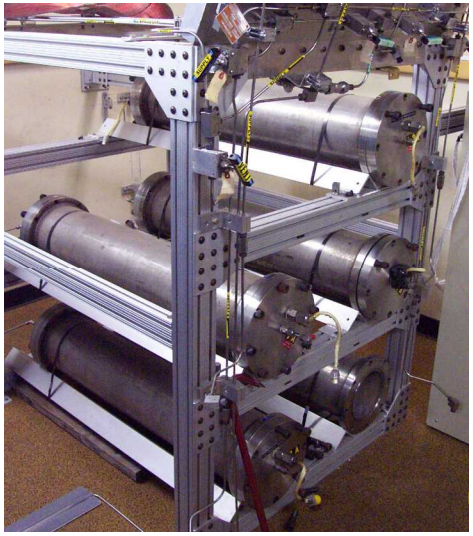
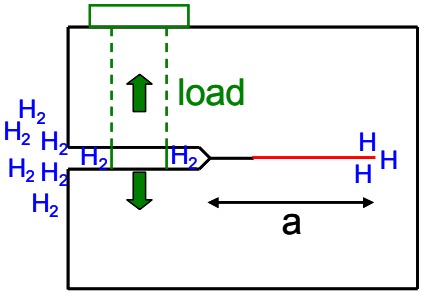
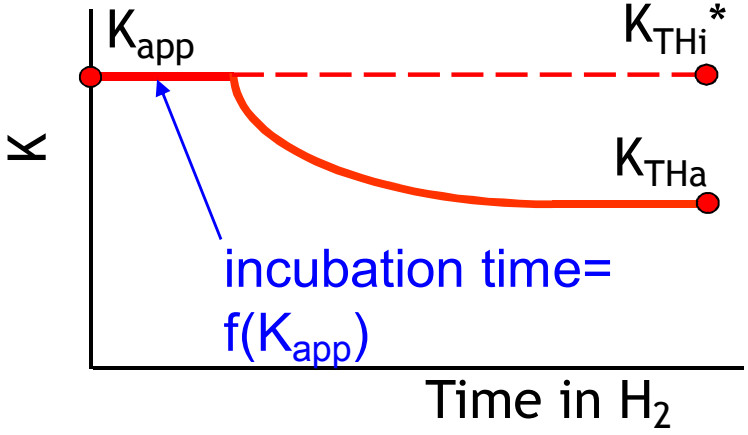
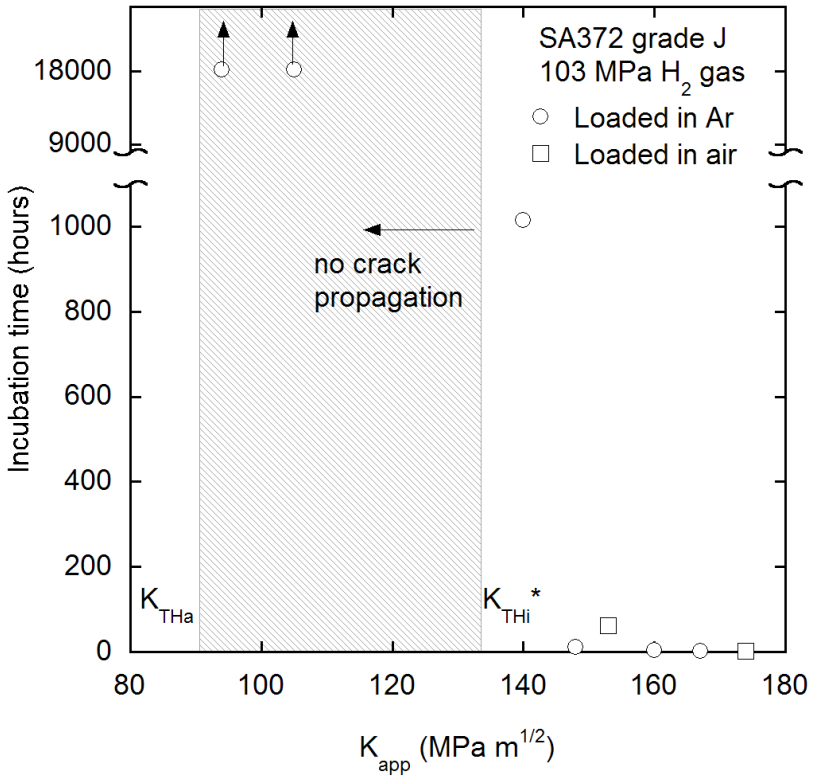
Sustained-load cracking threshold measurements are not reliable: non-propagating cracks









Defining threshold based on non-propagating cracks is not conservative

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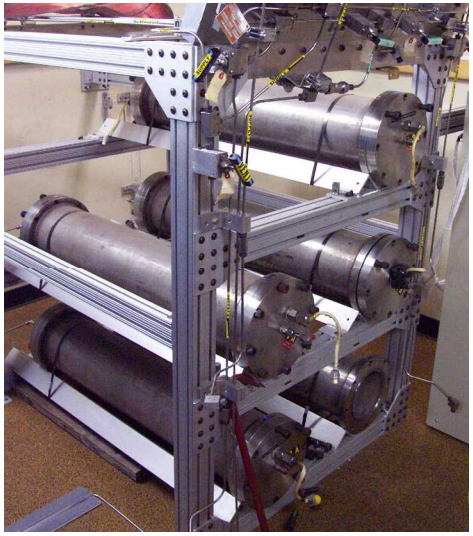
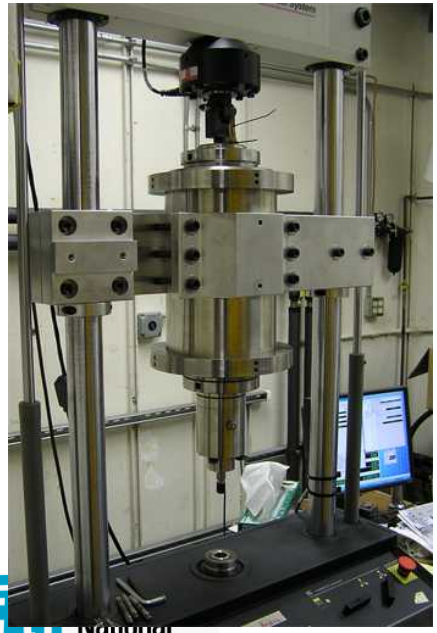
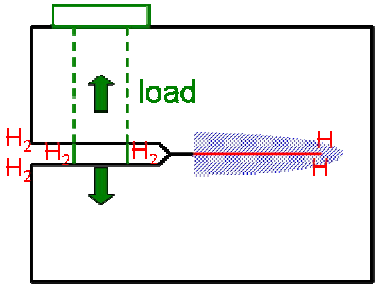
Sustained-load cracking threshold measurements are not reliable: "arrest" thresholds are non-conservative

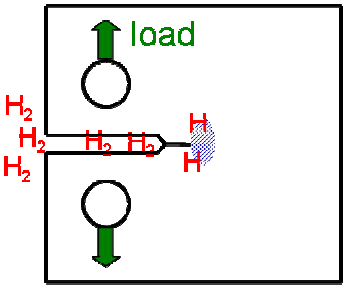


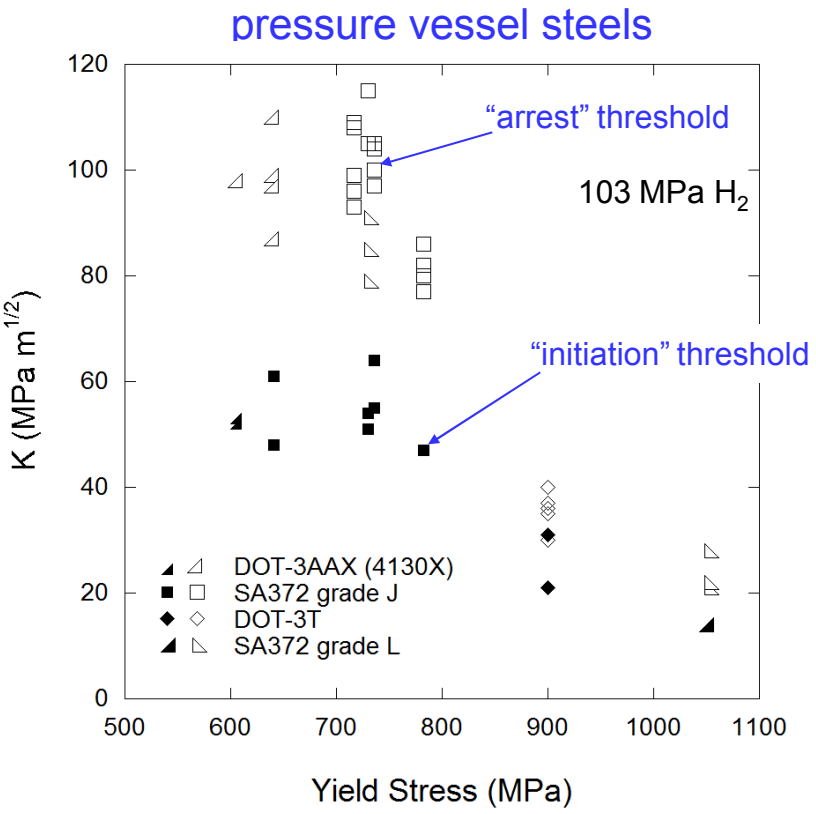


"arrest" threshold



"initiation" threshold





Goal: *demonstrate that rising-displacement "initiation" threshold measurements are relevant for H_2 tanks*

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Summary

- ASME developed design method for hydrogen tanks and pipelines
  - calculate crack depth, a, *vs* number of pressure cycles, N
  - a *vs* N depends on both material properties as well as structural parameters
- Fatigue-life calculation requires measurement of two material properties in H_2
  - threshold stress-intensity factor, K_{TH}
  - fatigue crack growth rate, da/dN, *vs* stress-intensity factor range, ΔK, relationship
- *Need to establish validity of rising-displacement K_{TH} measurement and enhance efficiency of da/dN measurement*

"Initiation" threshold measurements must consider effect of loading rate

- K_{JH} measurement is more conservative at low loading rates
- Loading rate effects will vary with material and environmental conditions
  - Available data suggest conservative values may be attained from reasonable length tests