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Fatigue Crack Growth Relationships for Cr-Mo Steels in H_2 Gas: Optimizing Measurements and Implications for Vessel Design Life

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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

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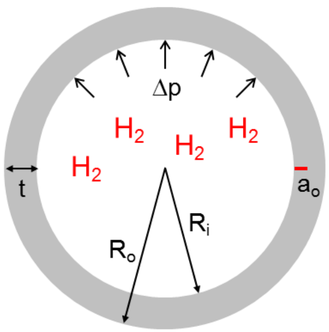
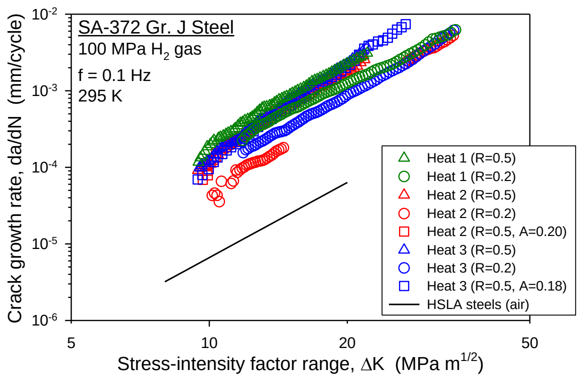
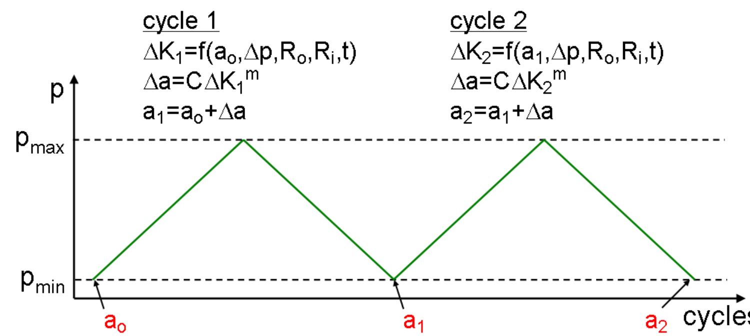
Design life analysis in ASME Article KD-10 employs damage-tolerance principles



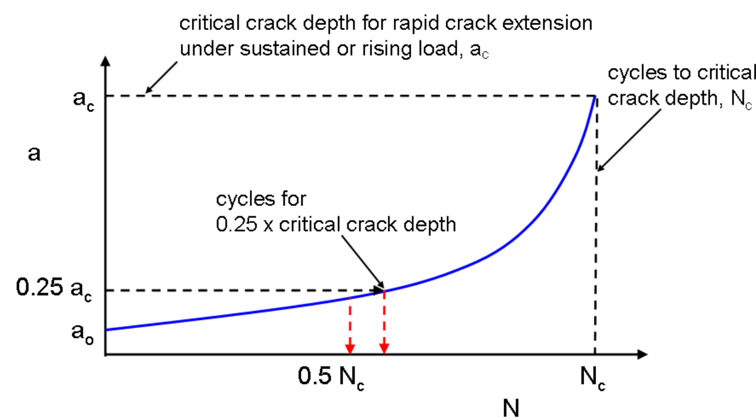




$\Delta K = \Delta p[f(a, t, R_o, R_i)]$

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

Need efficient and reliable measurements of fatigue crack growth relationships in H_2 gas



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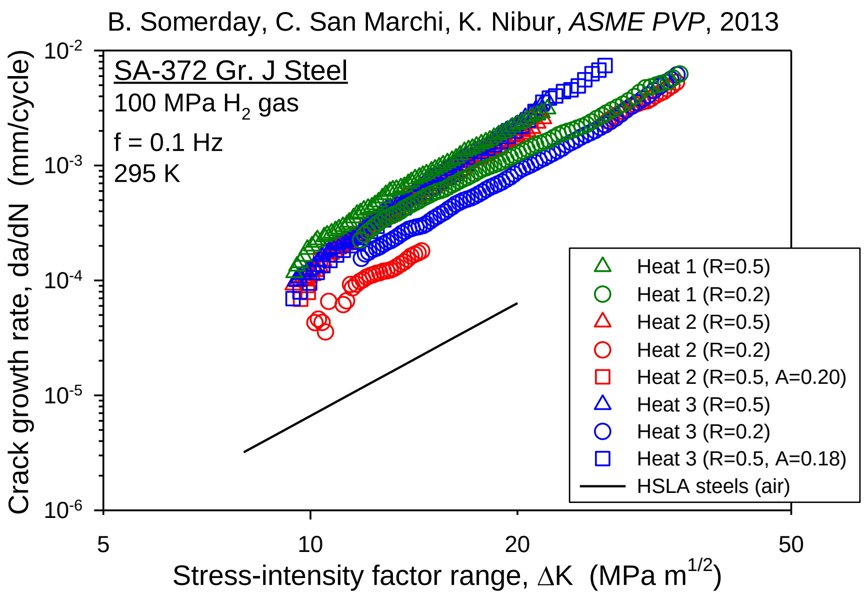
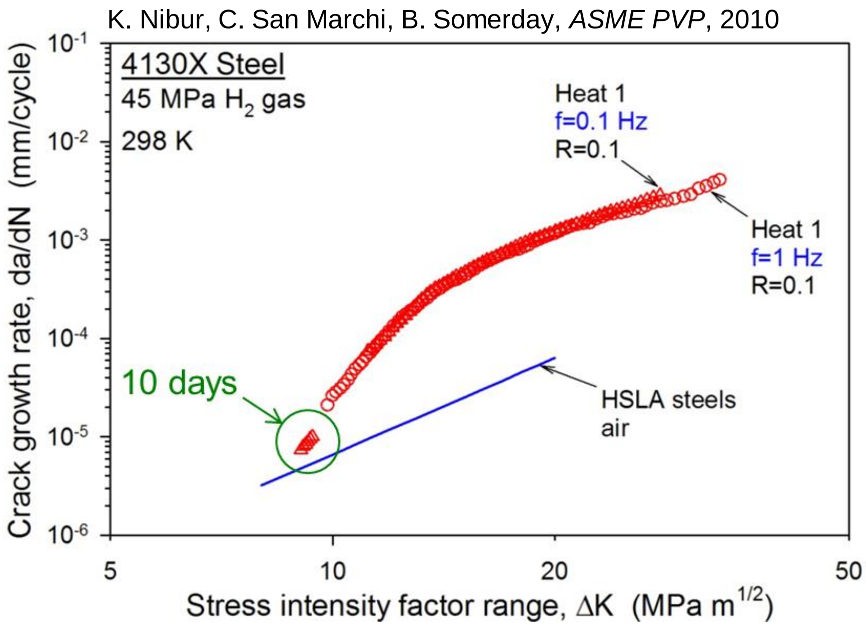
Measurements on SA-372 Gr. J steel for 1000 bar H_2 vessel design revealed non-optimum test procedures





- Load-cycle frequency prescribed in ASME KD-10 (0.1 Hz) led to compromise in measurements to limit the duration of each test
  - Impractical test durations can arise from test frequency of 0.1 Hz
  - Test durations curtailed by initiating tests at higher ΔK, but extrapolations to lower ΔK excessively inflate da/dN
- ***Goal: explore modified procedure that shortens test duration while maintaining data value***

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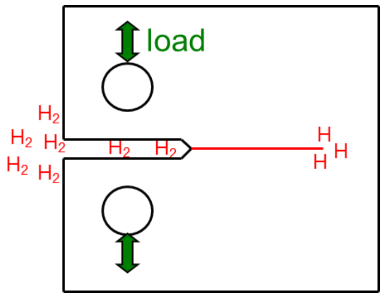
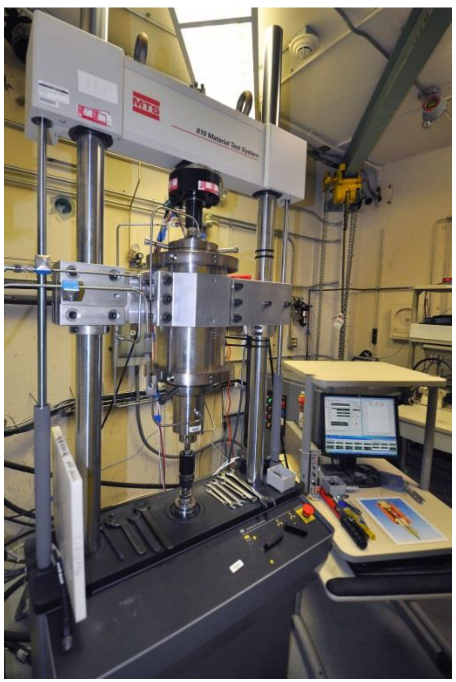
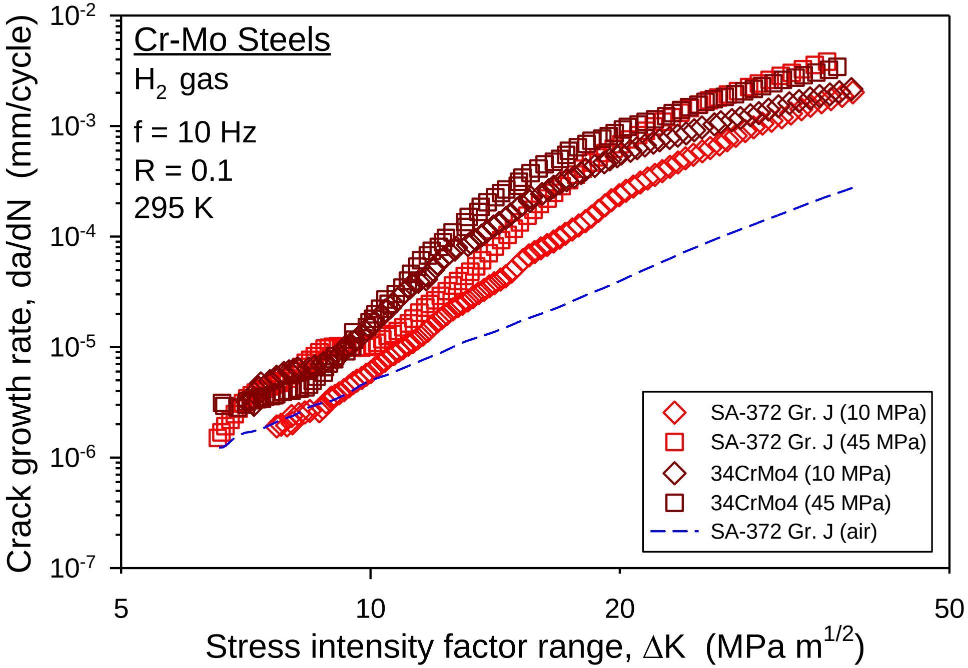
Fatigue crack growth relationships measured for two Cr-Mo steels in high-pressure H_2 gas





- **Materials**
  - SA-372 Grade J (S_y = 760 MPa, S_u = 890 MPa)
  - 34CrMo4 (S_y = 950 MPa, S_u = 1045 MPa)
- **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, frequency range 0.002 to 10 Hz
  - Constant load amplitude or constant ΔK
- **Environment**
  - 99.9999% H_2 supply gas
  - Pressures = 10, 45, and 100 MPa
  - Room temperature

Baseline fatigue crack growth relationships (da/dN vs. ΔK) measured at 10 Hz for two steels



- At higher ΔK, fatigue crack growth rates in H_2 gas ~10x higher than air
- At lower ΔK, fatigue crack growth rates in H_2 gas approach rates in air
  - Measurements at 10 Hz capture essential lower-ΔK data without prolonged testing times
  - ***Crack growth rates measured at 10 Hz may not represent upper-bound behavior***

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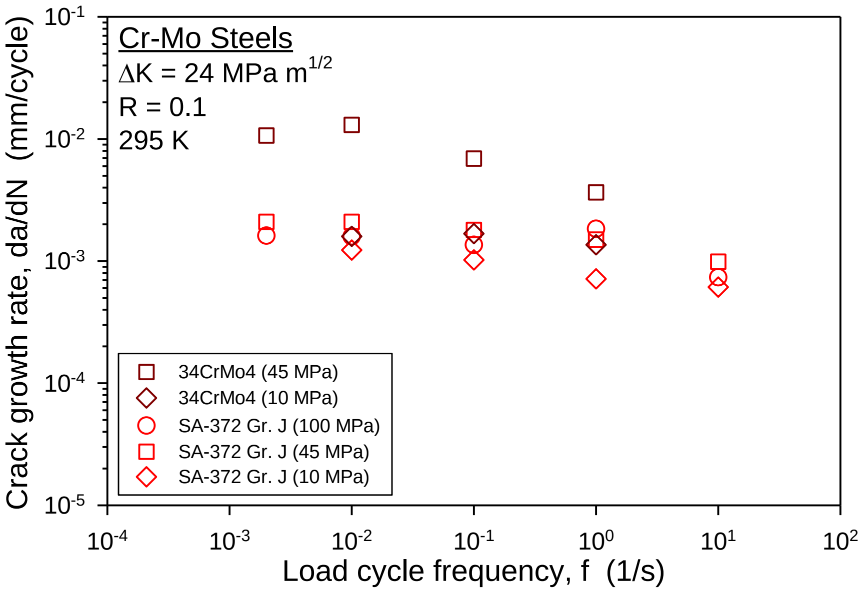
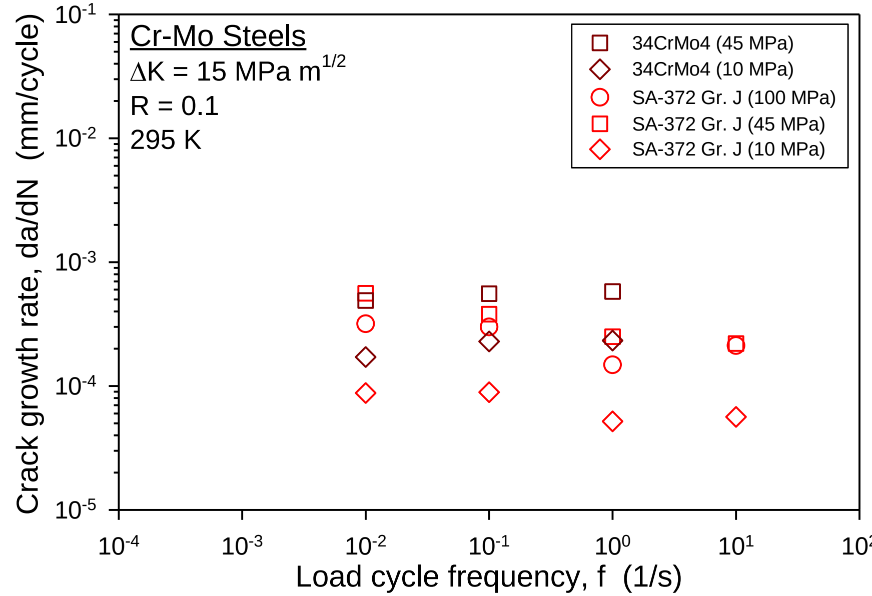
Measurement of da/dN vs. frequency indicates that crack growth rates at 10 Hz are not upper bounds





- ***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

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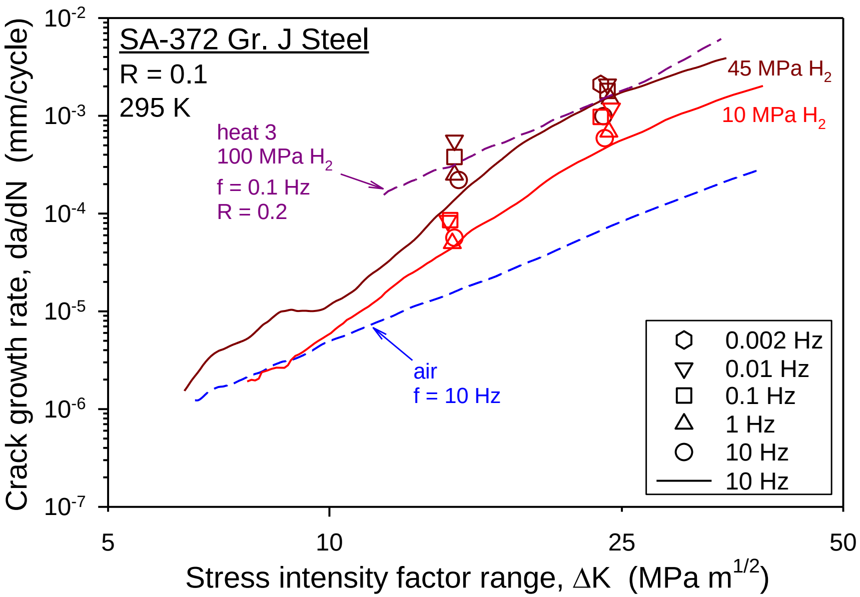
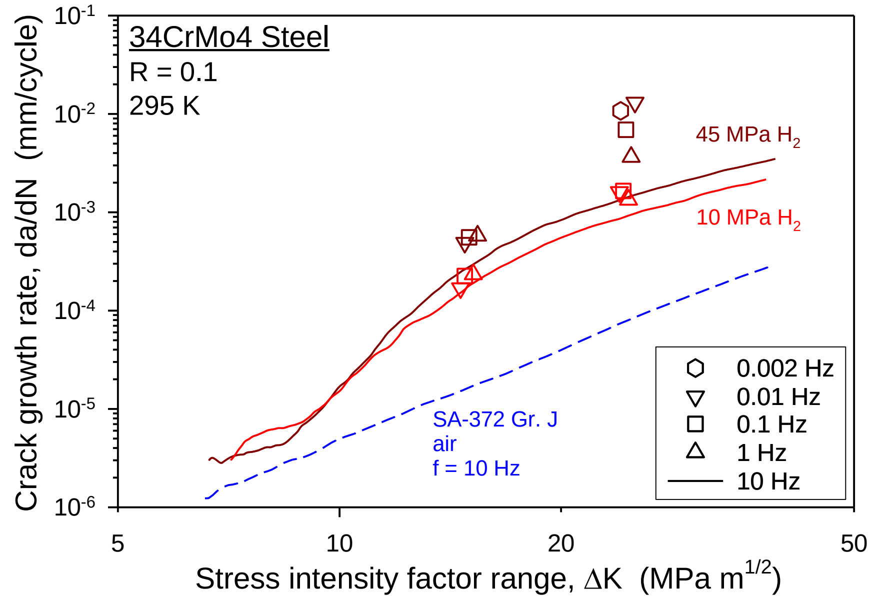
Possible modified approach: measure da/dN vs. ΔK at 10 Hz, correct data based on da/dN vs. frequency





- Baseline da/dN vs. ΔK relationships measured efficiently at 10 Hz, indicate essential regimes that must be represented
  - Baseline relationships reveal that da/dN in H_2 gas approaches da/dN in air
- Since da/dN vs. ΔK relationships are non-conservative at 10 Hz, da/dN vs. f measured at constant ΔK serve as correction to baseline
  - ***da/dN vs. f must be measured at multiple ΔK levels to provide most reliable correction → are ΔK = 15 and 24 MPa $m^{1/2}$ sufficient?***

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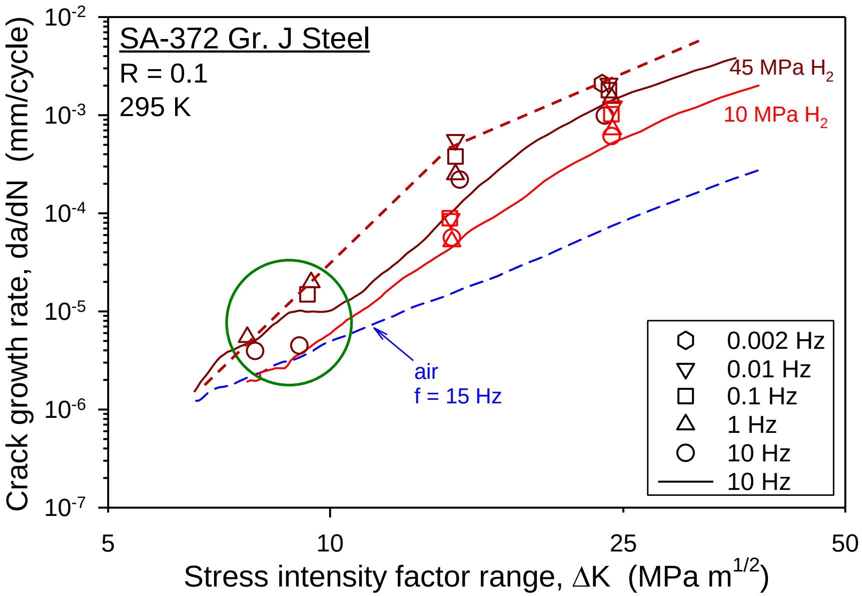
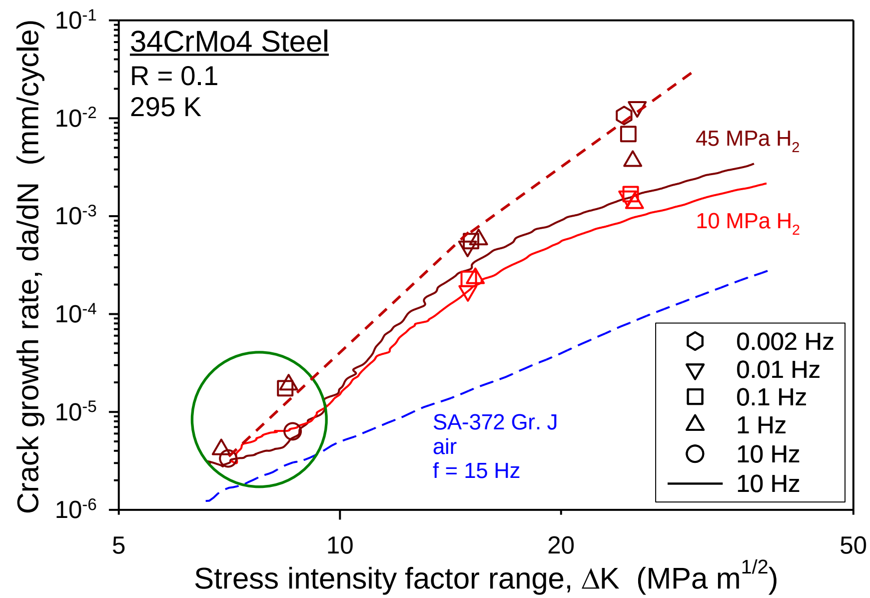
Additional da/dN vs. frequency measurements at lower ΔK clarify onset of H_2-accelerated crack growth





- Crack growth rate (da/dN) vs. frequency data at lower ΔK verify that da/dN measurements at 10 Hz may not represent upper-bound values
- Corrected da/dN vs. ΔK relationship must reflect onset of H_2-accelerated crack growth at lower ΔK relative to da/dN vs. ΔK curve at 10 Hz
- ***Reliable correction to da/dN vs. ΔK relationship measured at 10 Hz must include da/dN vs. frequency data sets measured at lower ΔK***

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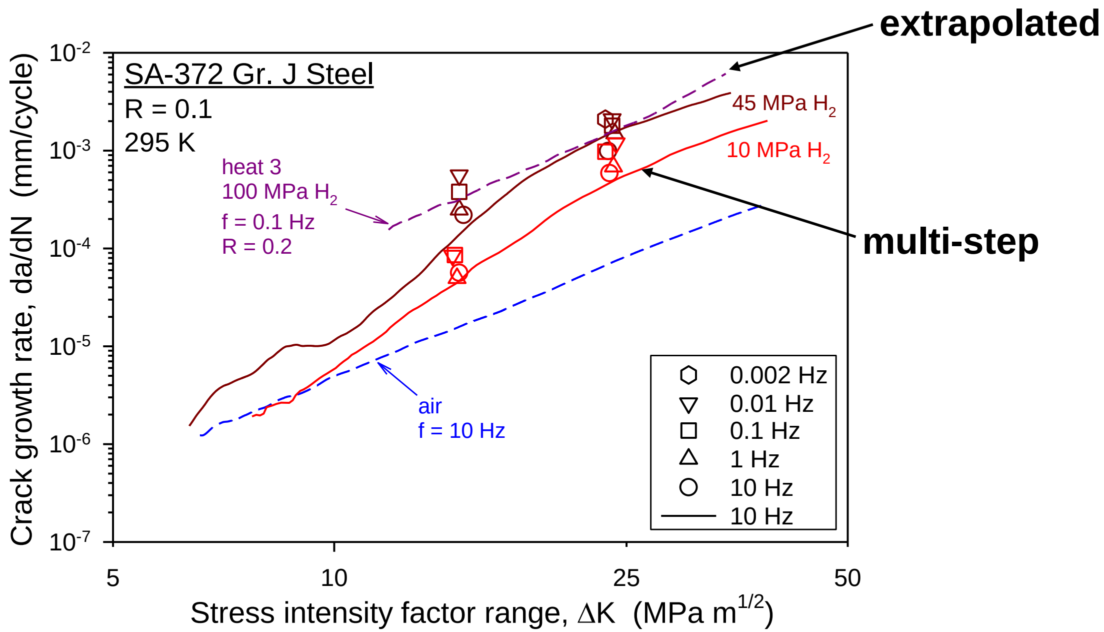
Fatigue-life analysis for manufactured vessel: consider extrapolated and multi-step FCG relationships

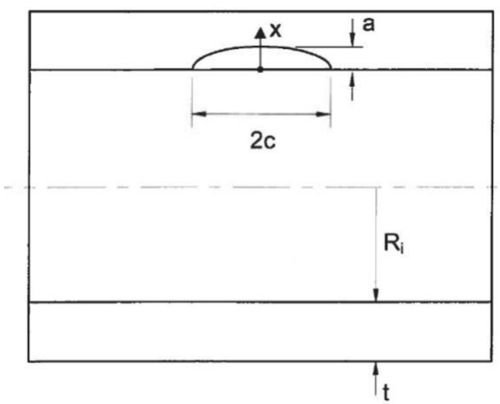


- Double-neck cylinder designed according to EN-1964-1 + 2010/35/EU (TPED qualification)
  - 220 x 9.1 mm (OD x WT min)
  - MAWP = 28 MPa
  - Fabricated from 34CrMo4 steel (S_y min = 600 MPa, 780 < S_u < 890 MPa): not ASME-qualified, but cylinder thickness compliant with Section VIII-2
  - For fatigue-life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

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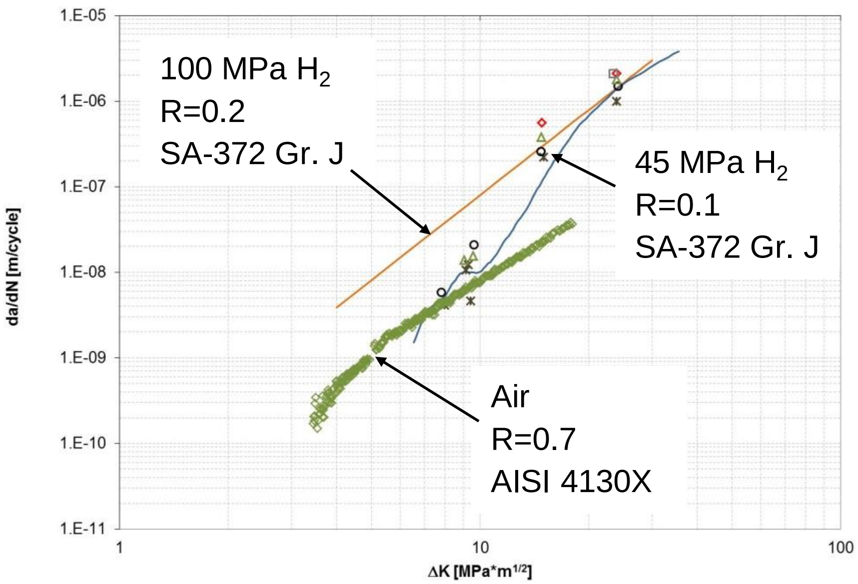
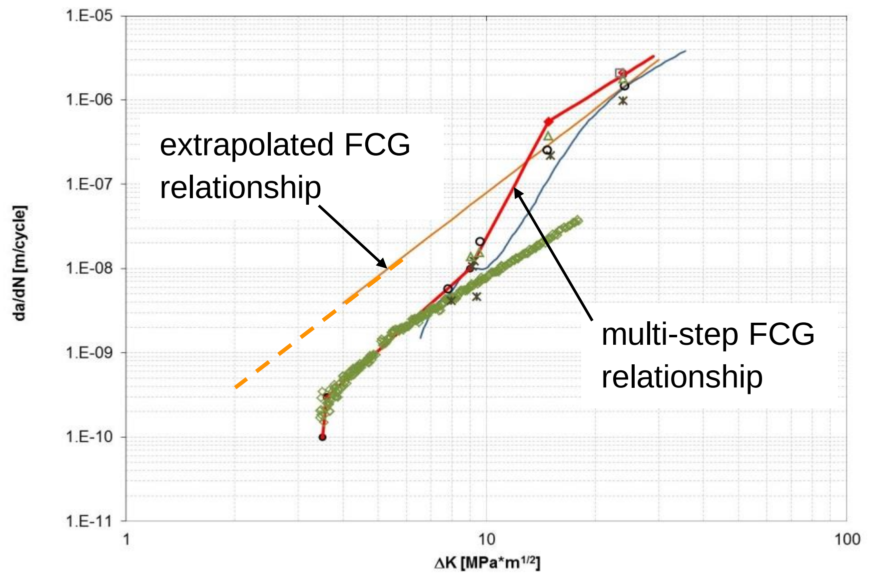
Extrapolated and multi-step FCG relationships formulated from multiple data sets





- 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)

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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

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Summary

- Fatigue crack growth rates measured for Cr-Mo pressure vessel steels SA-372 Grade J and 34CrMo4 in H_2 gas as function of ΔK, f, and pressure
- da/dN vs. ΔK relationships measured in H_2 gas at 10 Hz suggest that capturing data at lower ΔK benefits design-life analyses
  - At lower ΔK, crack growth rates in H_2 gas approach rates in air
- da/dN vs. f data measured in H_2 gas at selected constant-ΔK levels demonstrate that crack growth rates at 10 Hz are not upper bounds
  - da/dN vs. ΔK relationships at 10 Hz not reliable inputs for design-life analyses
- Hybrid approach: measure the da/dN vs. ΔK relationship at 10 Hz, apply correction based on da/dN vs. f data
  - Possible approach to efficiently establish fatigue crack growth relationship in H_2 gas without compromising data quality
- Fatigue-life analysis of industrial cylinder demonstrates advantage of multi-step FCG relationship formulated from hybrid data

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Back-up Slides

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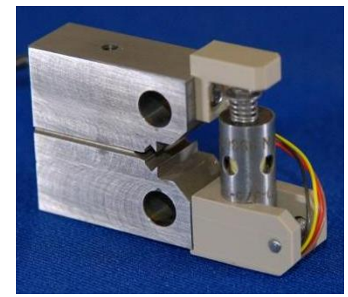
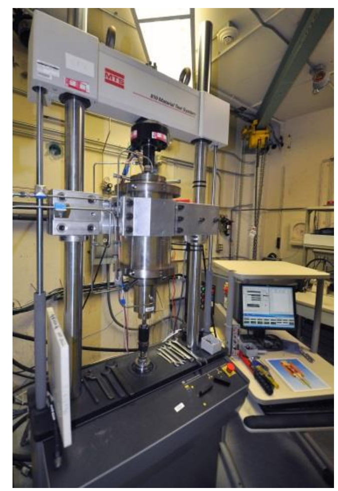
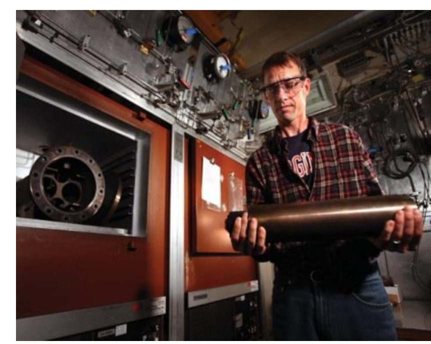
SNL core capability in hydrogen embrittlement features Hydrogen Effects on Materials Lab

- Static-loading crack-growth system
  - Wedge opening load (WOL) and double cantilever beam (DCB) specimens
  - H_2 pressure up to 200 MPa
  - Temperature -70 to 170 ^{o}C
- Dynamic-loading crack-growth system
  - Compact tension (CT) and single edge notch (SEN) specimens
  - H_2 pressure up to 138 MPa
  - New pressure vessel design with target temperatures -100 to 200 ^{o}C







Materials testing in H_2 supports technology development in several mission areas

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