Measurement of Fatigue Crack Growth Rates for SA-372 Gr. J Steel in 100 MPa Hydrogen Gas Following Article KD-10

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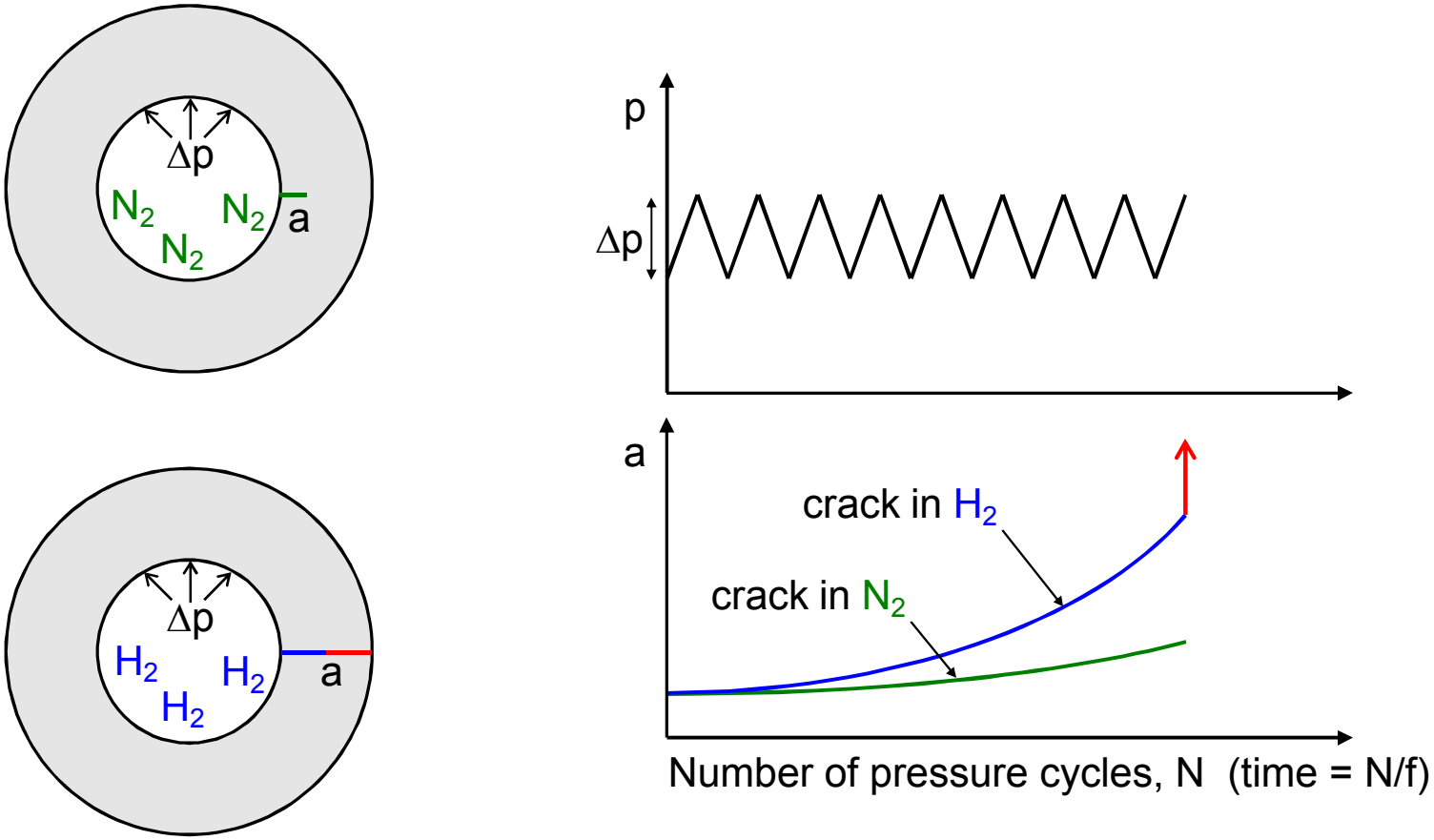
Pressure vessels and pipelines are central components for hydrogen storage and delivery

- Current examples:
  - Cr-Mo ferritic steels
  - <45 MPa H_2 gas

- Current examples:
  - C-Mn ferritic steels
  - <15 MPa H_2 gas

Two H_2-assisted crack propagation modes: fatigue crack growth and rapid failure



Fatigue crack growth followed by rapid failure requires less pressure cycles in H_2 components

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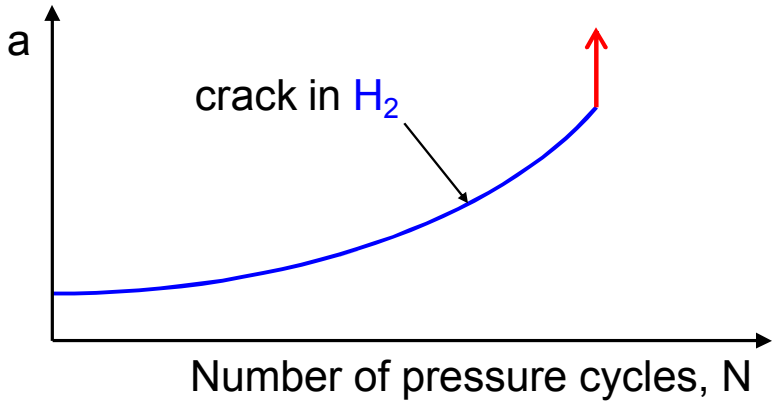
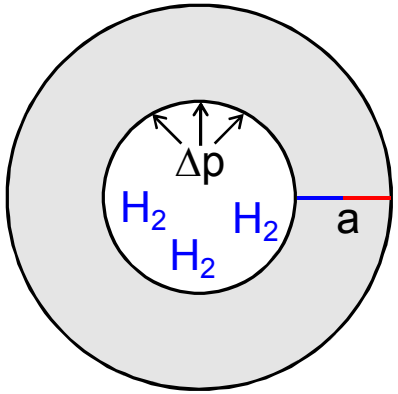
Example: failure of H_2 cylinder



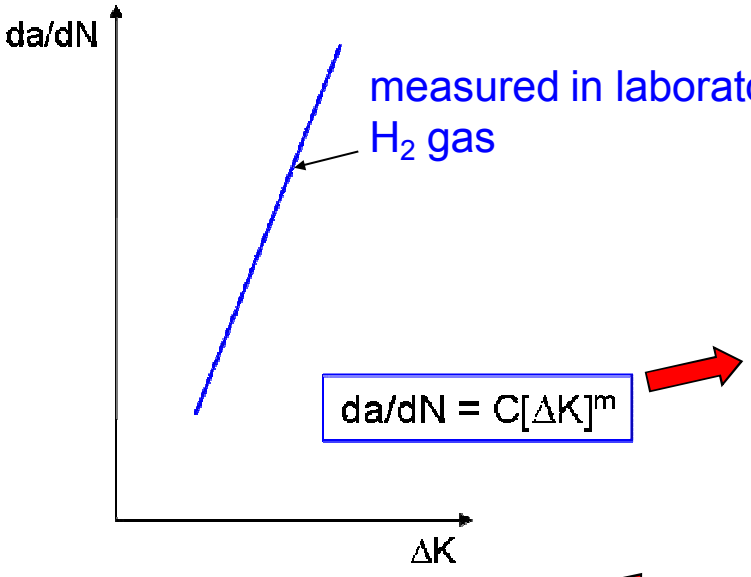


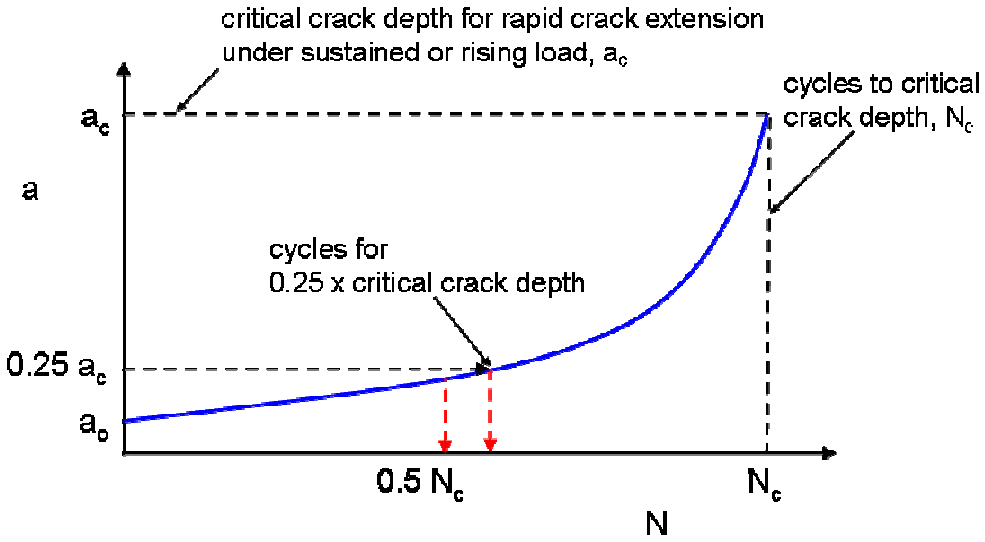
Barthélémy, 1st ESSHS, 2006

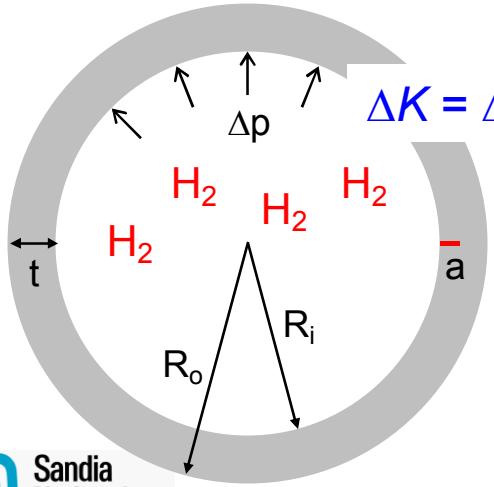
ASME developed design-life framework for high-pressure hydrogen vessels

- Article KD-10 in Section VIII, Division 3 of BPVC
  - "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
  - Allows H_2 pressure up to 100 MPa
  - Design-life framework 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 calculations

Design-life calculations in Article KD-10 require fracture data measured in high-pressure H_2







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

- Two fracture properties in H_2 needed
  - Fatigue crack growth law
  - Fracture threshold
- Design-life calculation accommodates H_2-accelerated fatigue crack growth

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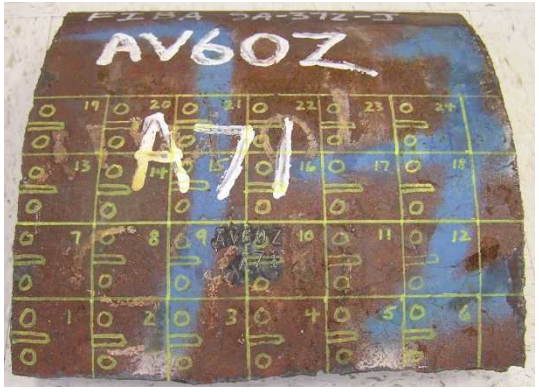
Objective: exercise procedures for measuring da/dN vs ΔK relationships following Article KD-10

- Measured fatigue crack growth (da/dN vs ΔK) relationships for technologically relevant steel
  - ASME code-qualified SA372 Gr. J steel
  - Standard composition range:

Cr	Mo	Mn	Si	C	S	P
0.80-1.15	0.15-0.25	0.75-1.05	0.15-0.35	0.35-0.50	<0.025	<0.025

  - Standard mechanical properties and measured properties for 3 heats:

Steel	Tempering Temperature (°C)	S_u (MPa)	S_y (MPa)	*El* (%)
Class 70	>595	825-1000	>485	>18
Heat 1	660	839	642	22.0
Heat 2	657	871	731	19.3
Heat 3	657	908	784	24.0



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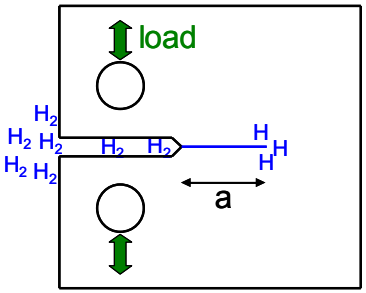
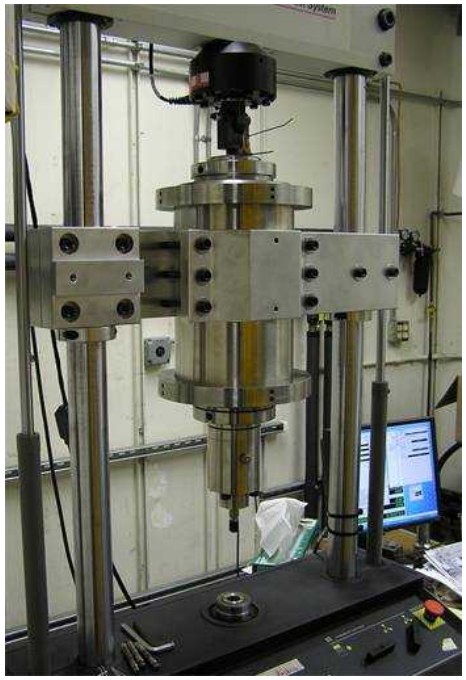
Fatigue crack growth relationships (da/dN vs. ΔK) measured in high-pressure H_2 gas





- 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 (0.1 Hz)
  - Constant or increasing load amplitude (increasing ΔK)
- Environment
  - Supply gas: 99.9999% H_2
  - Test gas: O_2 < 7 vppm, H_2O < 1 vppm
  - Pressure = 15,000 psi (100 MPa)
  - Room temperature

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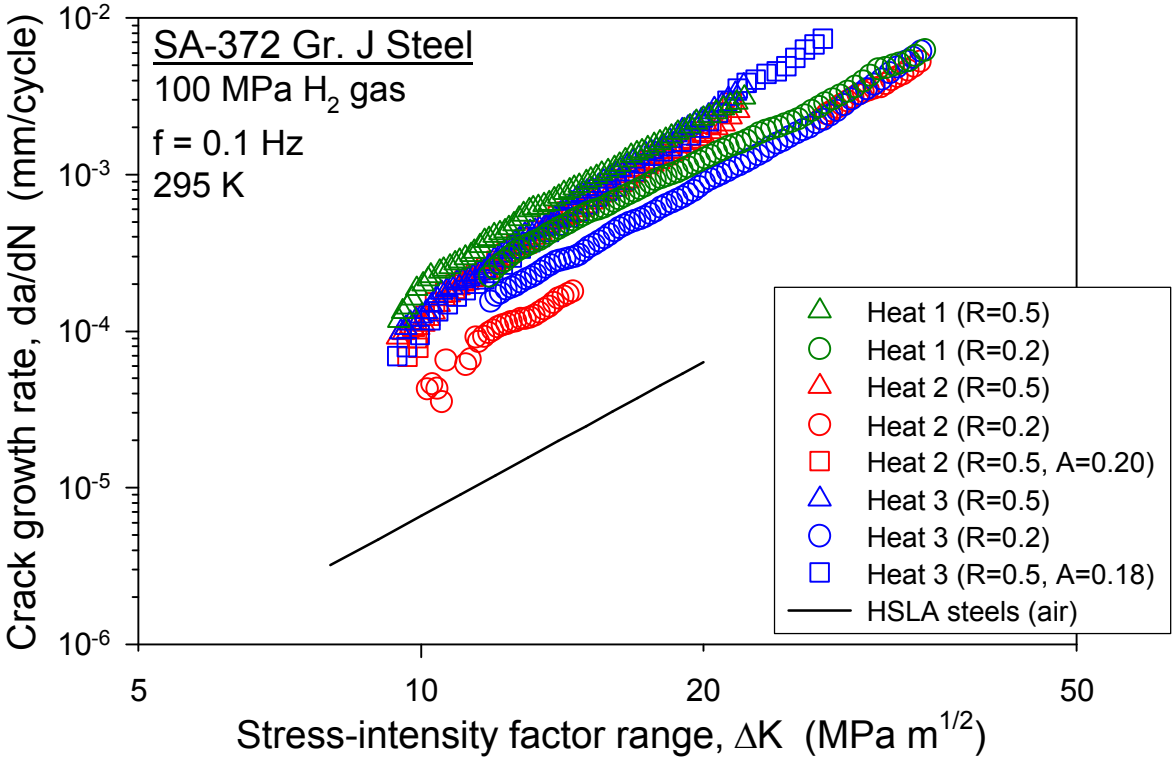
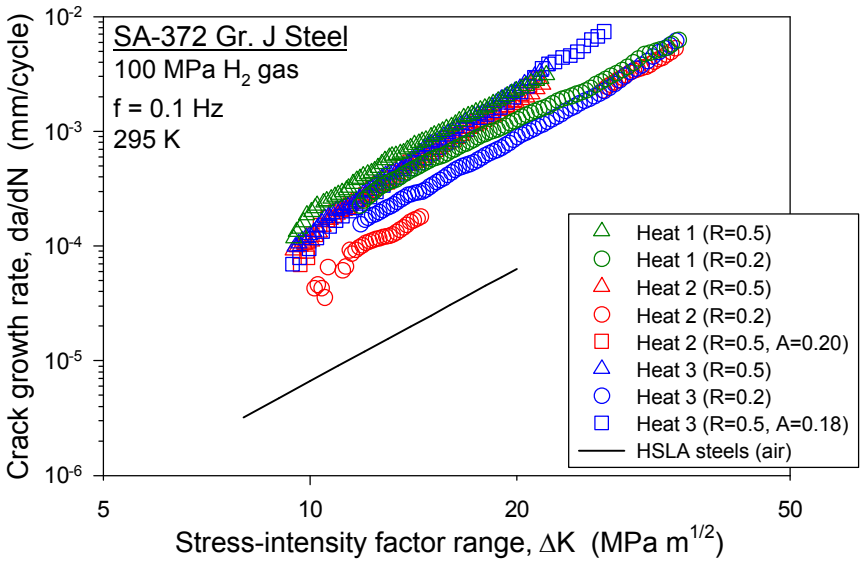
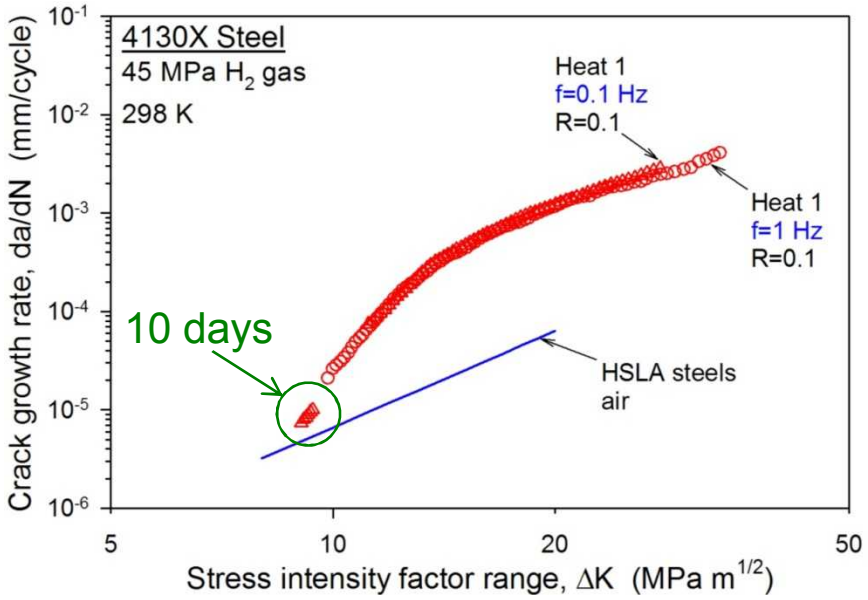
Testing emphasizes details in KD-10: max. pressure = 100 MPa, frequency = 0.1 Hz, and 3 steel heats



- Results reveal several trends:
  - For each steel heat, H_2 gas accelerates da/dN about 10-fold
  - At R = 0.5, da/dN in H_2 gas nearly invariant for all steel heats
  - da/dN in H_2 gas increases mildly as R increases

Exercising test procedures in KD-10 reveals potential pathways for modification





- Measuring relationship only at high da/dN may lead to overly conservative extrapolation at low ΔK
- Capturing transitions at lower ΔK is time consuming at load-cycle frequency specified in KD-10 (0.1 Hz)
- Correcting da/dN relationship with constant-ΔK points may balance test efficiency and data reliability

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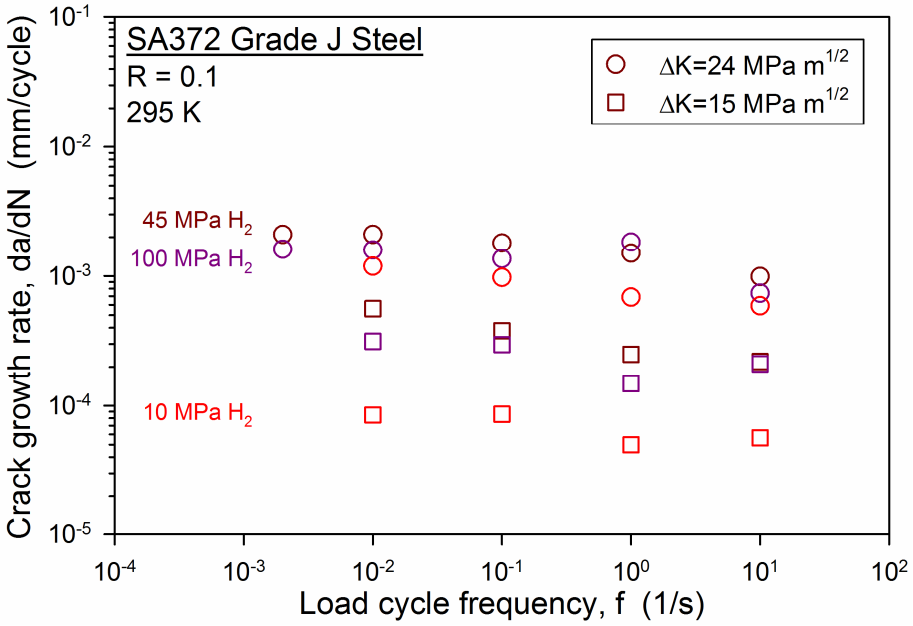
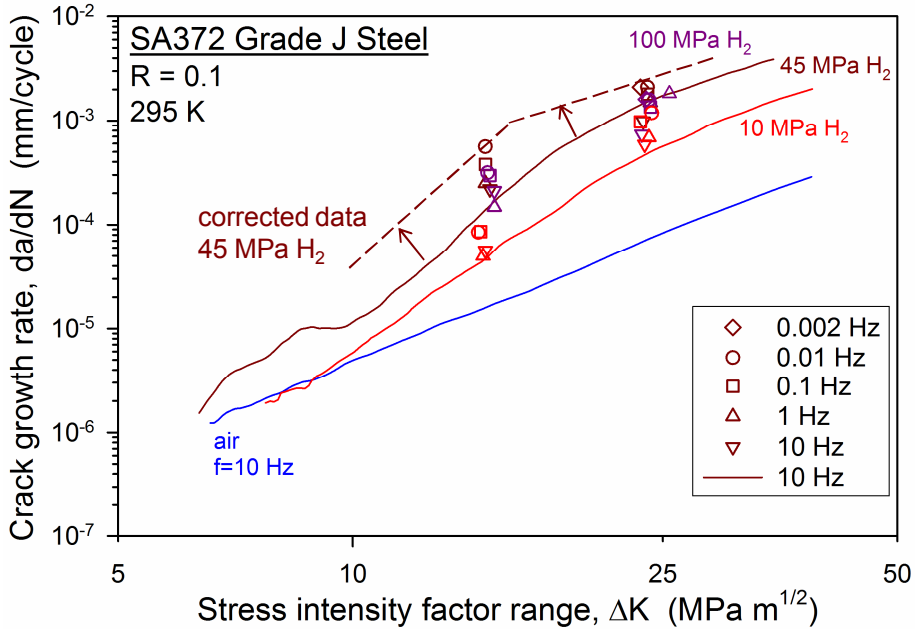
Possible procedure: measure da/dN vs. ΔK at 10 Hz, correct curve based on da/dN vs. f data





- Conducting test at 10 Hz allows measurement of lower-ΔK transitions without extended test durations
  - da/dN vs. ΔK curve measured at 10 Hz is non-conservative
- Measure da/dN vs. f to determine upper-bound da/dN for correcting data at selected ΔK levels

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Summary

- Exercised method for measuring fatigue crack growth rates in H_2 gas following ASME Article KD-10, emphasizing:
  - maximum allowed H_2 pressure (100 MPa)
  - load-cycle frequency = 0.1 Hz
  - 3 heats of pressure vessel steel
- Low load-cycle frequency (0.1 Hz) imposes practical constraints on ΔK range sampled in measurements
  - Measuring data only at high ΔK leads to overly conservative extrapolations at lower ΔK
- Consider alternate procedure of measuring da/dN vs. ΔK at 10 Hz, correcting curve based on da/dN vs. f data