

# Fatigue testing methodologies in gaseous hydrogen

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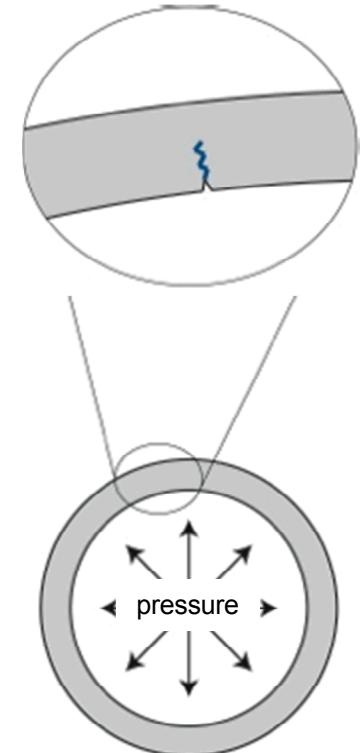
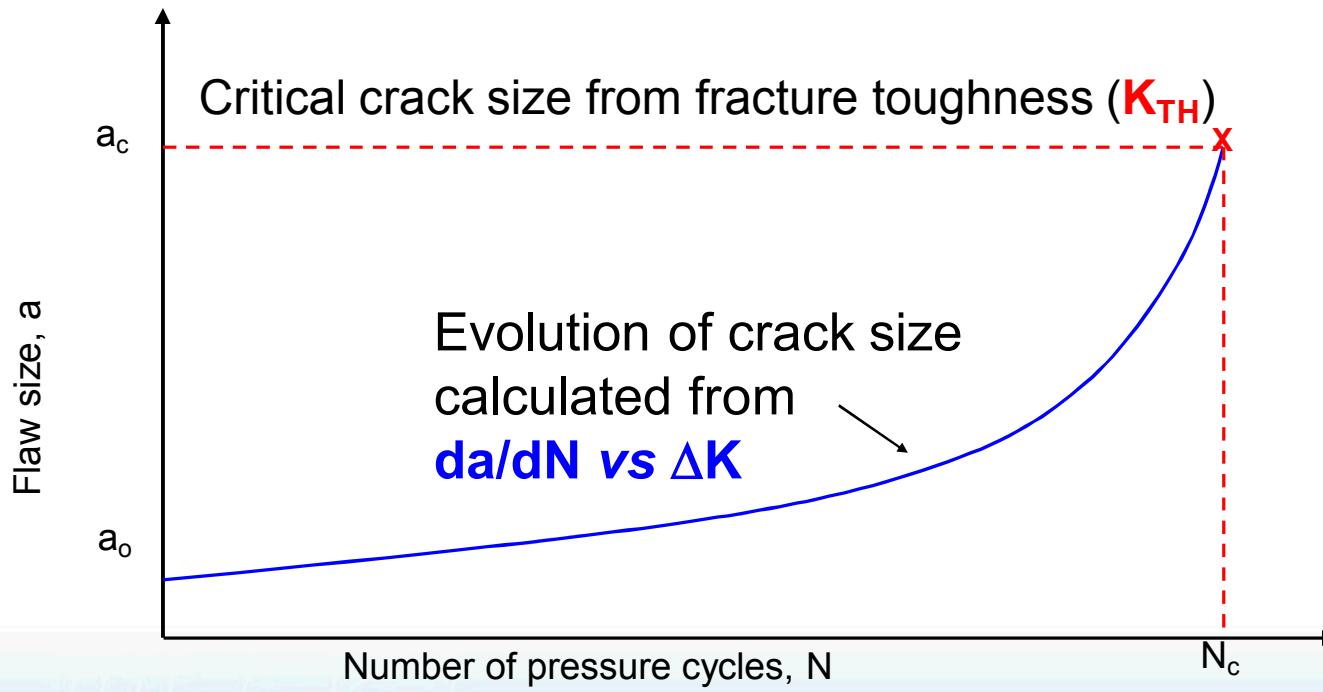
# Outline

- ***Fracture Mechanics Evaluation*** using fatigue crack growth testing to determine inspection interval or design life
- ***Structural Stress Methods*** to determine design life
- ***Pneumatic Pressure Cycling*** of full-scale components to determine design life

# ASME Boiler and Pressure Vessel Code

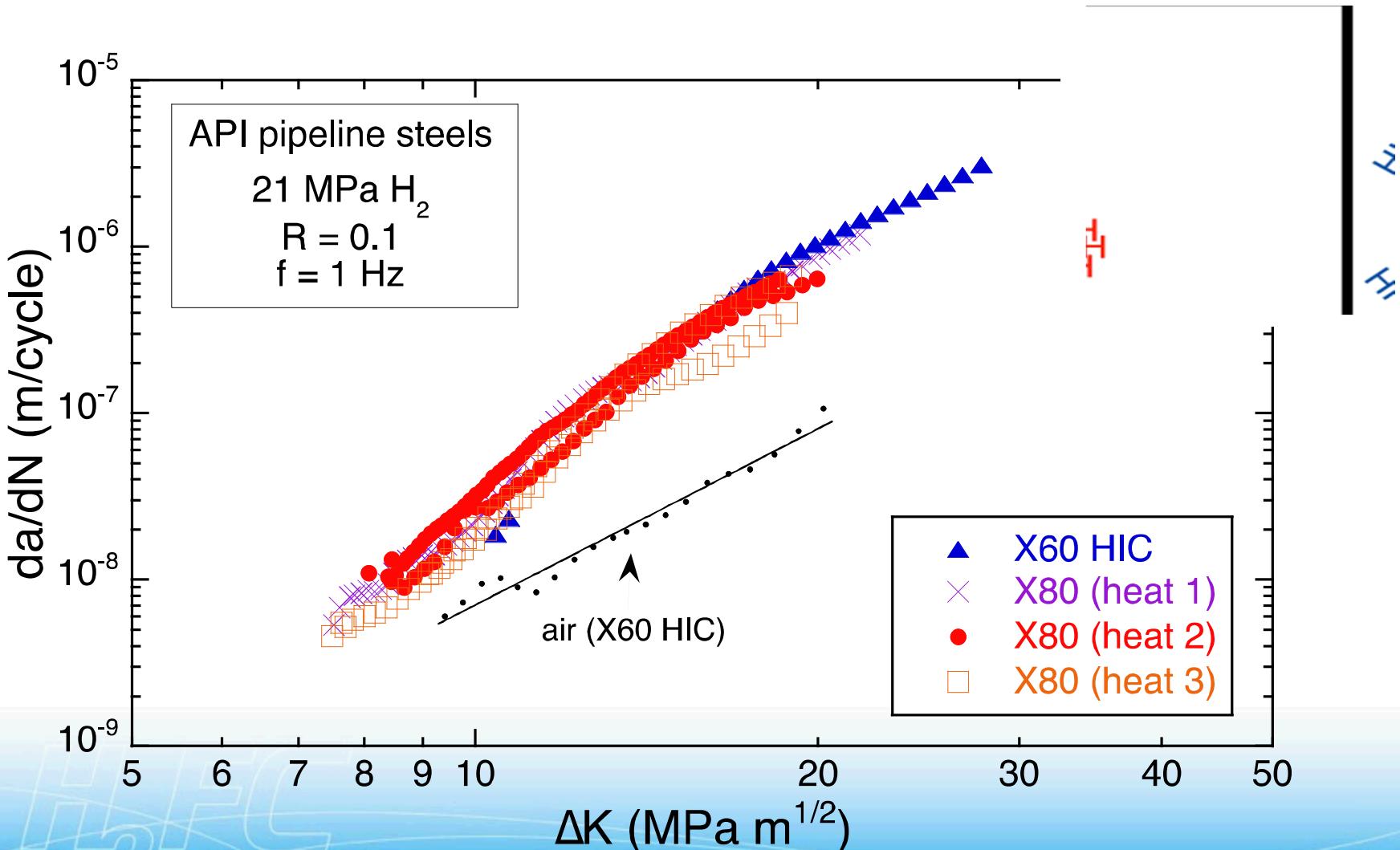
## Section VIII, Division 3, Article KD-10

**Fracture mechanics approach** to hydrogen pressure vessel and pipeline design, using **fatigue crack growth analysis**

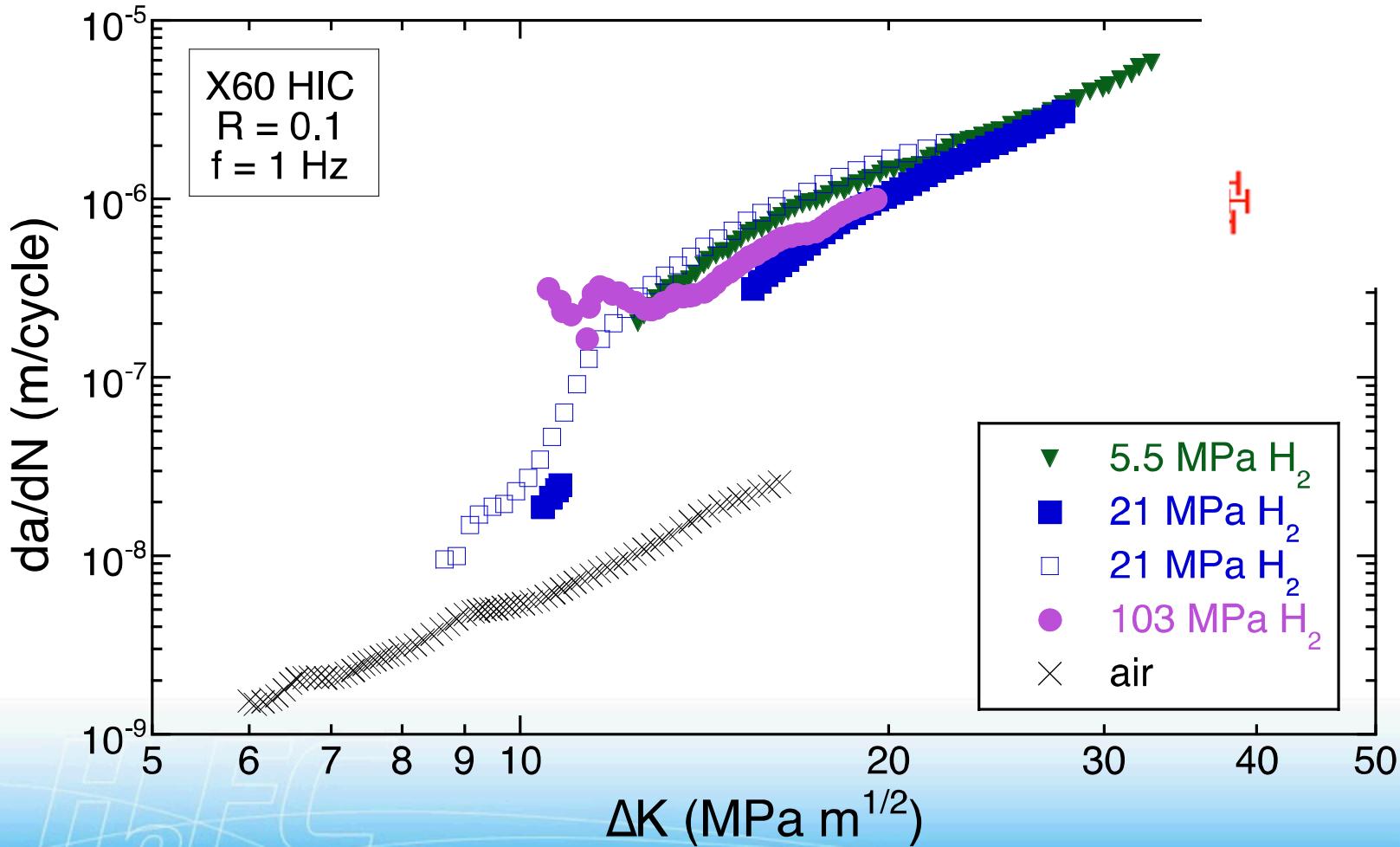


Method based on BPVC VIII.3 Article KD-4

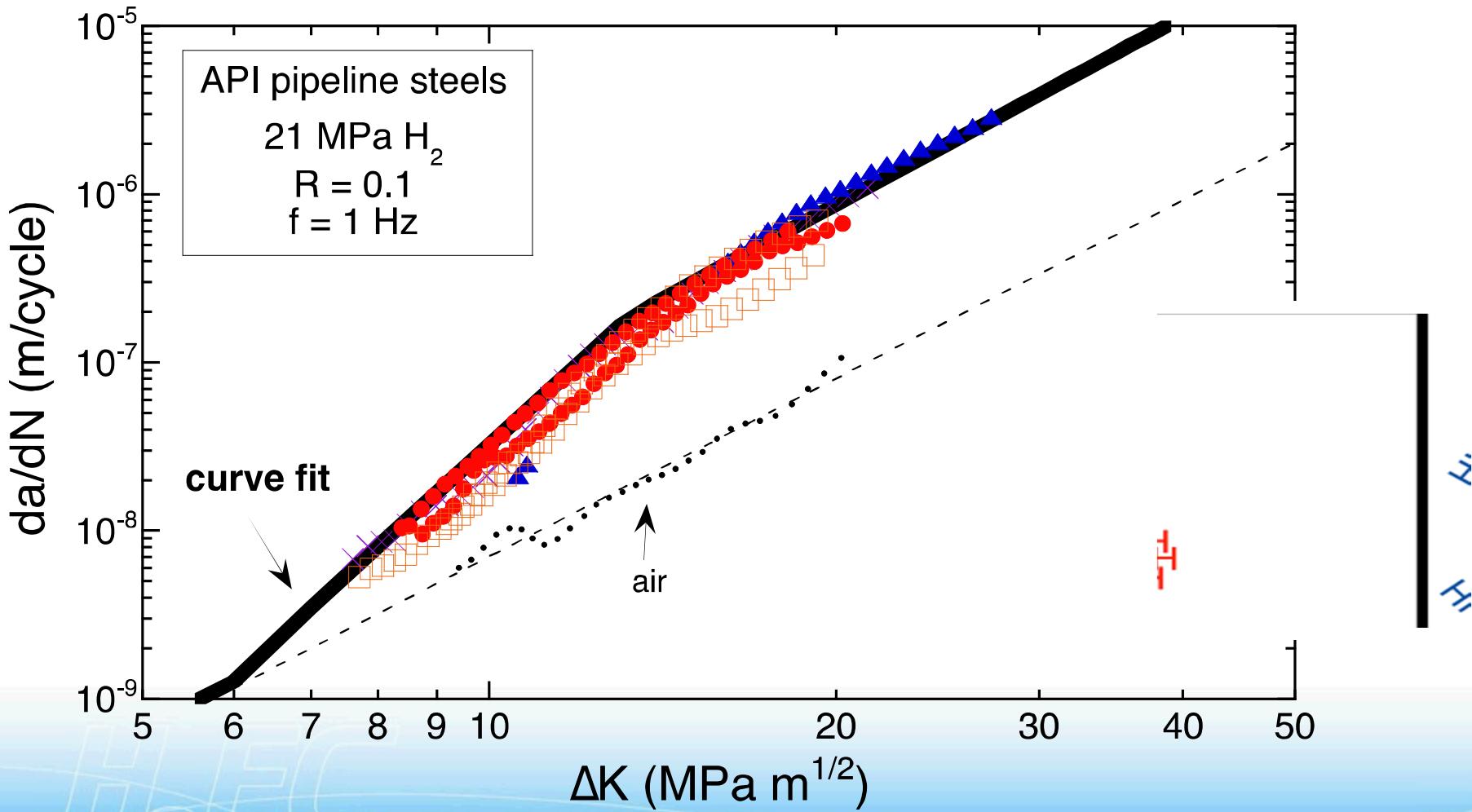
# Trends for fatigue crack growth are consistent for a broad range of pipeline steels



# Pressure effects on fatigue crack growth are modest (except perhaps at low $\Delta K$ )



# Power-law fit to bounding behavior in hydrogen is used to behavior to predict crack evolution



# Consider X70 pipeline

## Dimension and materials

OD = 762 mm

t = 12.7 mm

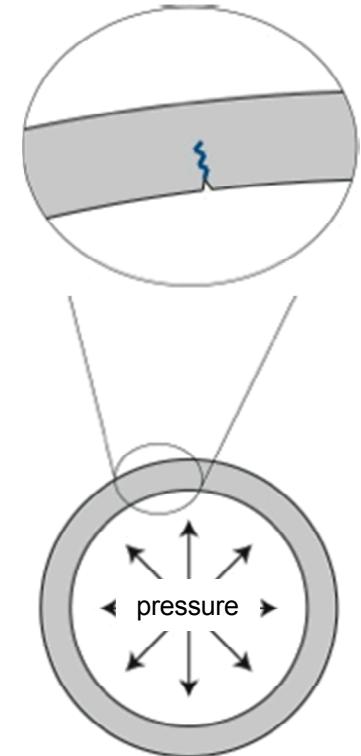
YS ~ 480 MPa

TS ~ 585 MPa

## Operating conditions

$P_{\max} = 7 \text{ MPa}$

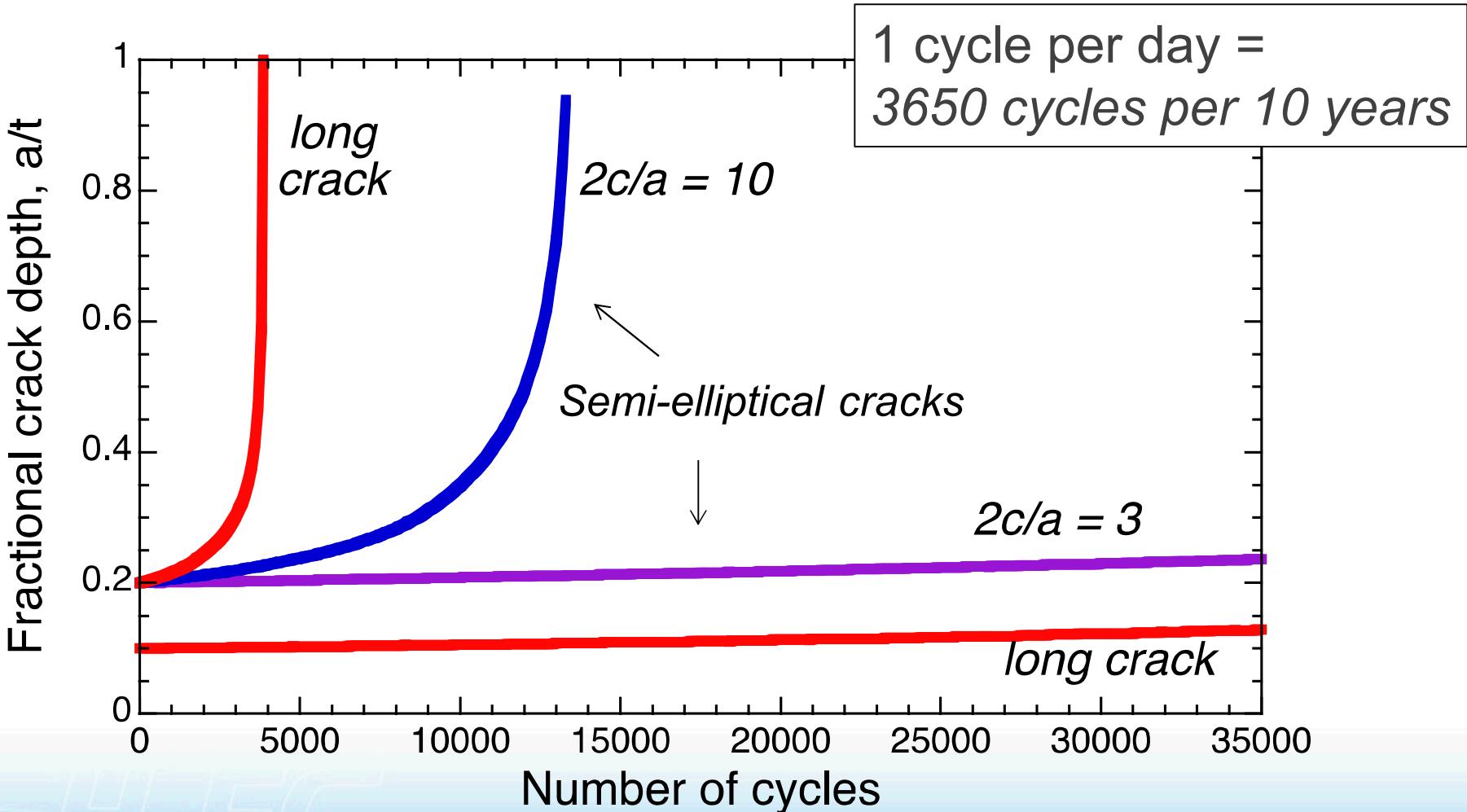
$P_{\min} = 4 \text{ MPa}$



Maximum nominal hoop stress = 204 MPa

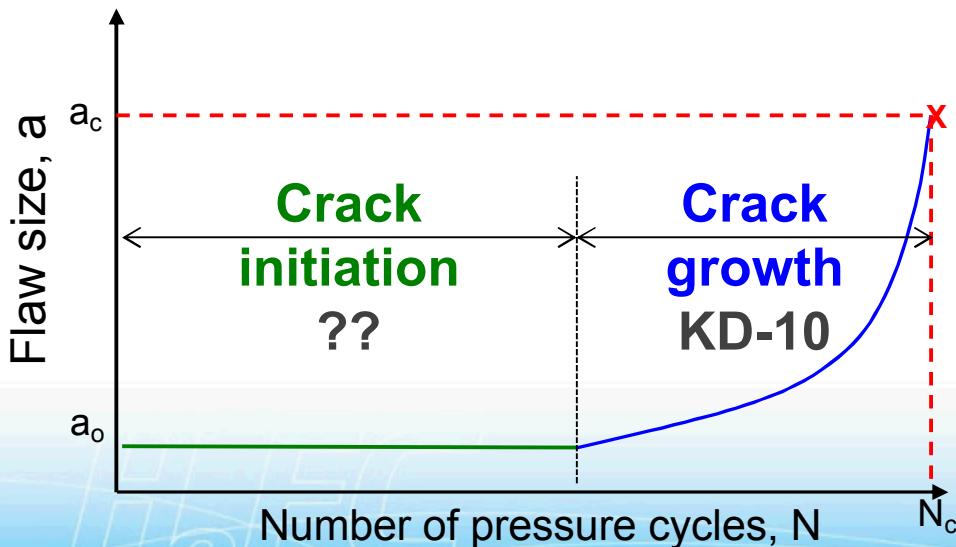
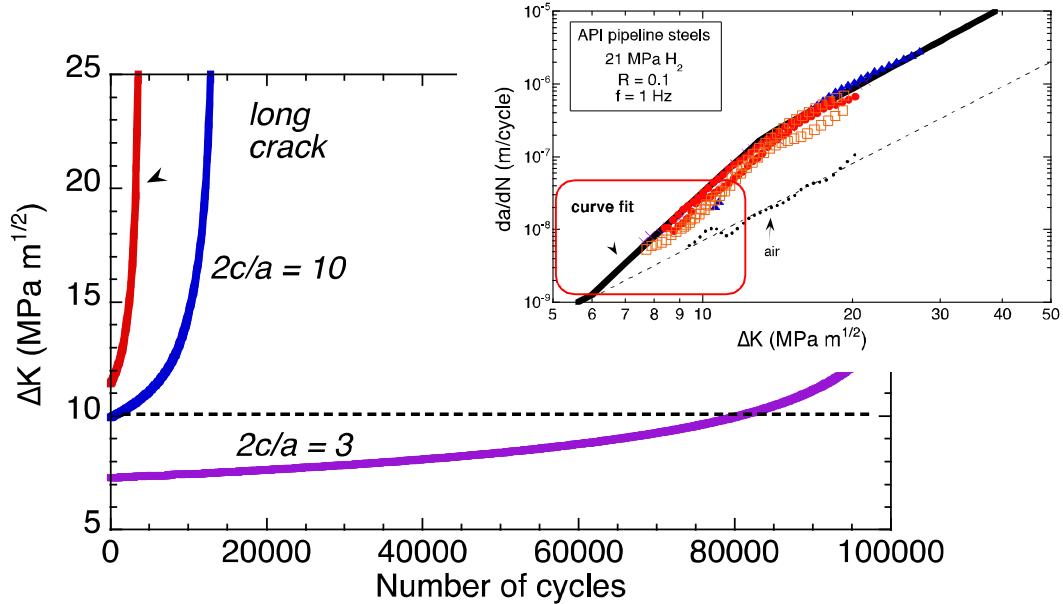
- 35% of Tensile Strength
- 42% of Yield Strength

# Crack evolution in X70 pipeline is relatively slow for low cycling



# Fracture mechanics approach has limits

- Long lives require  $\Delta K < 10 \text{ MPa m}^{1/2}$ 
  - Hydrogen effects are modest in area of interest



- Crack growth method ignores crack initiation
  - Initiation can be majority of life

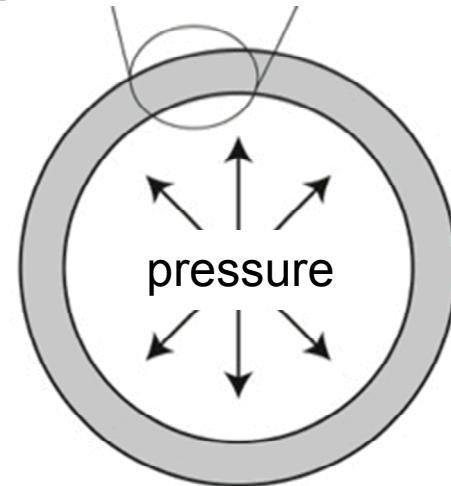
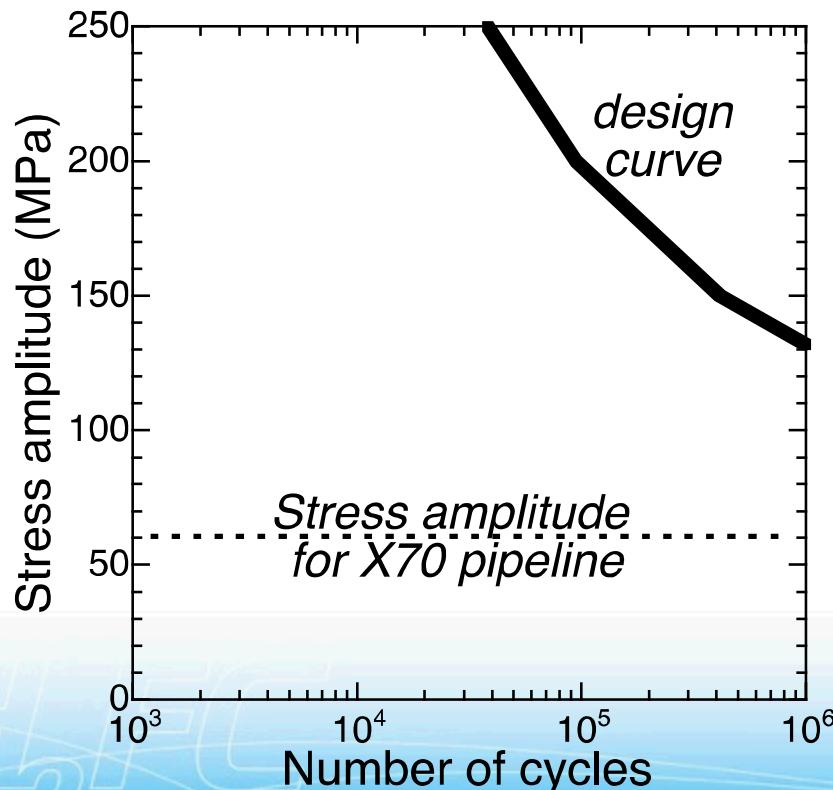
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# ASME Boiler and Pressure Vessel Code

## Section VIII, Division 3, Article KD-3

Structural stresses calculated and compared to design S-N curves to determine design life



Pipe:  $OD = 762 \text{ mm}$

$t = 12.7 \text{ mm}$

Operating pressure:

$P_{max} = 7 \text{ MPa}$

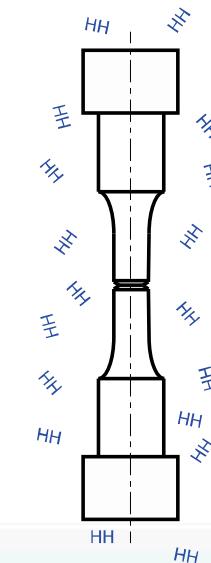
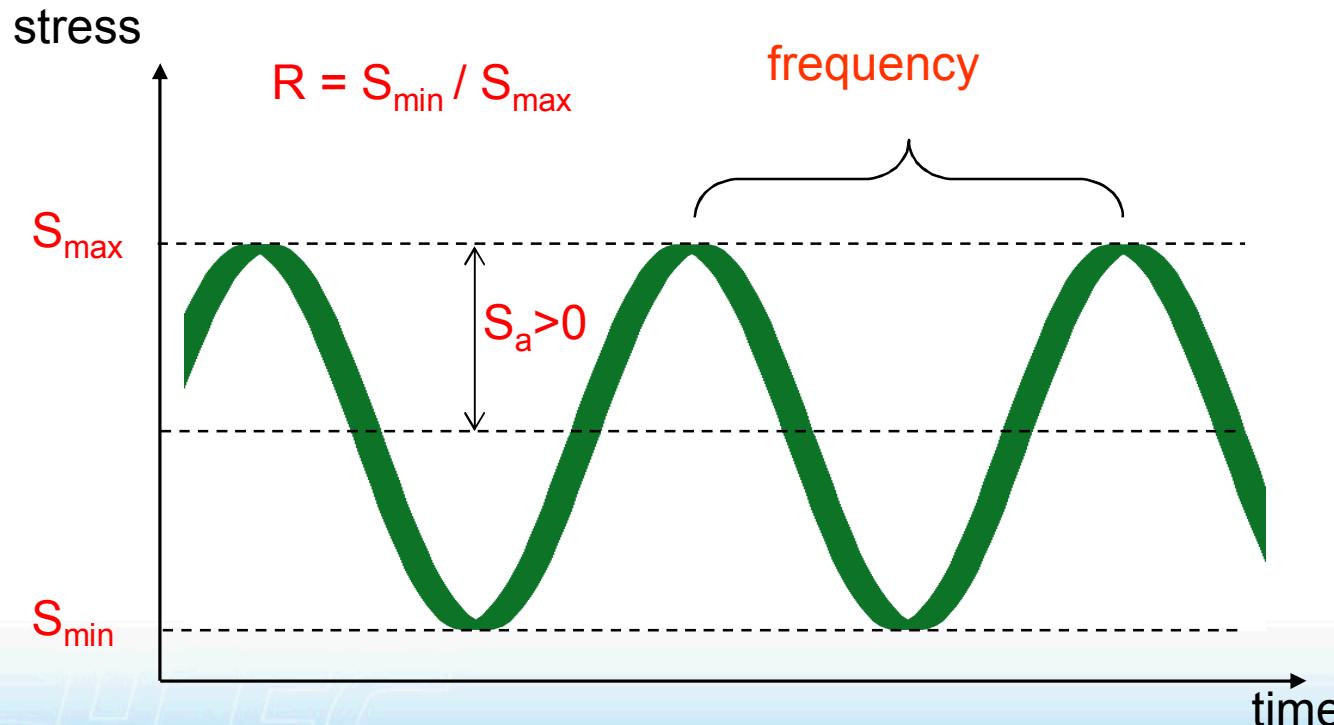
$P_{min} = 4 \text{ MPa}$

ASME design curve: carbon and low alloy steels with UTS = 620 MPa

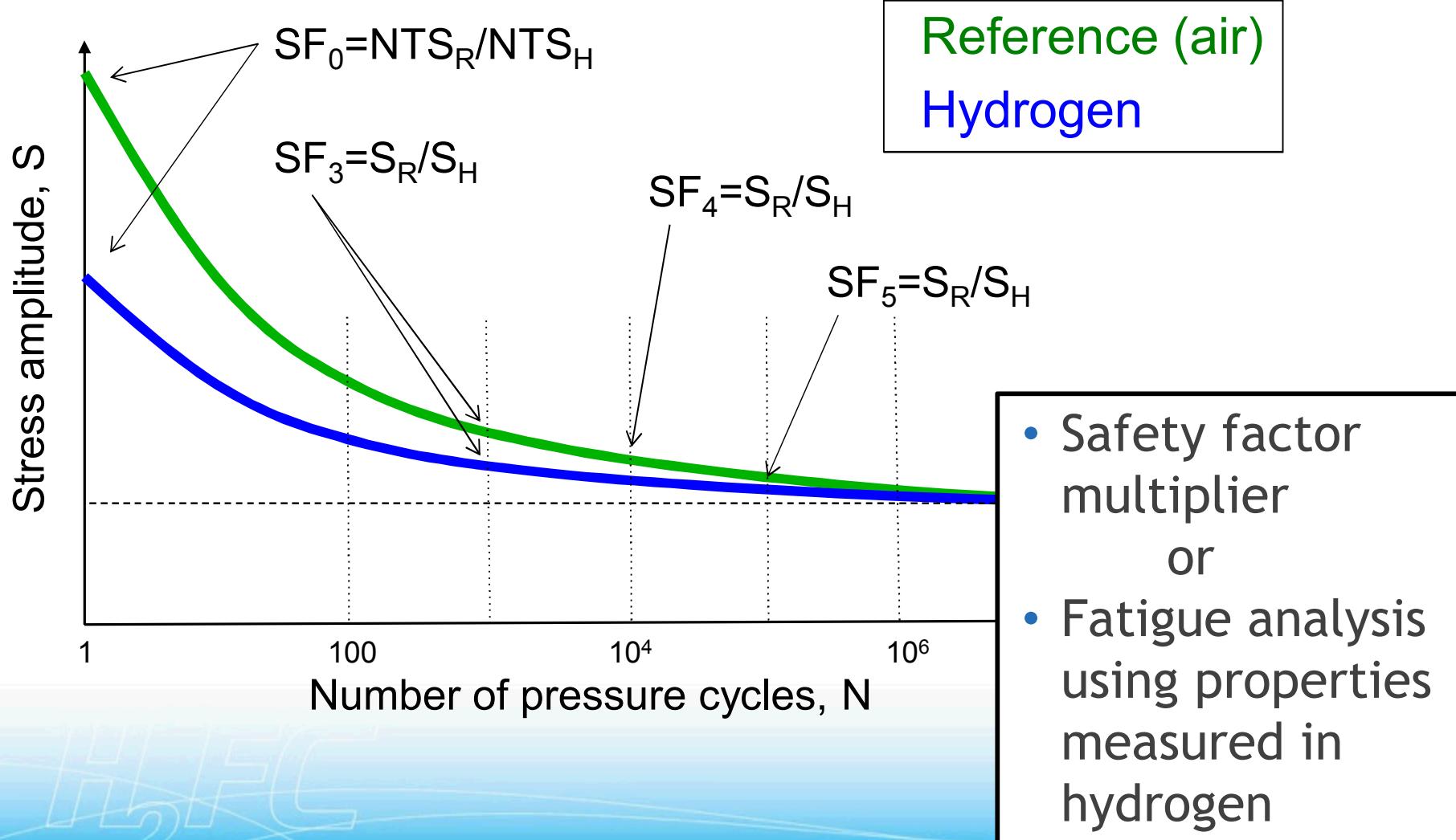
# Fatigue loading for pressure applications

Proposed testing condition to simulate *pressure loading*

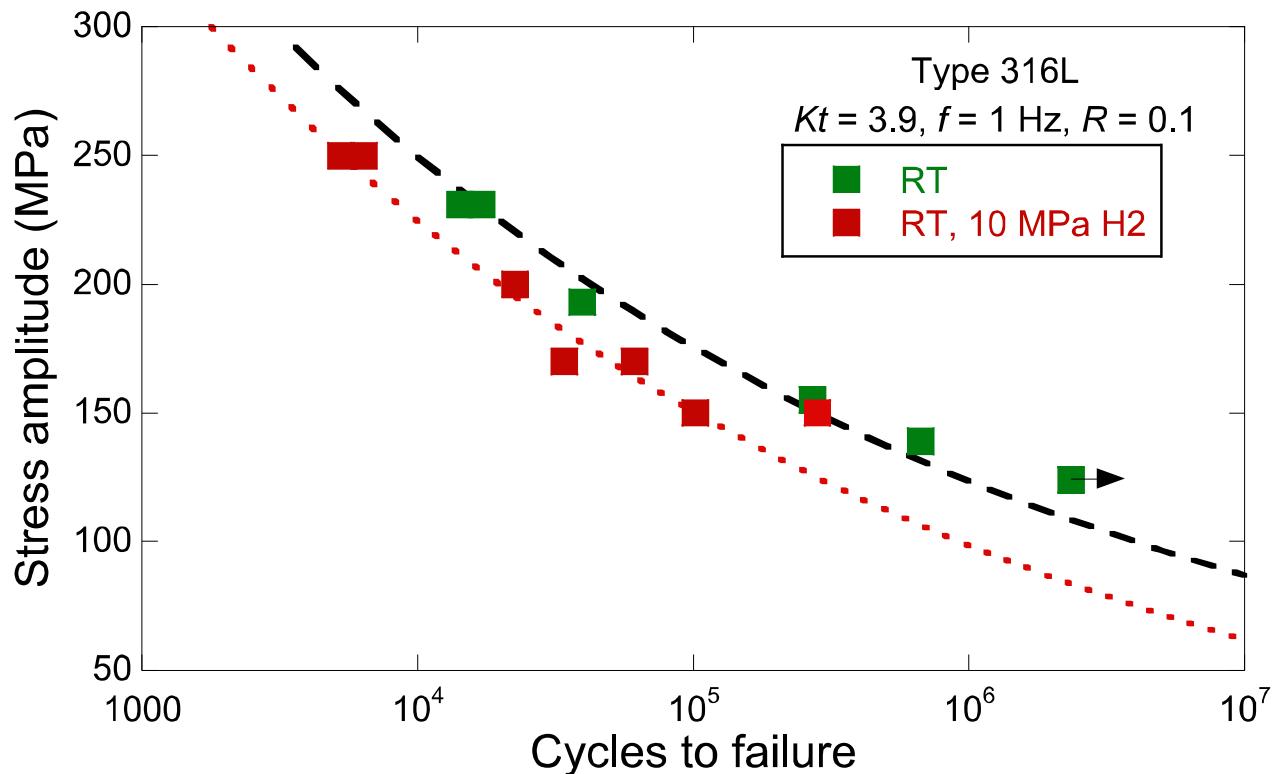
- $R \geq 0$  (tension-tension)
- Notched specimens to account for stress concentration



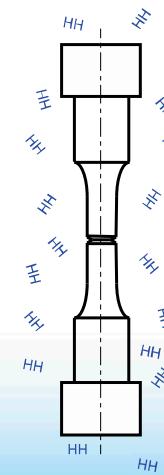
# Notched fatigue test methodology proposed in CSA CHMC1 standard



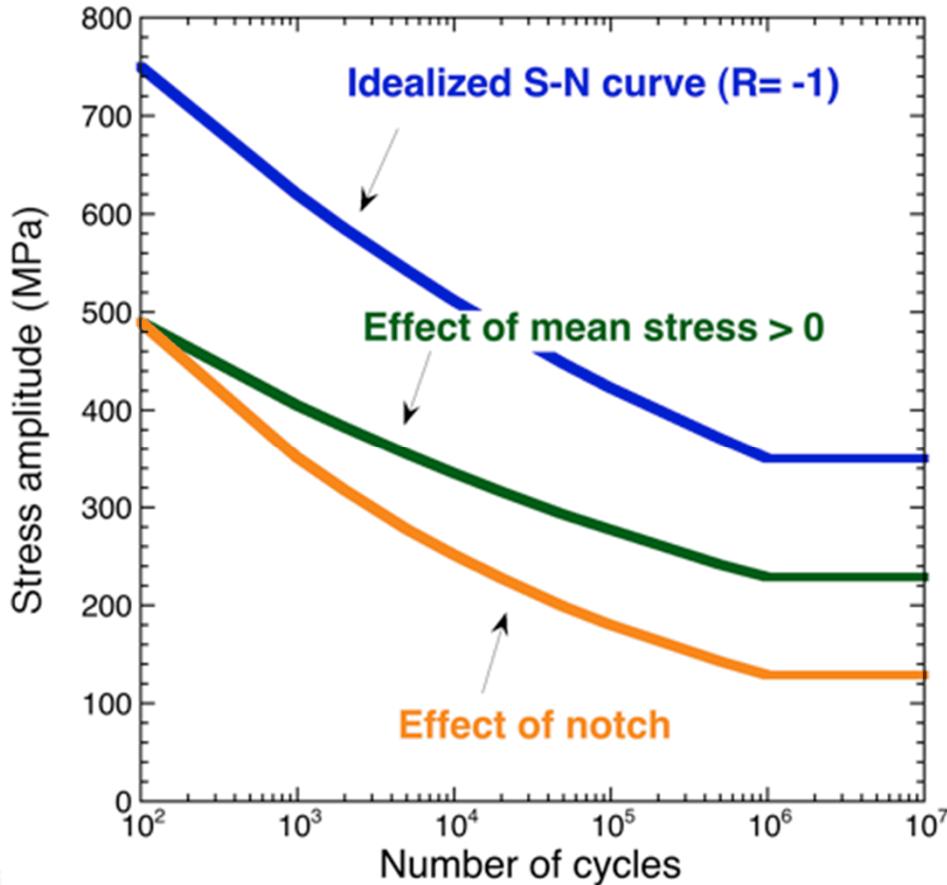
# Tension-tension fatigue testing facilitates data generation on hydrogen



- Fatigue life curve is affected by hydrogen
- Similitude of the notch to engineering stress concentrations needs further analysis (hydrogen-enhanced notch sensitivity?)



# Lack of harmonization of test methods to support structural stress analysis for hydrogen



- Conventional fatigue testing:
  - $R = -1$
  - Smooth specimen
- Fatigue applied to hydrogen
  - Tension-tension loading
  - Notched specimen

Effect of mean stress:

$$S_f^* = S_f \left[ 1 - \frac{S_m}{S_u} \right]$$

Effect of notch:

$$S_f^N = \frac{S_f}{K_f}$$

Methods exist to explore similitude between methodologies

# Outline

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- ***Pneumatic Pressure Cycling*** of full-scale components to determine design life

# Full-scale pressure cycling of pressure vessels

- Two pressure vessel designs from different manufacturers
  - Nominal hoop stress at  $P = 43.5 \text{ MPa}$ 
    - T1 design:  $\sim 340 \text{ MPa}$
    - T2 design:  $\sim 305 \text{ MPa}$



- Steel for both pressure vessels designs: 4130X
  - Quench and tempered, 1 wt% Cr - 0.25 wt% Mo
  - TS for transport applications: 700 to 900 MPa
    - T1 design:  $\sim 750 \text{ MPa}$
    - T2 design:  $\sim 850 \text{ MPa}$



Typical design rule: maximum wall stress  $< 40\%$  of TS

T1 design: 300 MPa

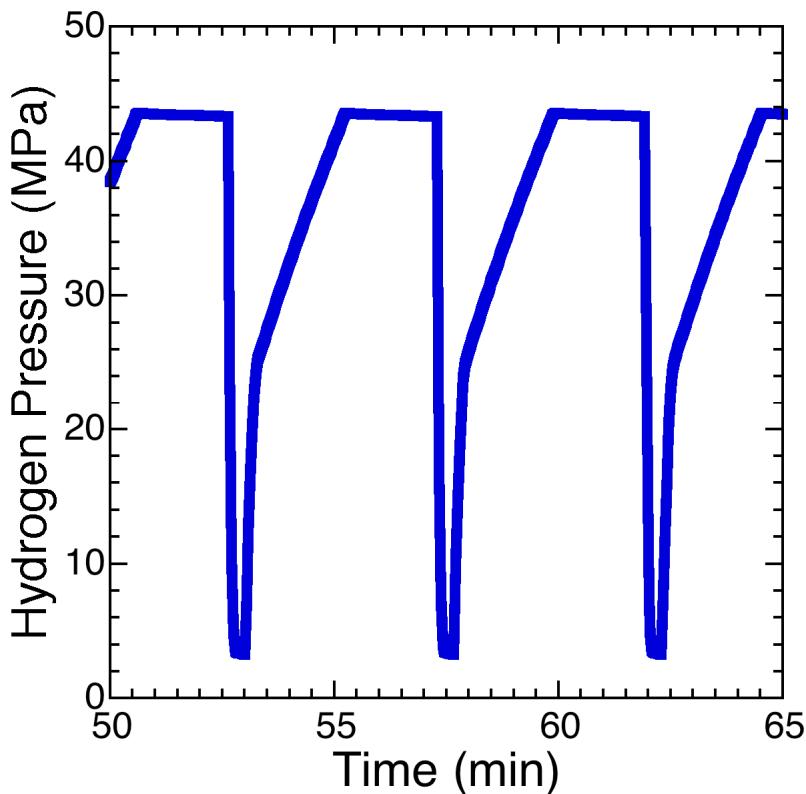
T2 design: 340 MPa

# Hydrogen pressure cycling of pressure vessels



Consider 35 MPa gaseous hydrogen fuel system

- Nominal pressure of 35 MPa
- Allow 25% over-pressure during rapid filling
- Minimum system pressure of ~3 MPa

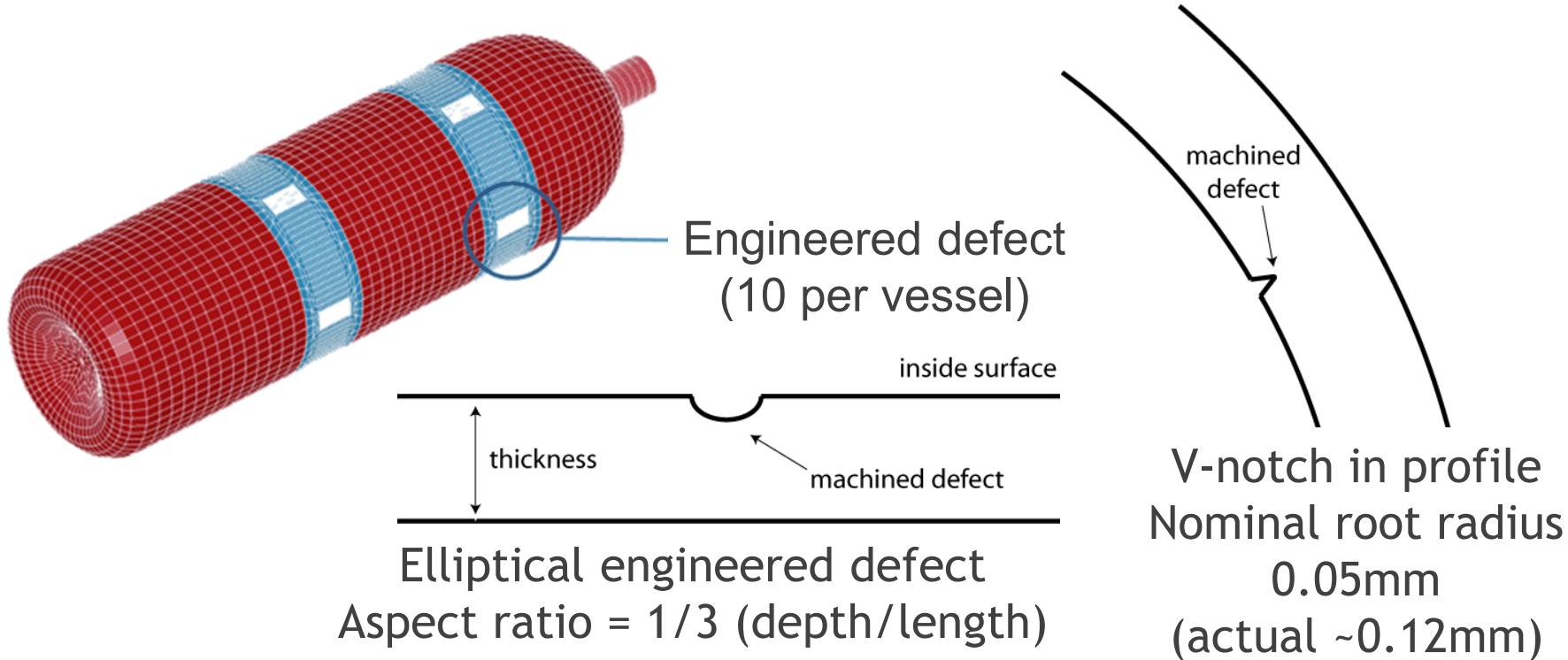


## Pressure cycle for testing

- maximum P = 43.5 MPa
- 2-minute hold at maximum P
- rapid depressurization to 3 MPa
- 30-second hold at minimum P
- pressurization time ~ 2 min

*4 to 5 minute cycle time  
(~300 cycles per day)*

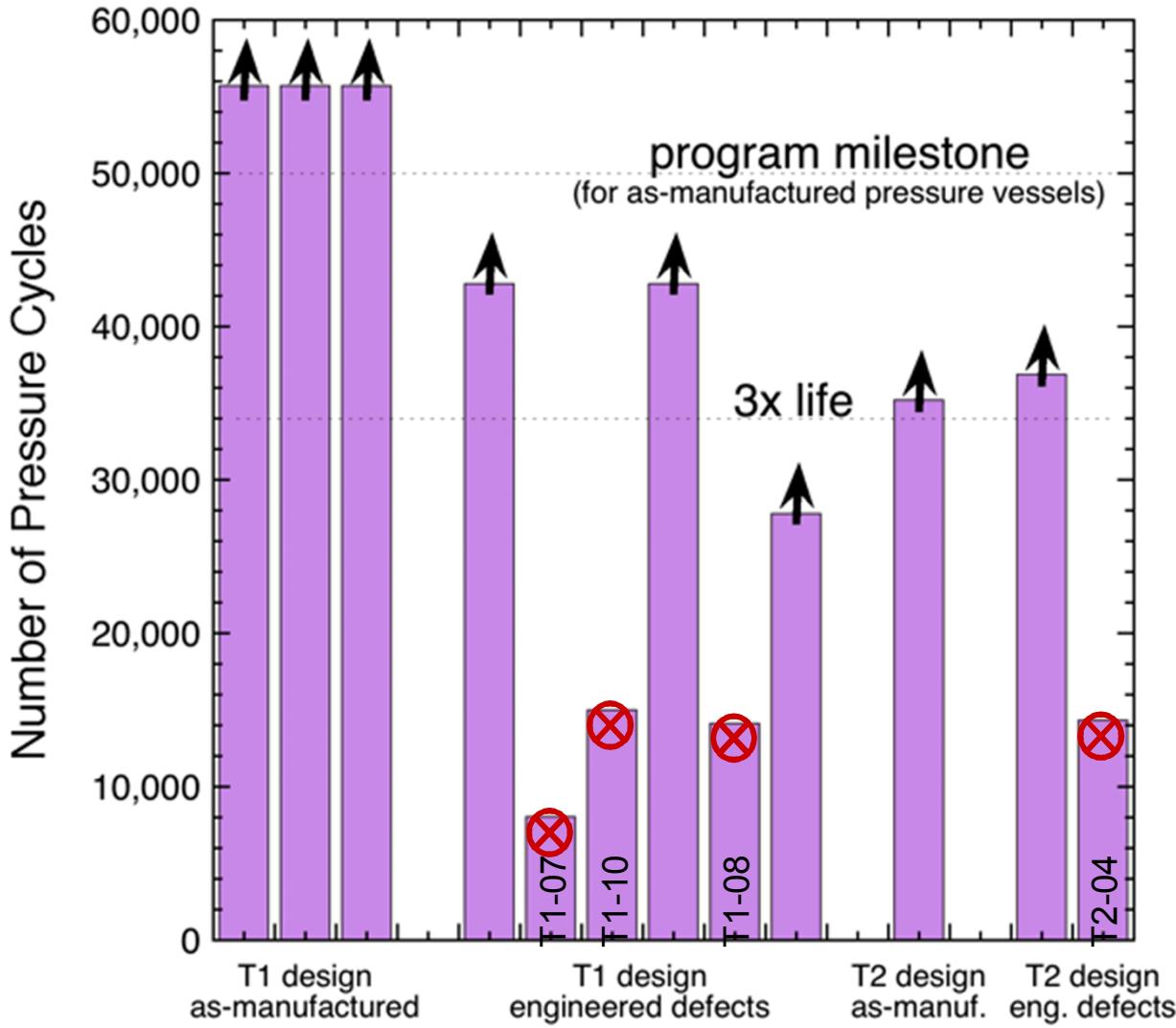
# Engineered defects used to initiate failures



## Depth of engineered defects

- Typically all 10 defects similar for a given vessel
- Smallest defects ~2% of wall thickness
- Largest defects ~10% of wall thickness
- For one vessel, aspect ratios were 1/2 and 1/12

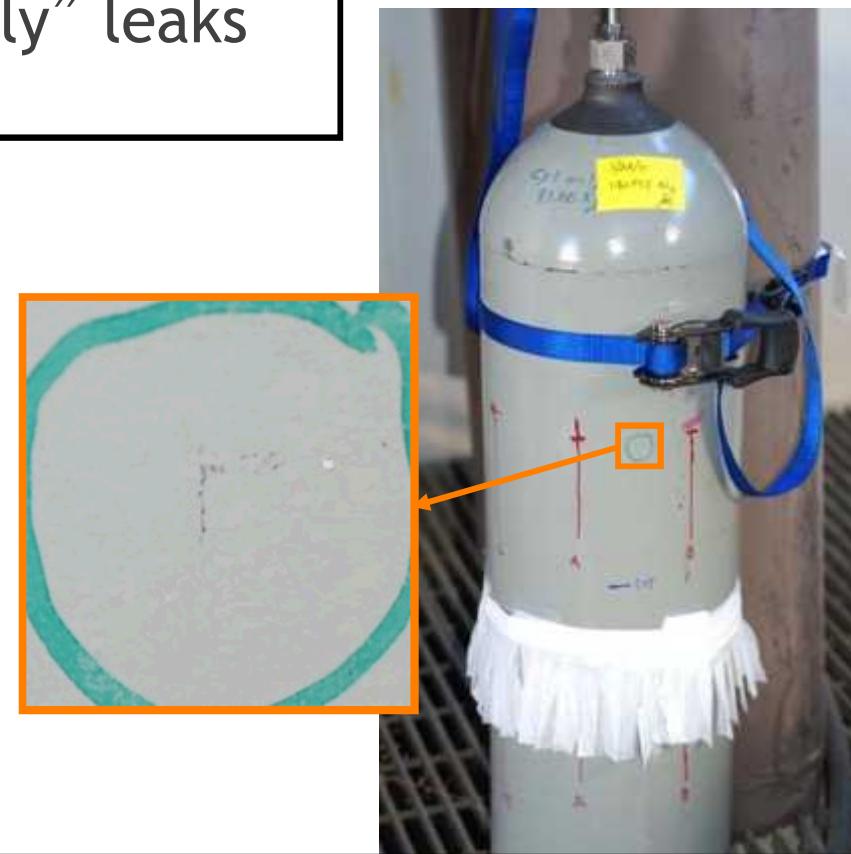
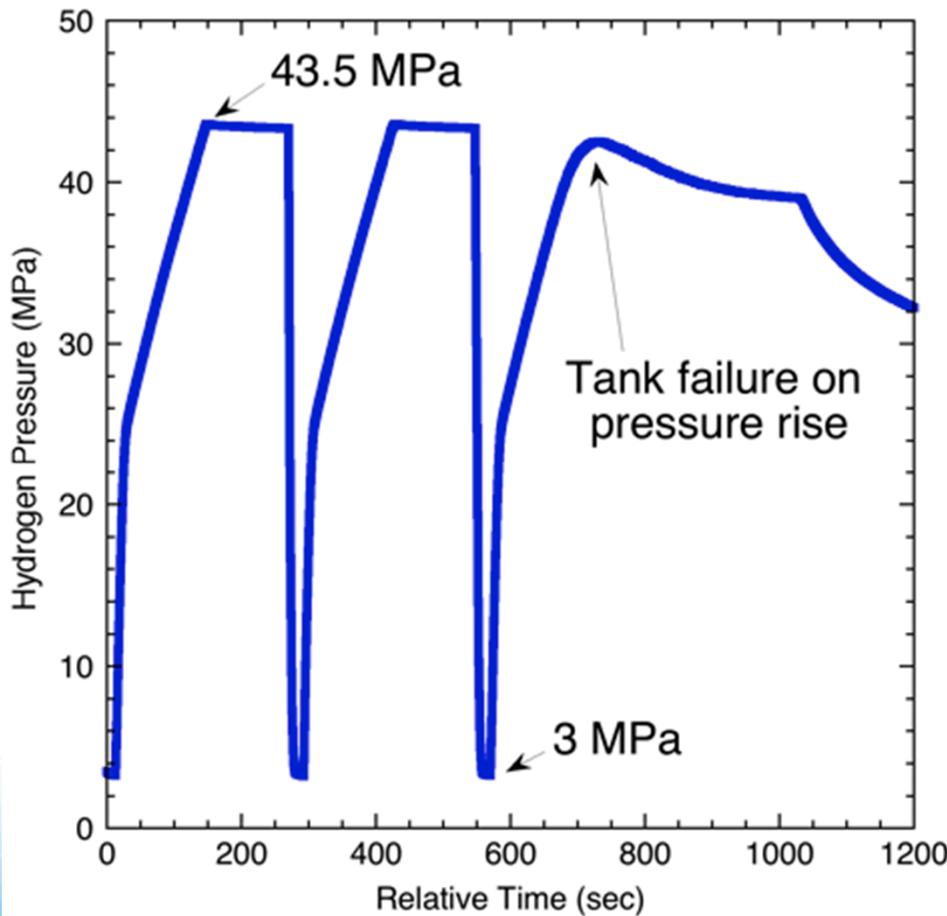
# Commercial pressure vessels exceed lifetime target of 11,250 cycles by >3 times



- Each pressure vessel with engineered defects contains 10 nominally equivalent defects
- Arrows indicate pressure vessels that did not fail
- In failed vessels, all defects initiate a crack
- All four failures were leak before burst

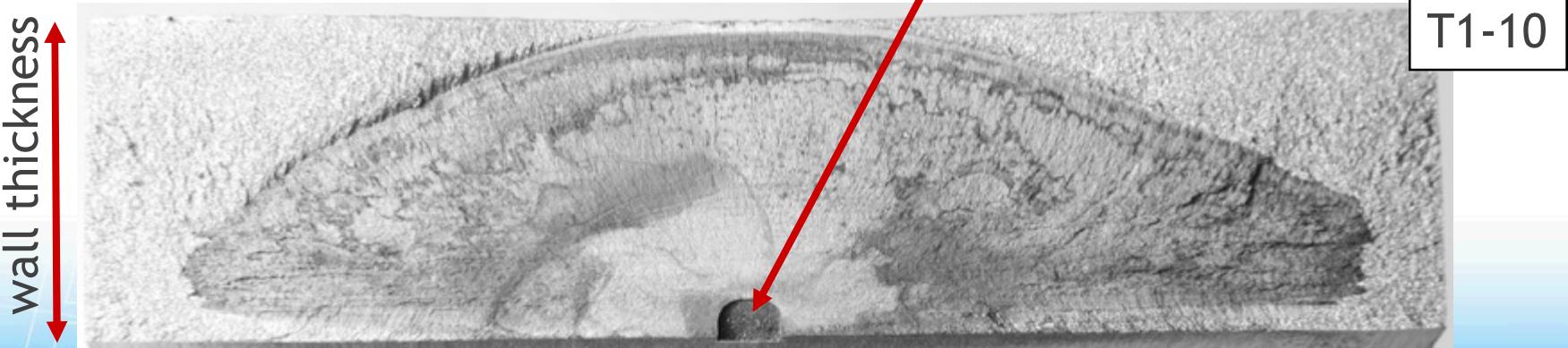
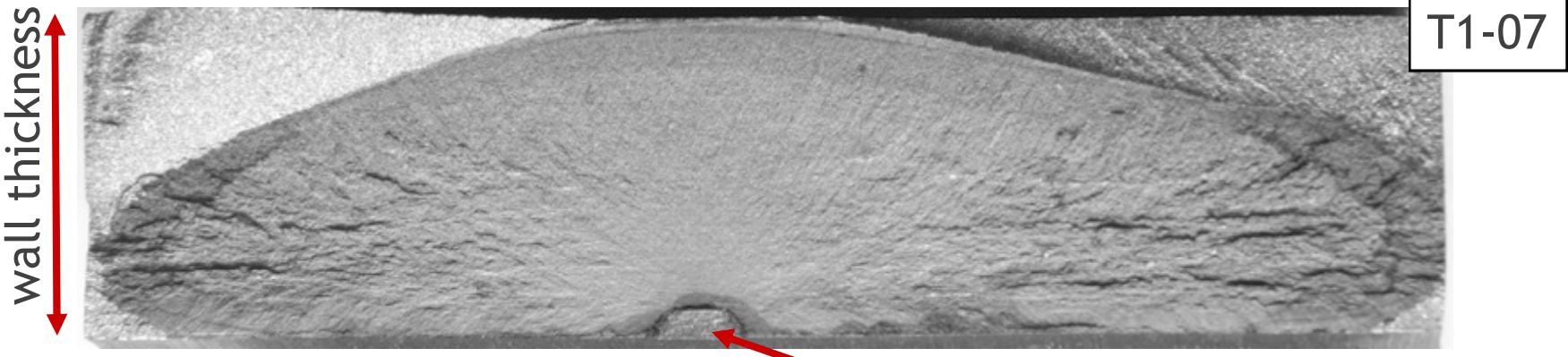
# All observed failures are leak-before-burst mode

At failure, pressure vessel “slowly” leaks gas into secondary containment

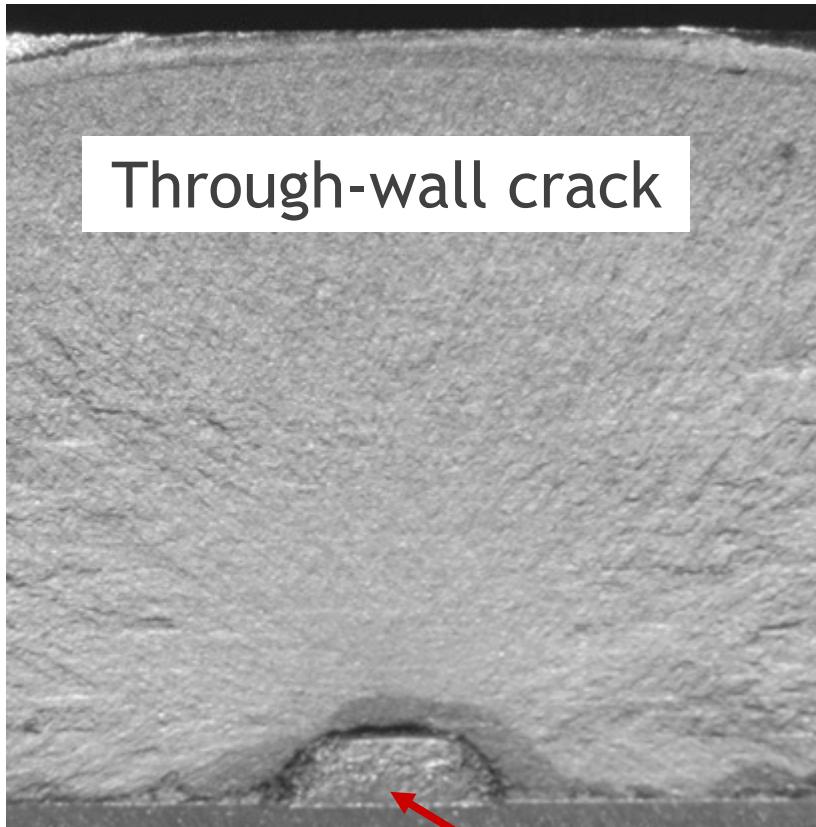


Through-wall crack cannot be detected visually

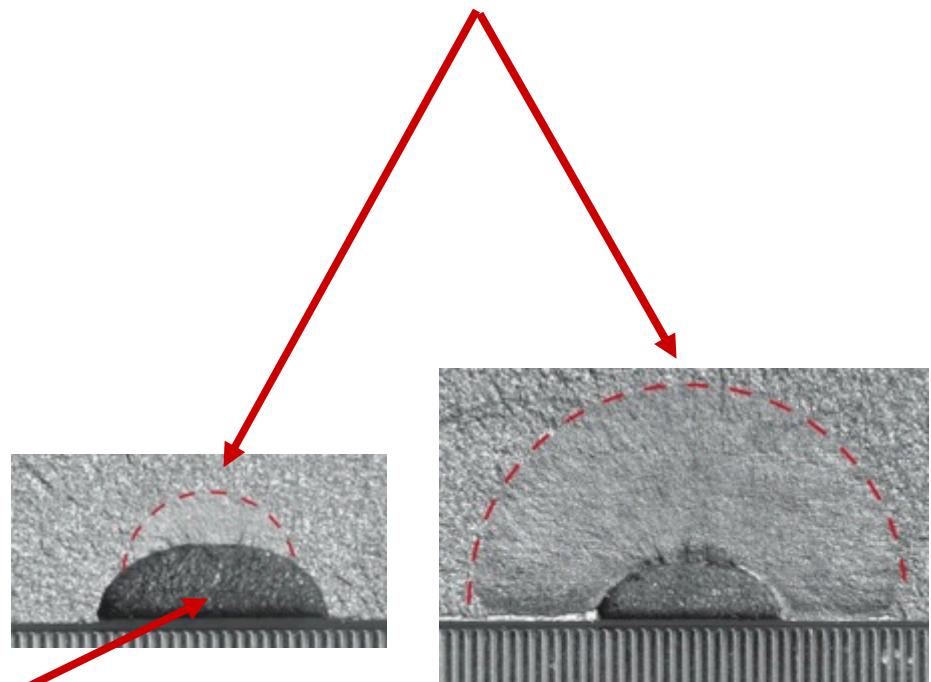
# Through-wall crack extend from “critical” engineered defect



# Cracks extend from all engineered defects

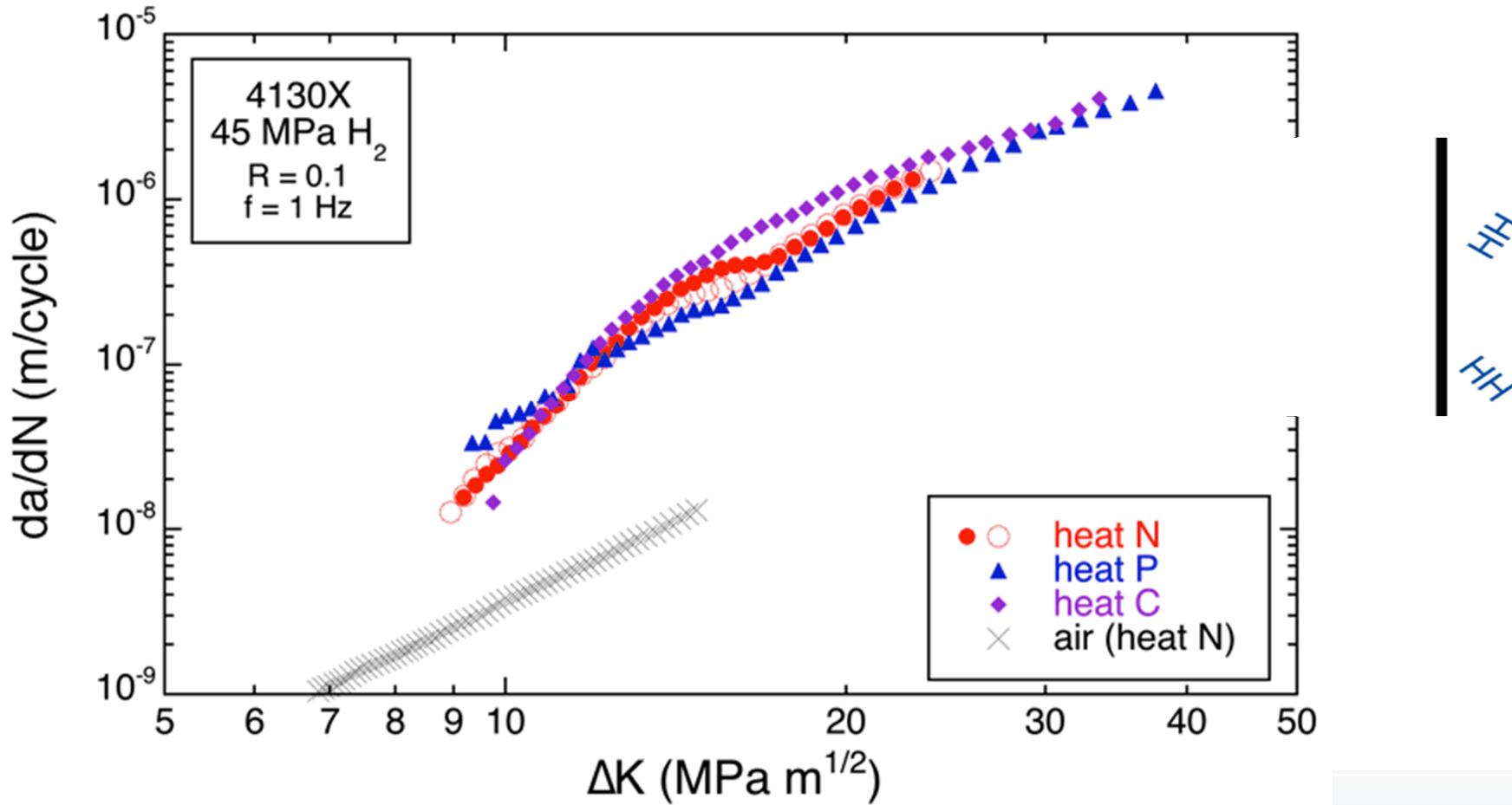


Growing (non-through-wall) cracks have semicircular profile



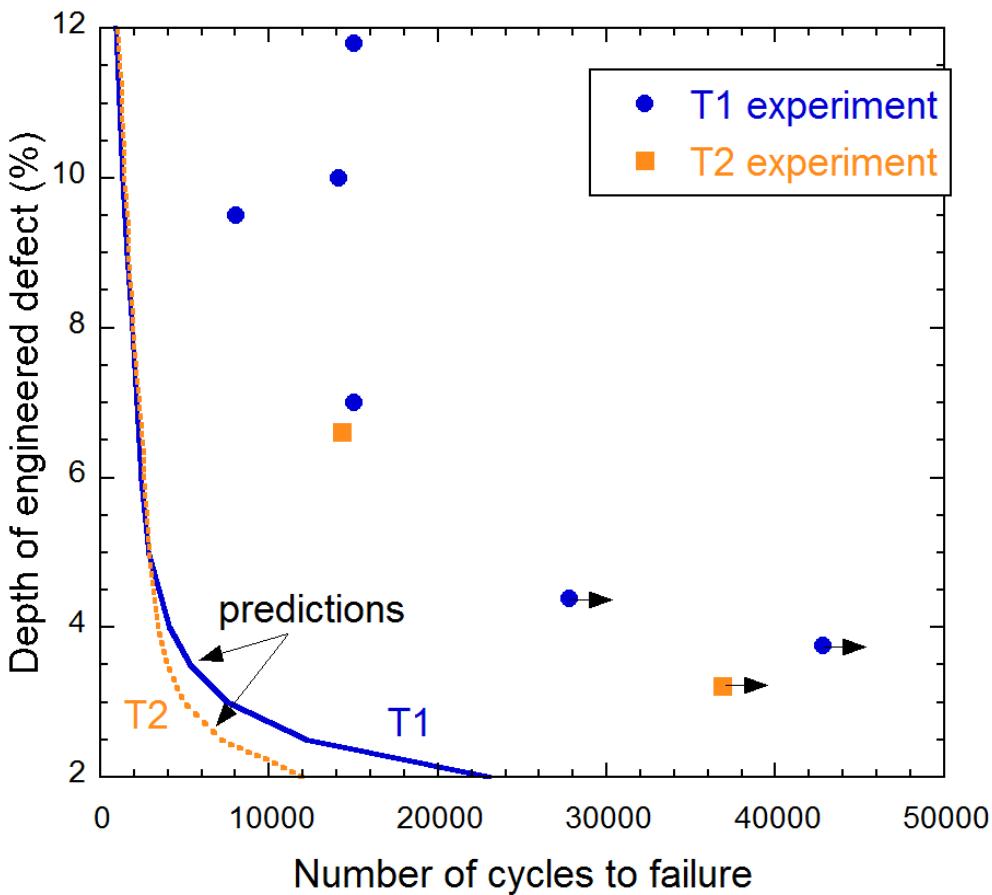
Same size engineered defect  
(same vessel)

# Fatigue crack growth of Cr-Mo PV steels in gaseous hydrogen is similar to pipeline steels



3 heats of 4130X steel all show approximately the same behavior

# Comparison of fracture mechanics evaluation to full-scale pneumatic experiments



- Curves are predictions based on *crack growth* only (of semicircular flaw)
- Arrows indicate vessels that did not fail

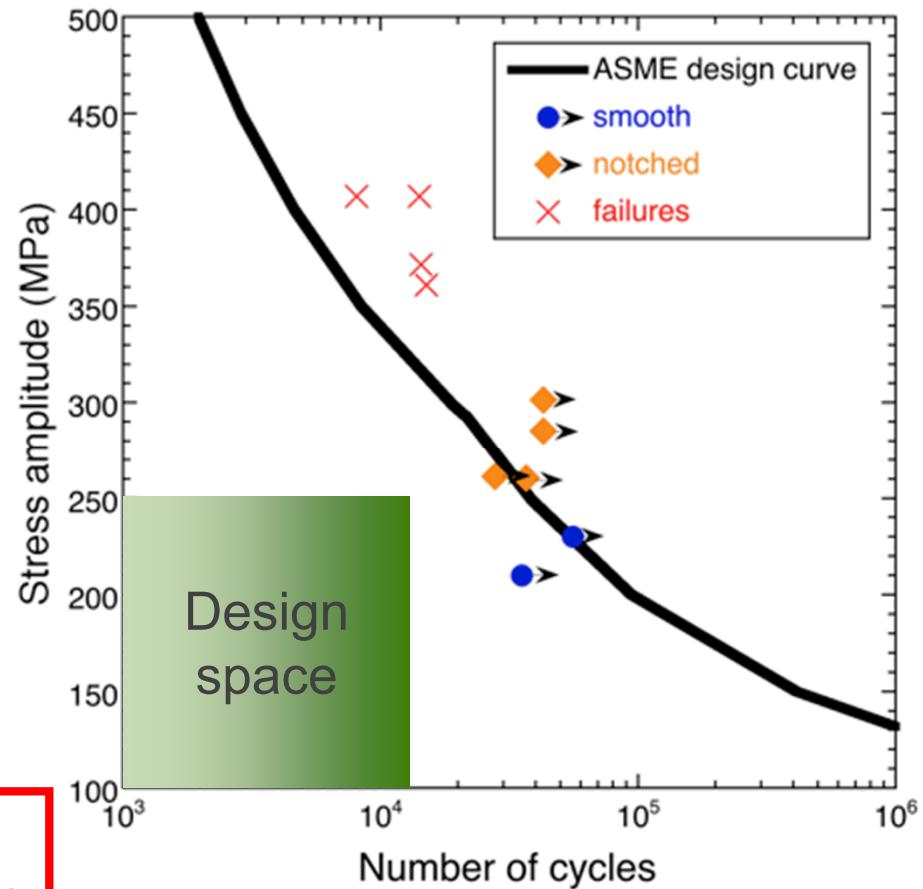
- Fracture mechanics predictions underestimate experiments for all defect sizes
- Conservativeness of fracture mechanics can be restrictive for small defects

# Comparison of structural stress method to full-scale pneumatic experiments

- Observed full-scale behavior is consistent with design curves
- Assessment of design requirements enables definition of appropriate design space
  - TS < 890 MPa limits stress amplitude to <230 MPa
  - Required design life <11,250 cycles

## Result:

conservative design space relative to established structural stress method



ASME design curve: carbon and low alloy steels with UTS = 620 MPa

# Summary

- ***Fracture mechanics evaluation*** using fatigue crack growth provides conservative design life
  - does not account for crack initiation
  - Relevant  $\Delta K < 10 \text{ MPa m}^{1/2}$
- ***Structural stress methods*** can be applied for hydrogen with appropriate data
  - Fatigue curves in hydrogen need to be determined
  - Harmonization of methods needs to be verified
- ***Pneumatic pressure cycling*** methods have been standardized
  - Limited validation to support design by analysis methods