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Hydrogen-Assisted Fatigue of Steel Pressure Vessels

Chris San Marchi

Sandia National Laboratories

with

Brian Somerday, Sandia National Laboratories and

Kevin Nibur, Hy-Performance Materials Testing

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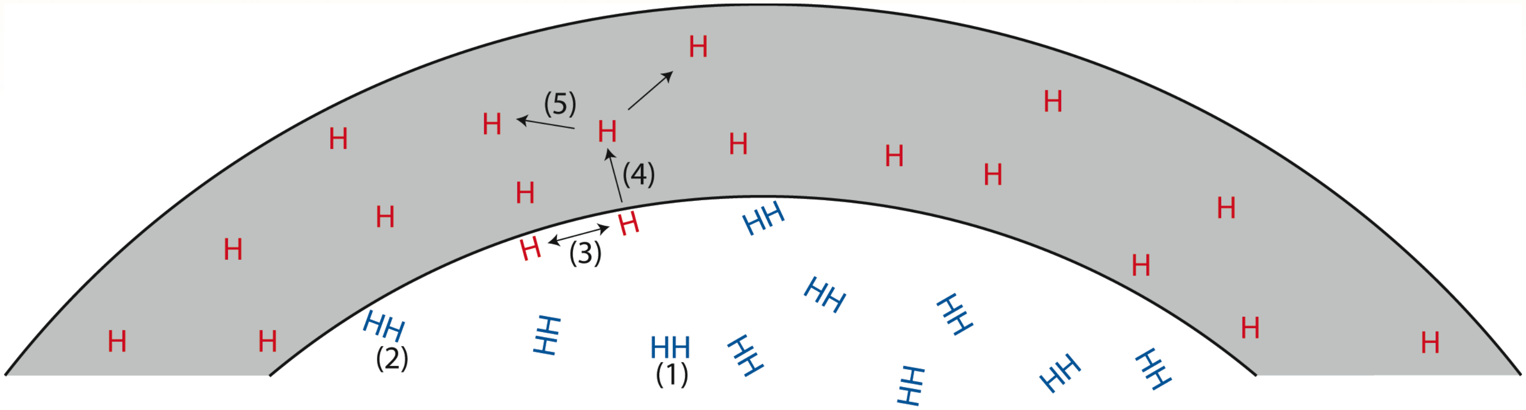
Hydrogen transport is essential to hydrogen embrittlement



(1) Hydrogen gas
(2) Physisorption
(3) Dissociation
(4) Dissolution
(5) Diffusion

Internal Hydrogen

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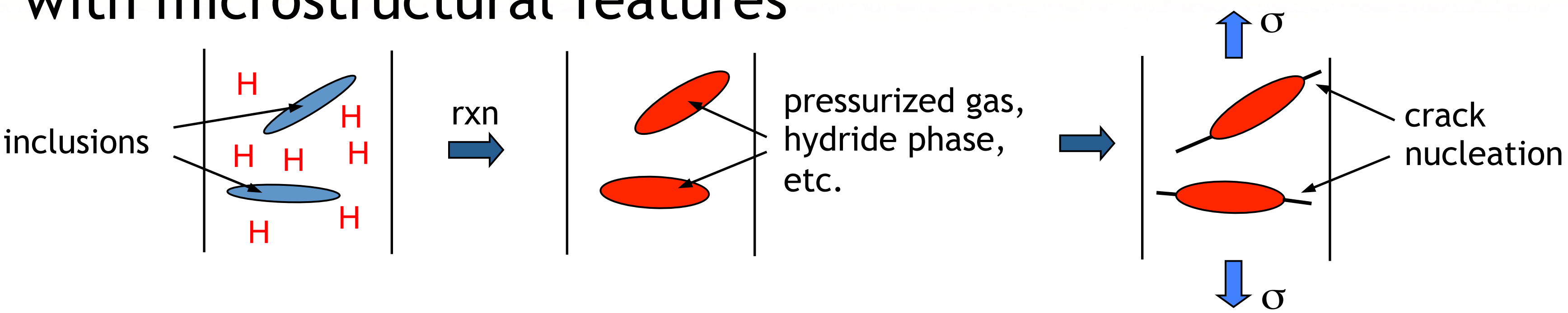
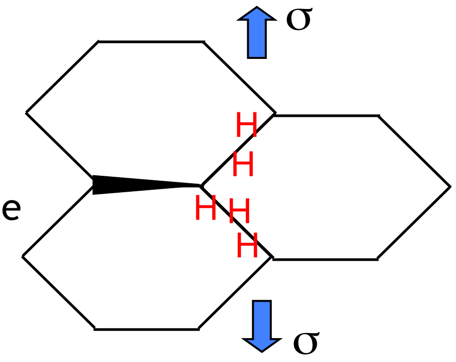
Hydrogen Embrittlement

A variety of mechanisms can produce hydrogen-assisted fracture in metals

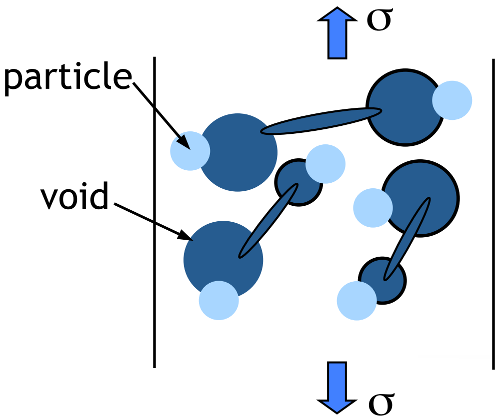
Hydrogen attack: chemical reaction of atomic hydrogen with microstructural features



Hydrogen solute effects: solute hydrogen enhanced failure of interfaces and deformation mechanisms

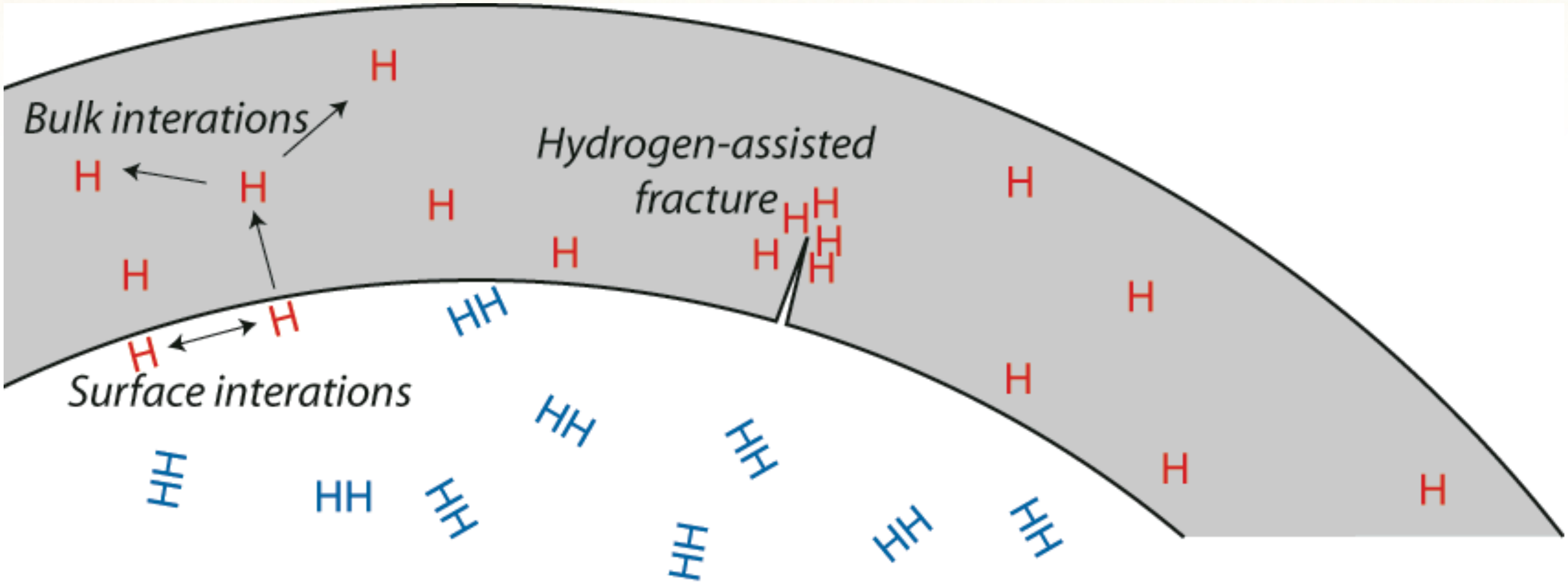


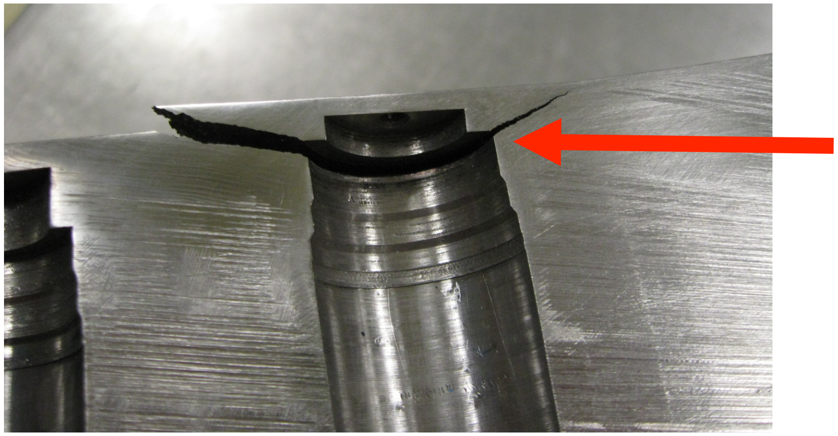
Hydrogen accumulation at interfaces affects strength of interface (grain boundaries, second phases, inclusions)



Hydrogen enhanced shear localization

Hydrogen-defect interactions are critical to hydrogen-assisted fracture





Hydrogen-induced failure in high-pressure compressor initiated at stress concentration

Outline and Objectives

- Demonstrate performance test method for evaluating compatibility of pressure vessel with gaseous hydrogen
- Determine failure characteristics of commercial pressure vessels
  - Do the pressure vessels leak-before-burst when cycled with gaseous hydrogen?
- Compare full-scale testing for steel pressure vessels for gaseous hydrogen with engineering design methods
  - Fracture mechanics-based design
  - Stress-life design
- Describe method proposed in CSA standard

Fracture and fatigue resistance of steels is degraded by exposure to hydrogen

Hydrogen-induced failure of transport cylinder

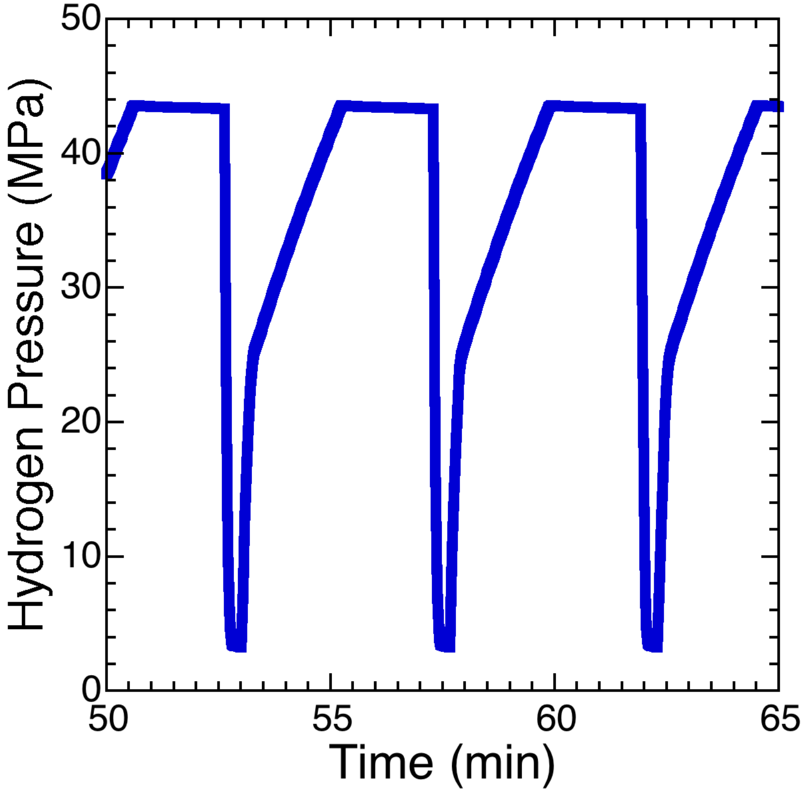
Ref.: *Barthélémy, 1st ESSHS, 2006*

Motivation:
innovative applications are expanding design space beyond engineering experience

>10,000 refueling cycles are anticipated for hydrogen-powered industrial trucks

Pressure cycle designed for accelerated testing

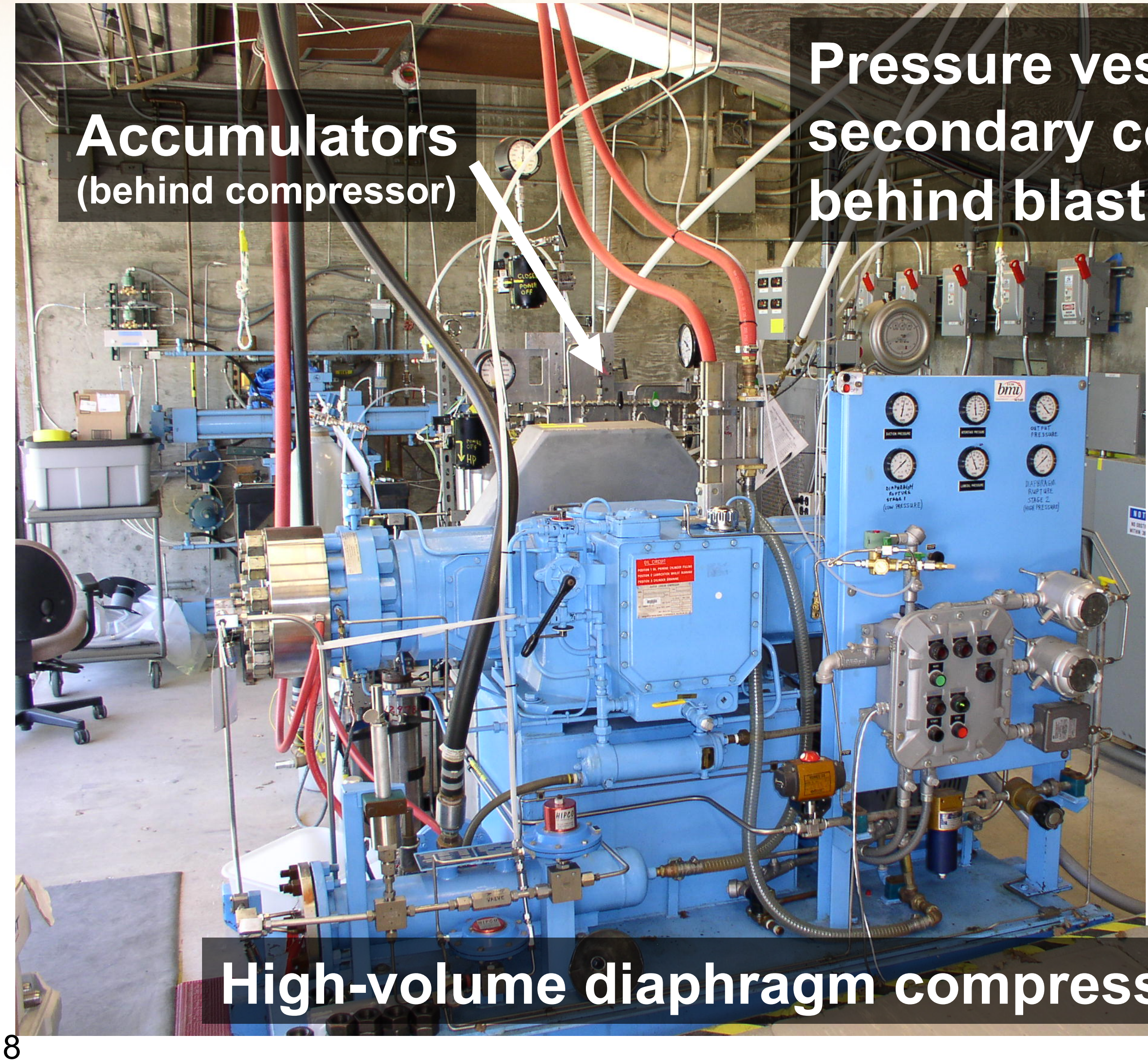
Consider 35 MPa gaseous hydrogen fuel system
- Nominal pressure of 35 MPa
- Allow 25% over-pressure during rapid filling
- Minimum system pressure of ~3 MPa



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)

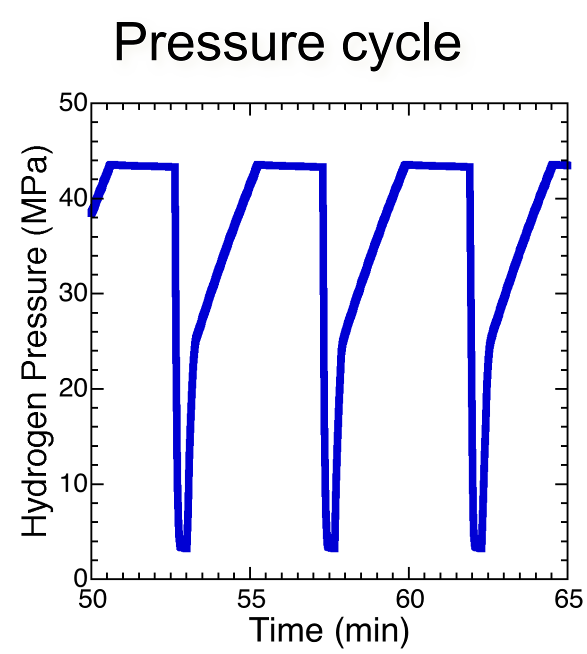
Closed-loop gas-handling system capable of simultaneously pressurizing 10 pressure vessels



Accumulators
(behind compressor)

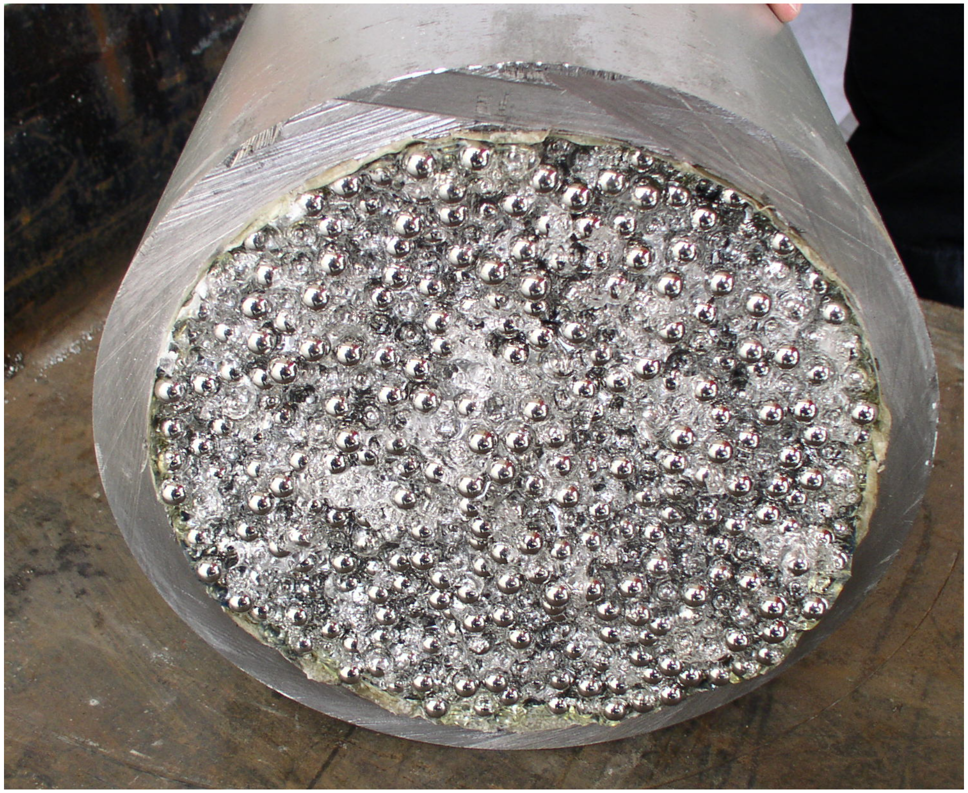
Pressure vessels in secondary containment behind blast door →

High-volume diaphragm compressor



Pressure cycle

Free volume within vessels reduced to facilitate pressure cycling



- Bladder used to isolate PV surface from filler material
- Epoxy and steel used as filler
- Volume reduction 90-95%

- Gas quality inspected periodically

  typical analysis
  - oxygen <2 ppm
  - hydrocarbons <5 ppm
  - water <5 ppm

Sectioned pressure vessel showing vessel, bladder, steel ball bearings and epoxy

Pressure vessels consistent with design rules for transportable gas cylinders

- Two pressure vessel designs from different manufacturers
  - Nominal hoop stress at P = 43.5 MPa
    - T1 design: ~340 MPa
    - T2 design: ~305 MPa

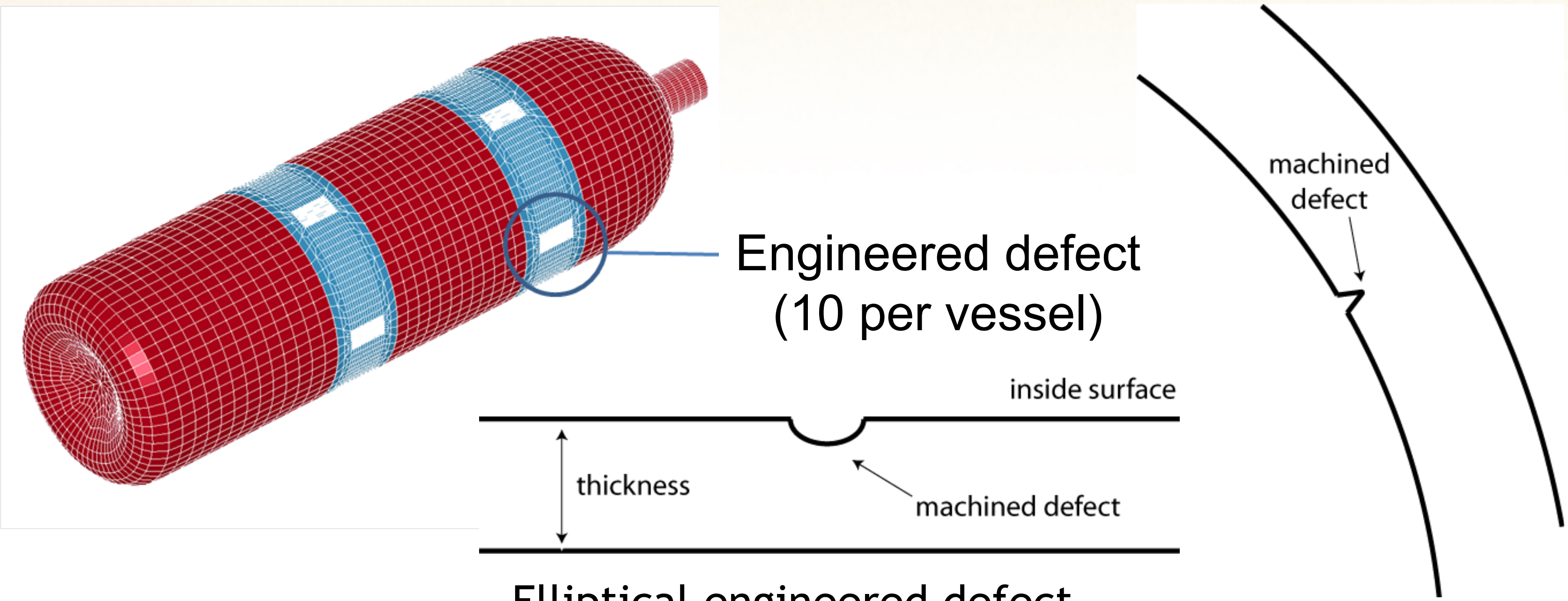
- Steel for both pressure vessels designs: 4130X
  - Quench and tempered, 1 wt% Cr - 0.25 wt% Mo
  - UTS for transport applications: 700 to 900 MPa
    - T1 design: ~750 MPa
    - T2 design: ~850 MPa

Typical design rule: maximum wall stress <40% of UTS

T1 design: 300 MPa

T2 design: 340 MPa

Engineered defects used to initiate failures



Elliptical engineered defect
Aspect ratio = 1/3 (depth/length)

V-notch in profile
Nominal root radius 0.05mm
(actual ~0.12mm)

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

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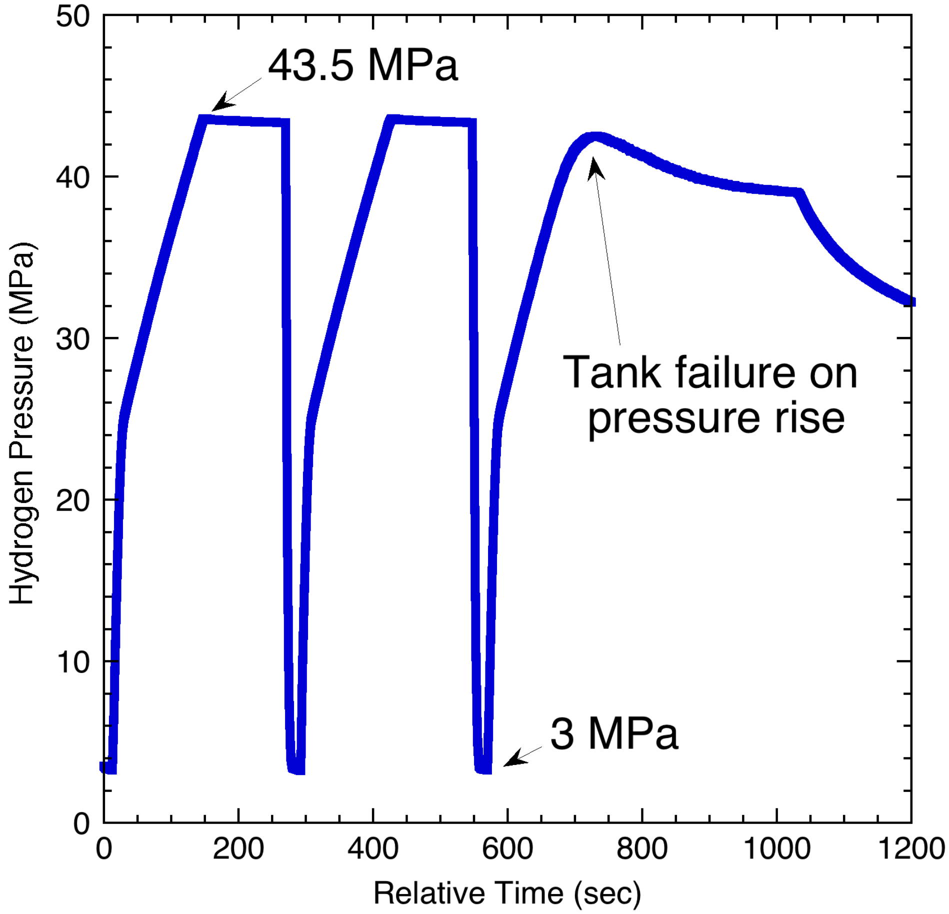
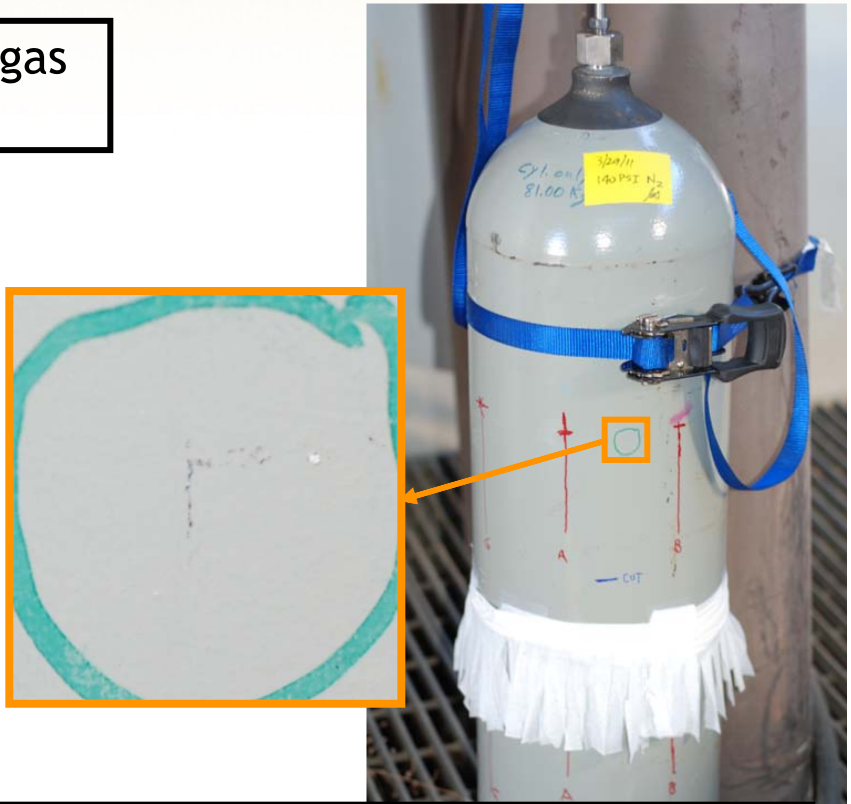
All observed failures are *leak-before-burst*

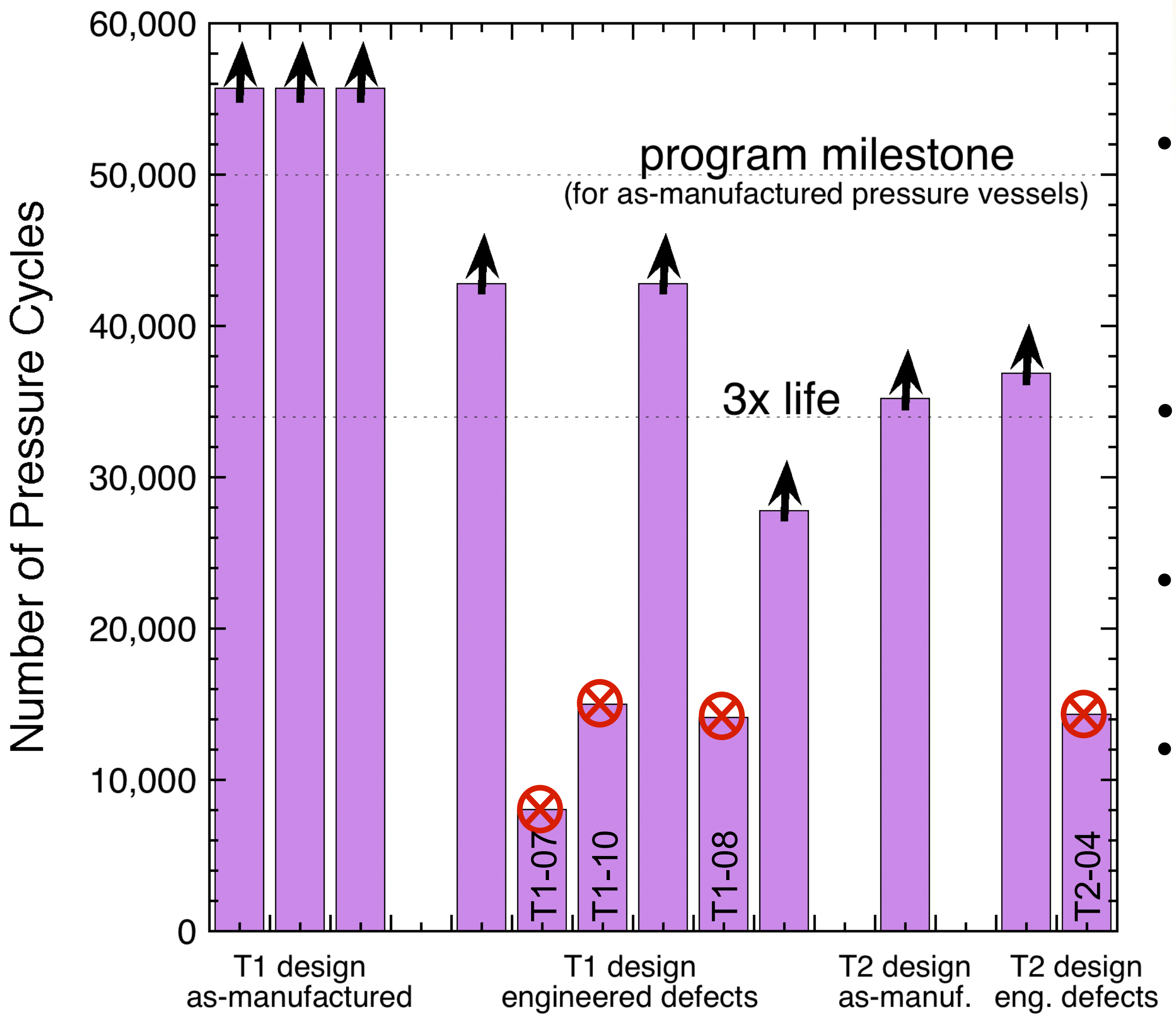
- At failure, pressure vessel “slowly” leaks gas into secondary containment





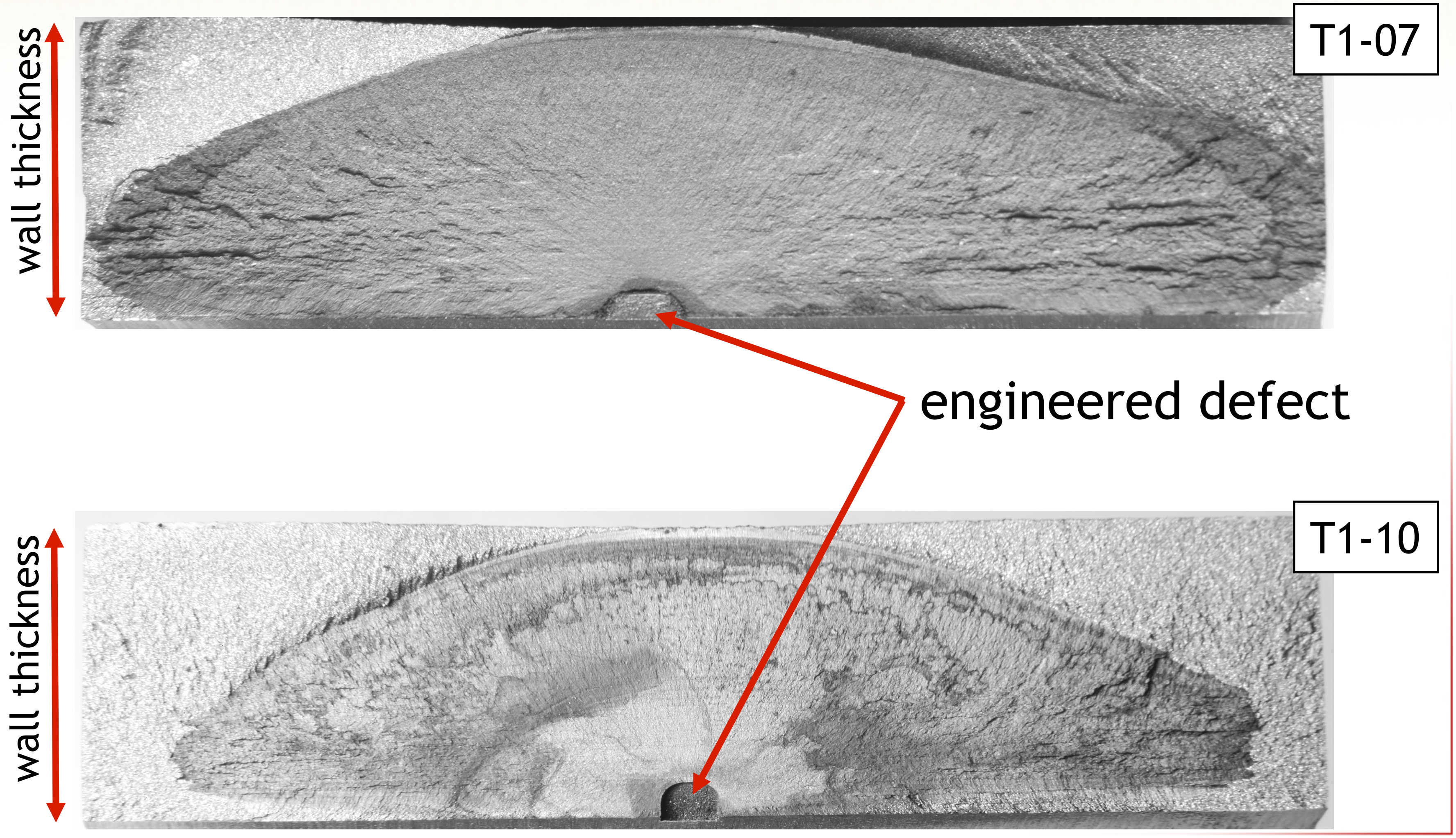
- Through-wall crack cannot be detected visually

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

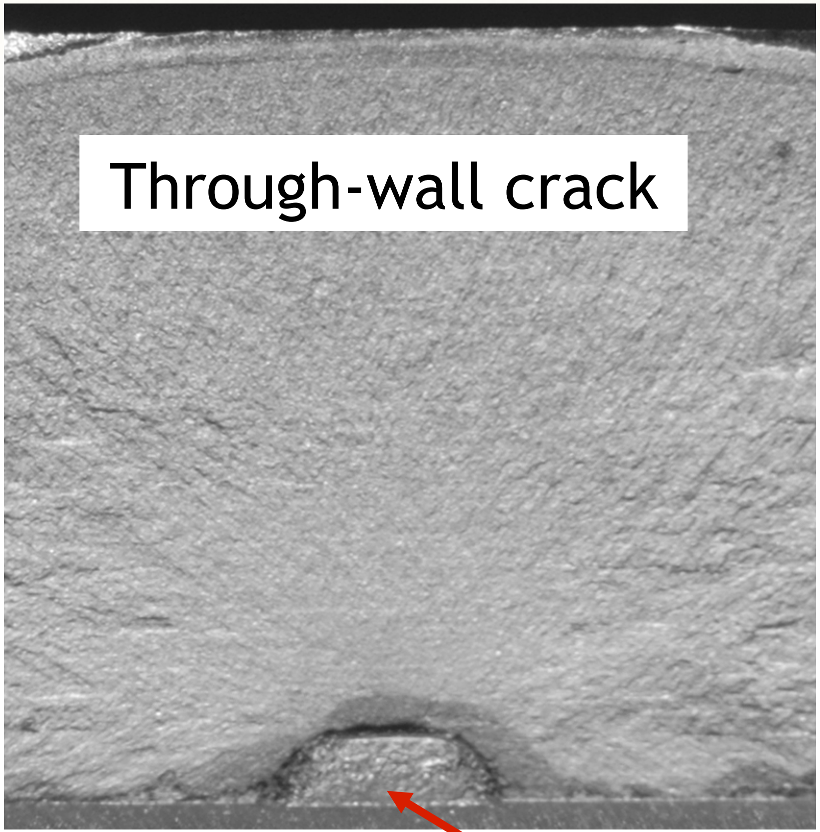


- Each pressure vessel with engineered defects contains 10 nominally equivalent defects
- Arrows indicate pressure vessels that did not fail
- In failed vessels, all defects initiate a crack
- All four failures were leak before burst

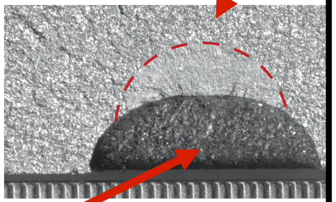
Through-wall cracks extend from "critical" engineered defect



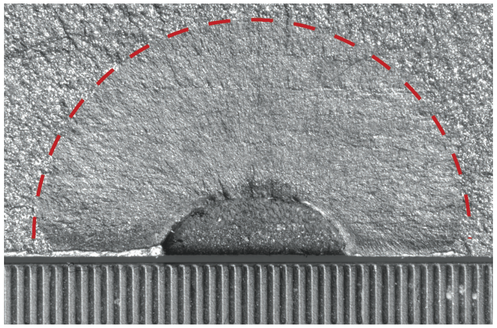
Cracks extend from all engineered defects



Non-through-wall (growing) cracks have semicircular profile



- Smaller engineered defect
- Greater number of cycles
  = more crack extension



Same size engineered defect
(same vessel)

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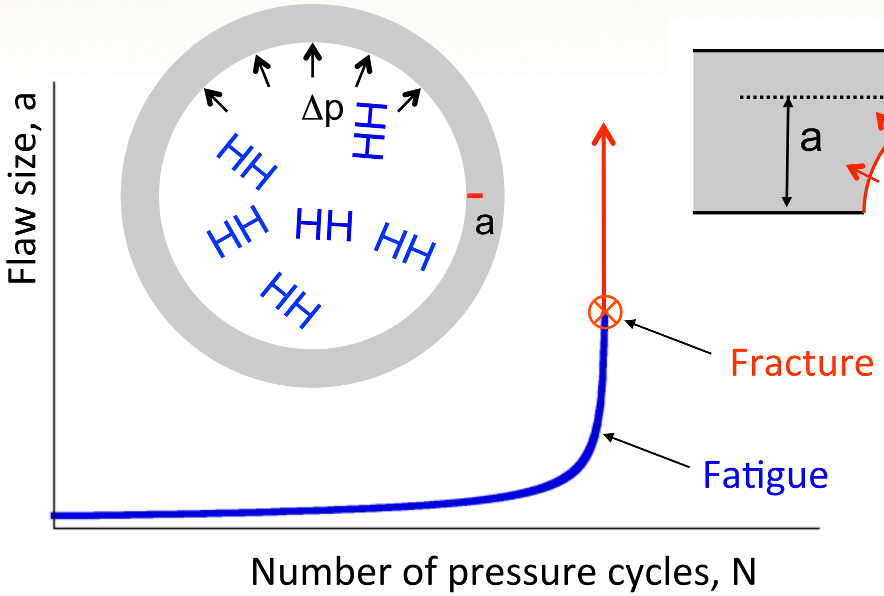
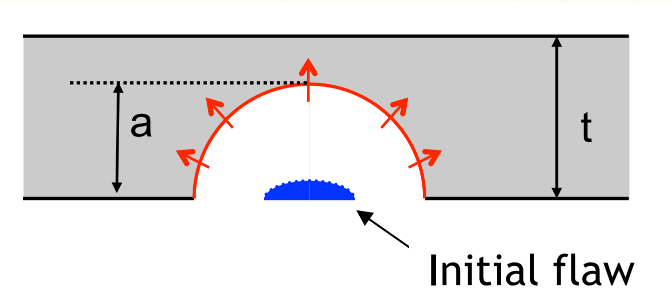
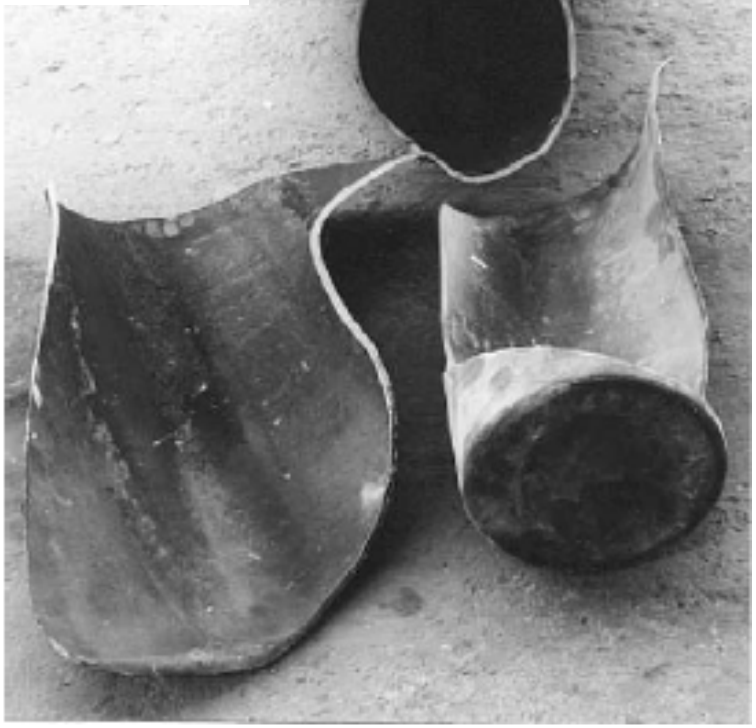
Fracture process consists of two components: fatigue and fracture







Fracture process can be modeled with materials properties measured in gaseous hydrogen:

- Fatigue crack growth under cyclic stress
- Fracture resistance

Image ref.: *Barthélémy, 1st ESSHS, 2006*

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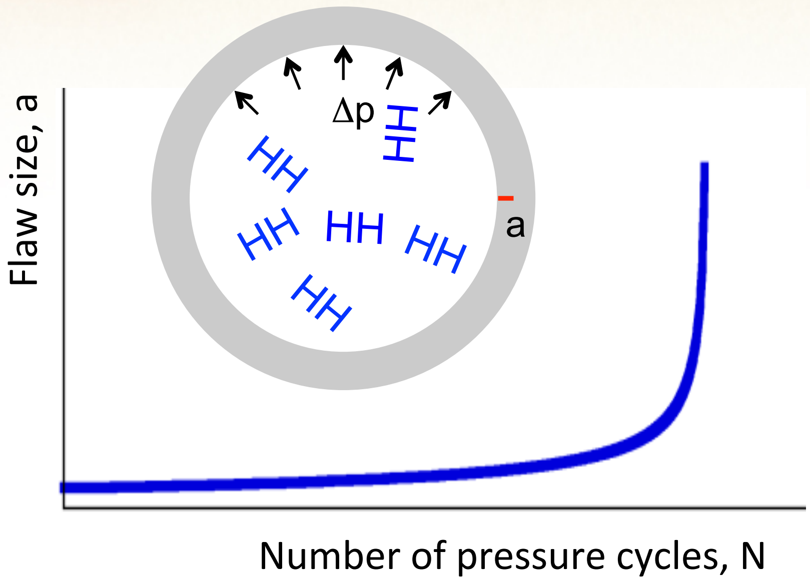
Fracture mechanics provides a methodology for quantifying crack extension



Fracture mechanics implies that single parameter (K) uniquely characterizes the cracking response

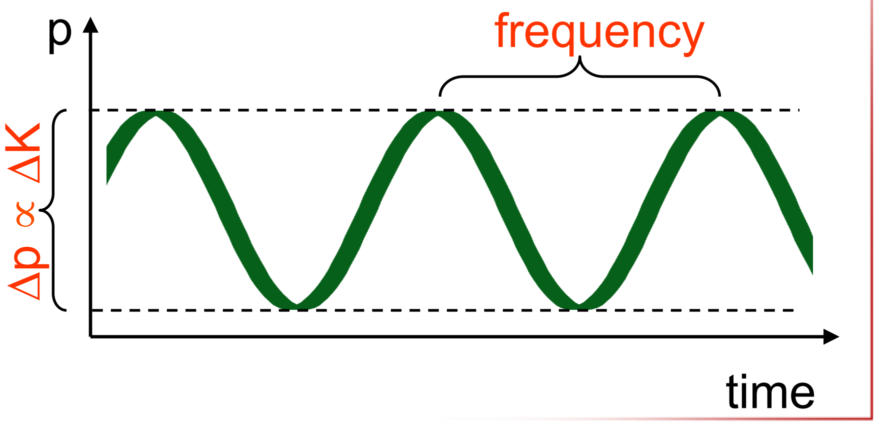
- Stress intensity factor (K) depends on pressure/load (p), size of the crack (a) and geometry
- Fatigue crack growth (da/dN) depends on ΔK

In the laboratory, one can measure the material's response to fatigue

$$da/dN = f\,(\Delta K)$$

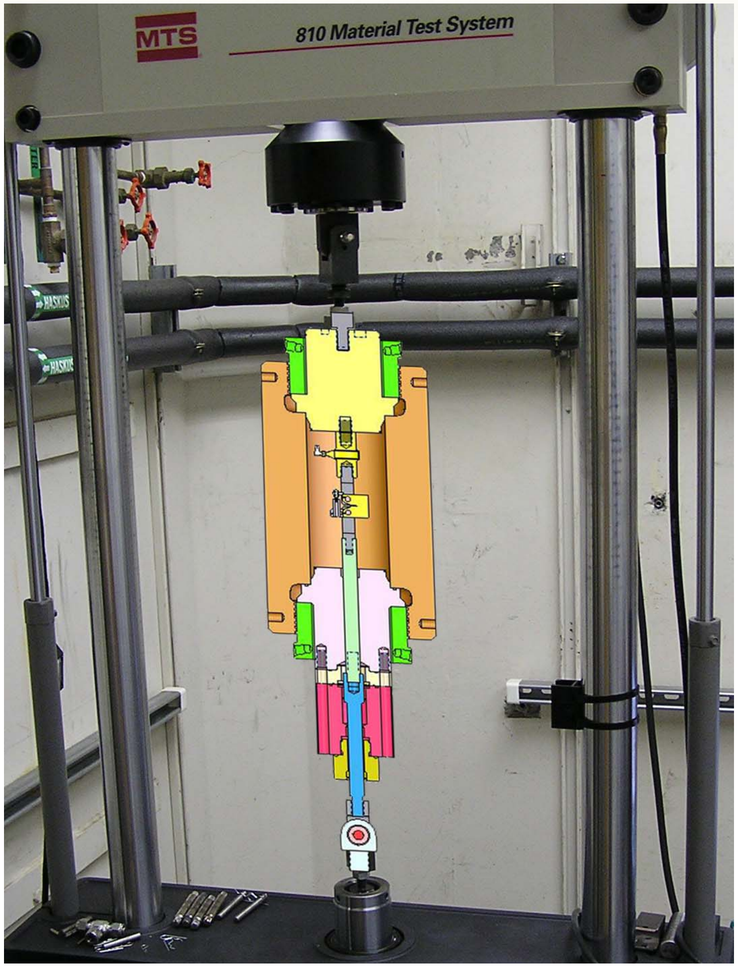
And integrate for a known geometry

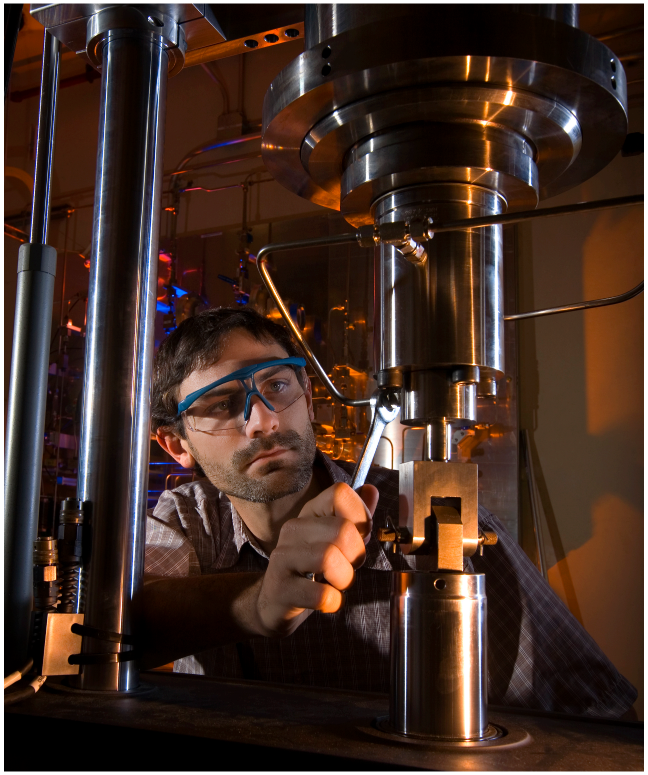
$$a_{i+1} = a_i + (da/dN)_i\,\Delta N$$

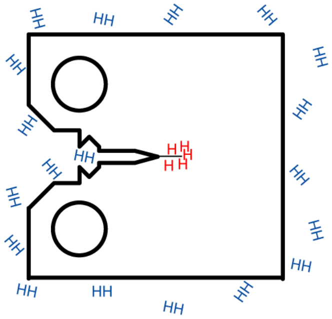


Fracture mechanics tests can be conducted in gaseous hydrogen at high pressure

- Fatigue crack growth: da/dN
  - ASTM E647, constant load amplitude
- Fracture resistance: K_{IH}
  - ASTM E1820, elastic-plastic analysis using J-R curve determination



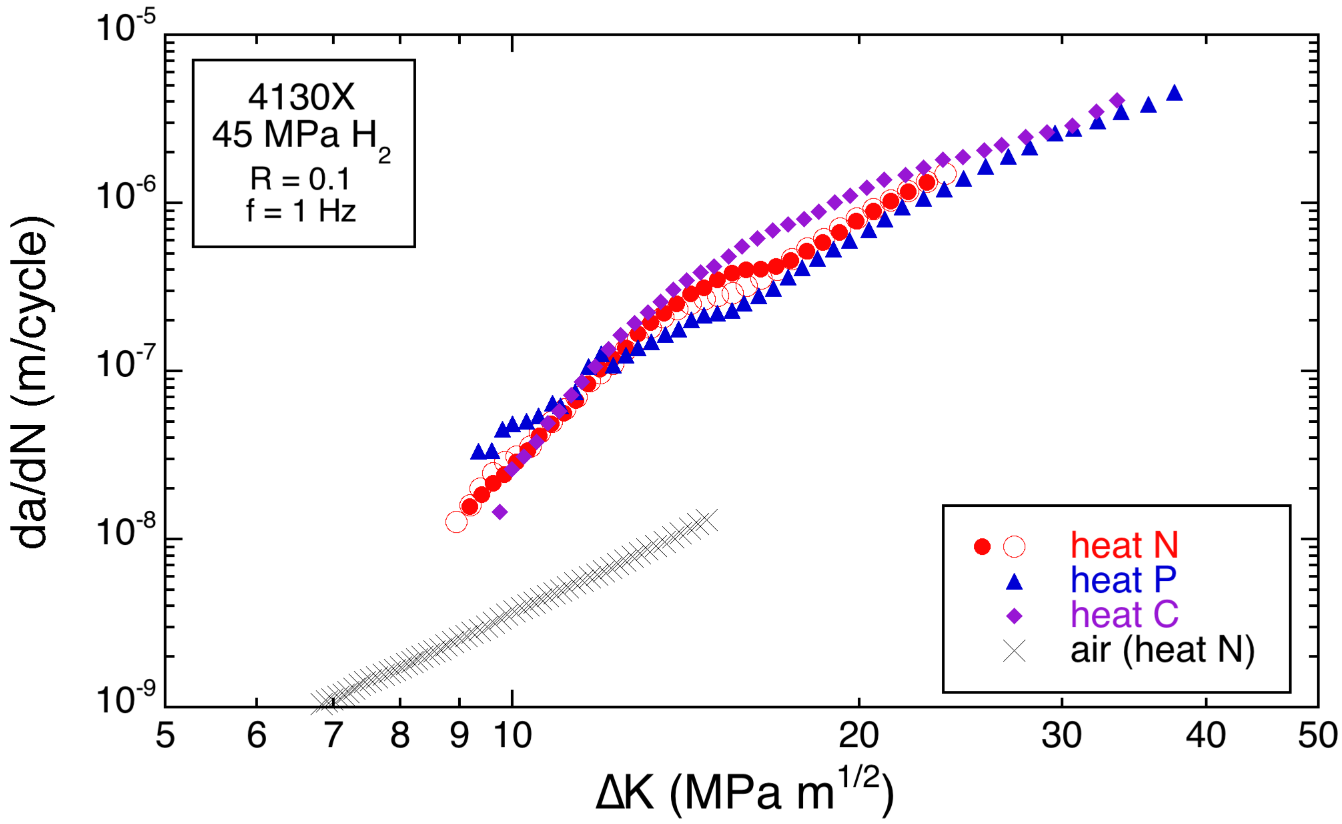


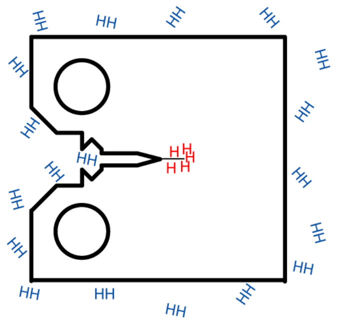


Fatigue crack in gaseous hydrogen is an order of magnitude greater than in air

Fatigue crack growth rates measured in gaseous hydrogen at pressure of 45 MPa

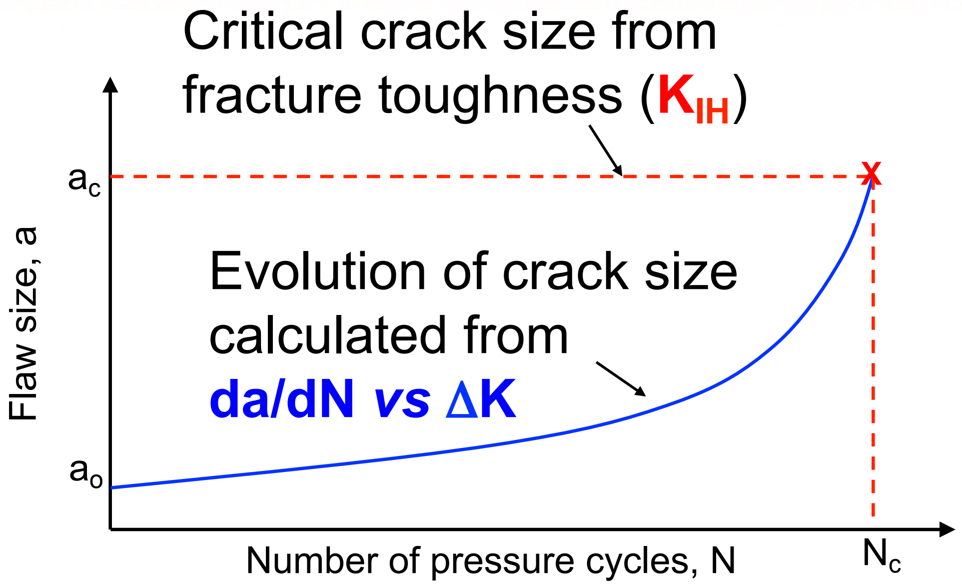
- 3 heats of 4130X steel from pressure vessels
- (unlike fracture resistance, fatigue crack growth in ferritic steels appears to be relatively insensitive to hydrogen pressure)





Fatigue life qualification by fracture mechanics (crack growth methodology)

ASME BPVC VIII.3 KD-10 (KD-4)



Critical crack size from fracture toughness (**K_{IH}**)

Evolution of crack size calculated from **da/dN *vs* ΔK**

Stress intensity at a/t = 0.8

T1: 55 MPa m$^{1/2}$
T2: 64 MPa m$^{1/2}$

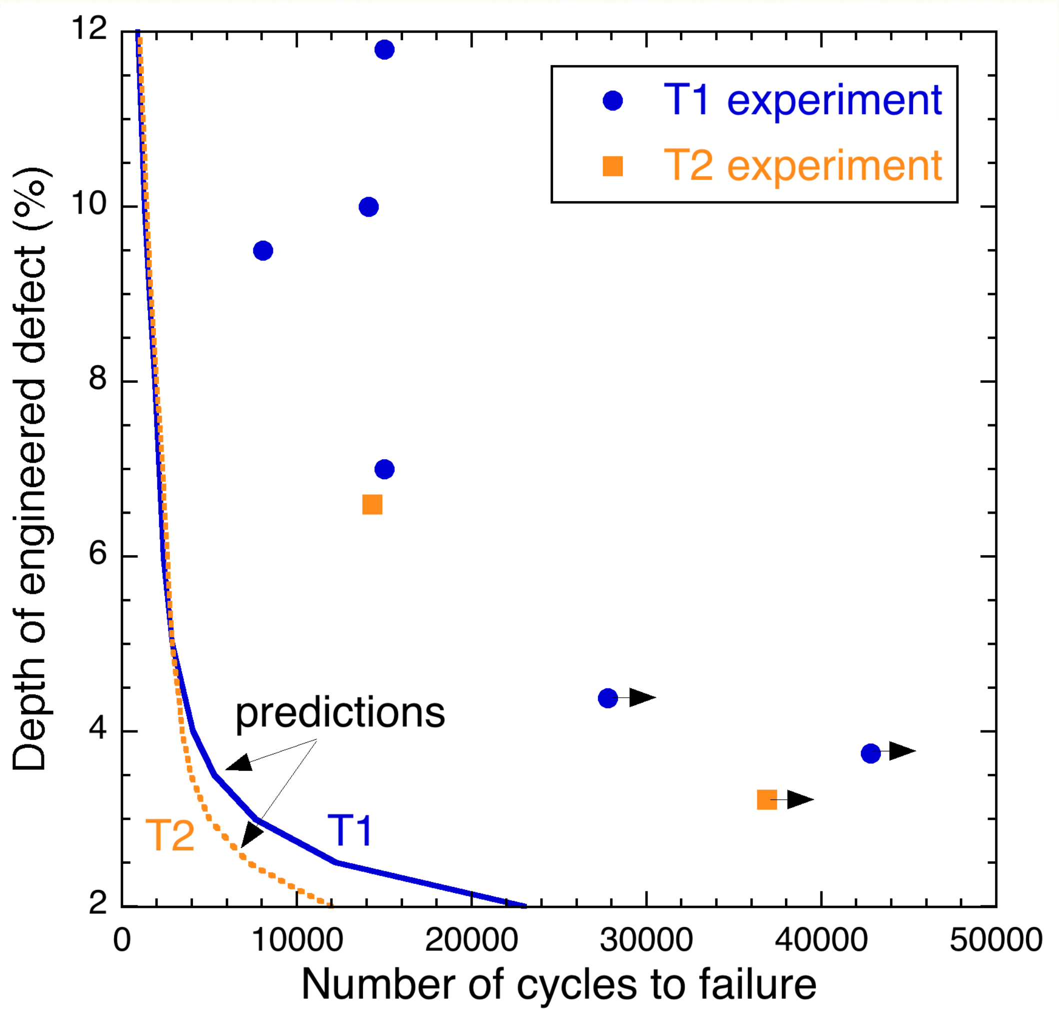
[†]K_{JIH} = 59 MPa m$^{1/2}$

Assumptions:

- a_c = thickness
- semicircular propagating cracks
- use data[†] for R = 0.1 and f = 0.1 Hz

[†] 4130X steel measured in gaseous H_2 at pressure of 45 MPa
Nibur et al. (PVP2010-25827)

Fracture mechanics is overly conservative when defects are not initially growing



- Curves are predictions based on *crack growth* only (of semicircular flaw)
- Arrows indicate vessels that did not fail
- Failures use measured dimensions (others assume nominal dimensions)

- Fatigue life calculation is conservative by factor of 4 or more
- For small initial defects, effective safety factor approaches 10

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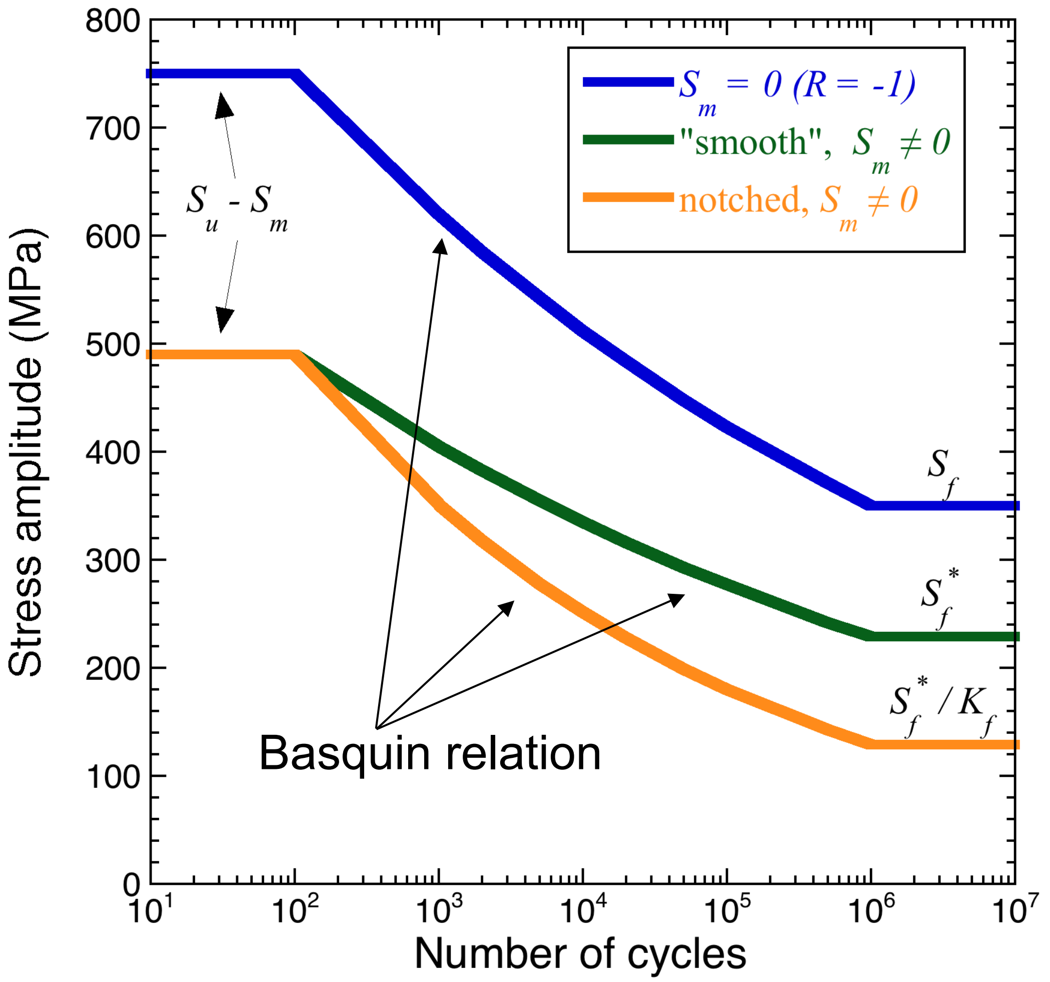
Fatigue life methods offer framework for incorporating crack initiation



- Idealized S-N curves based on
  - Materials properties: S_u (UTS) and S_f
  - Geometry and loading: K_f and S_m

Effect of mean stress:

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

Effect of notch:

$$S_f^N = {S_f}/{K_f}$$

Effect of hydrogen on S-N curve and fatigue limit is unknown

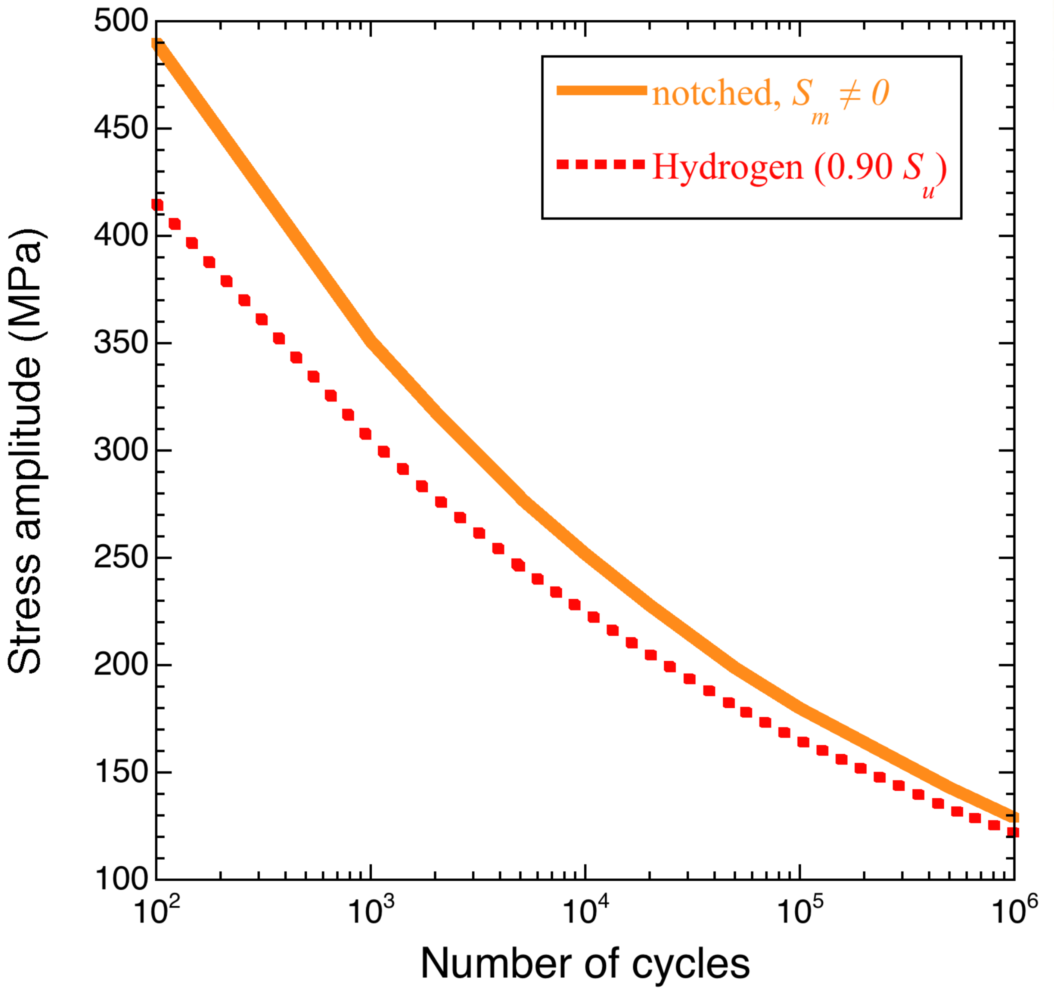
Data for Cr-Mo steels in tension-compression fatigue *suggests*

$S_f(H_2) \approx S_f(\text{air})$†

Implication: at low stress hydrogen does not affect fatigue crack initiation

Conservative assumption based on notched tension‡ in gaseous hydrogen:

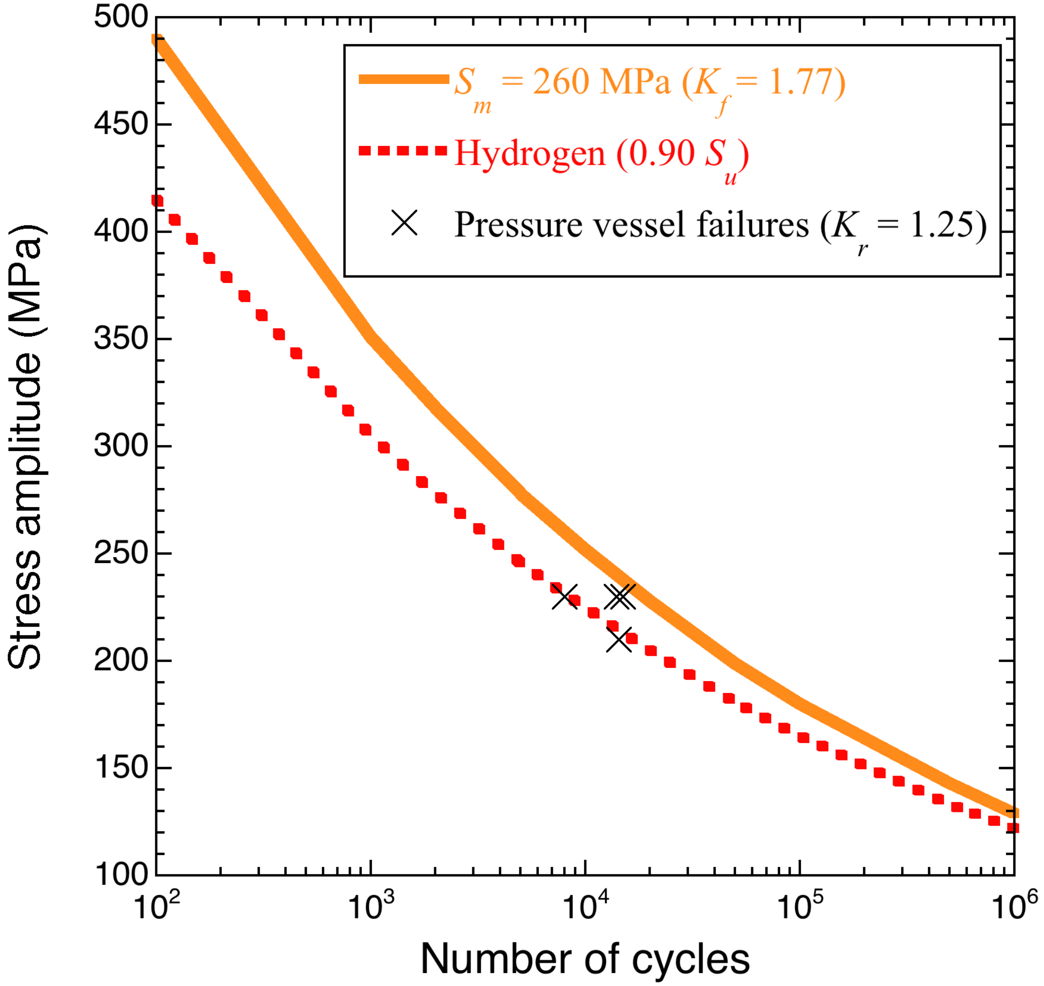
$S_u(H_2) \sim 0.9\ S_u$



† Ref. Wada et al. ICHS 2005

‡ Ref. Steinman et al. Welding J Res Supp 44 (1965)

Fatigue of pressure vessels with engineered defects compare favorably with predictions



Materials properties:

S_u = 750 MPa
S_f = 350 MPa (est.)

Geometry and loading:

K_f = 1.77 (Neuber est.)
S_m = 260 MPa (K_r = 1.25)

Fatigue notch sensitivity (K_f)

$K_f = f(K_t, \rho, S_u)$
ρ = notch root radius
K_t estimated from FEA

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Draft CSA Standard for Compressed Hydrogen Powered Industrial Truck On-Board Fuel Storage and Handling Components (HPIT1)

Performance requirements

- Leak-before-break requirements
  - type 1, 2 and 3: ASME VIII.3 KD-141 using K_{IC}
  - type 4: ISO 15869 Annex B.8

- Two performance options:
  - Fatigue life verification by ***testing***

  OR

  - Fatigue life qualification by ***analysis***

Draft CSA Standard for Compressed Hydrogen Powered Industrial Truck On-Board Fuel Storage and Handling Components (HPIT1)

- Fatigue life verification by ***testing***

  <u>Requirement</u>: 3X maximum fill cycles specified by manufacturer
  - Pressure cycling with gaseous hydrogen
  - Artificial defect: depth ≥ NDE; aspect ratio >3:1 (length:depth)
  - 10 to 125% service pressure

- Fatigue life qualification by ***analysis***

  <u>Requirement</u>: maximum fill cycles determined from ASME VIII.3 KD-3
  - Design pressure = 125% service pressure (25 or 35 MPa service)
  - DOT 3AA 4130X or ASME SA-372 (Cr-Mo) steels
  - S_u < 890 MPa
  - Wall stress (hoop stress) < 0.4 S_u
  - Surface roughness: R_a < 6.4 µm and R_{max} < 20 µm

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Fatigue life qualification by analysis

Proposed requirements for type 1 steel pressure vessels in gaseous hydrogen service

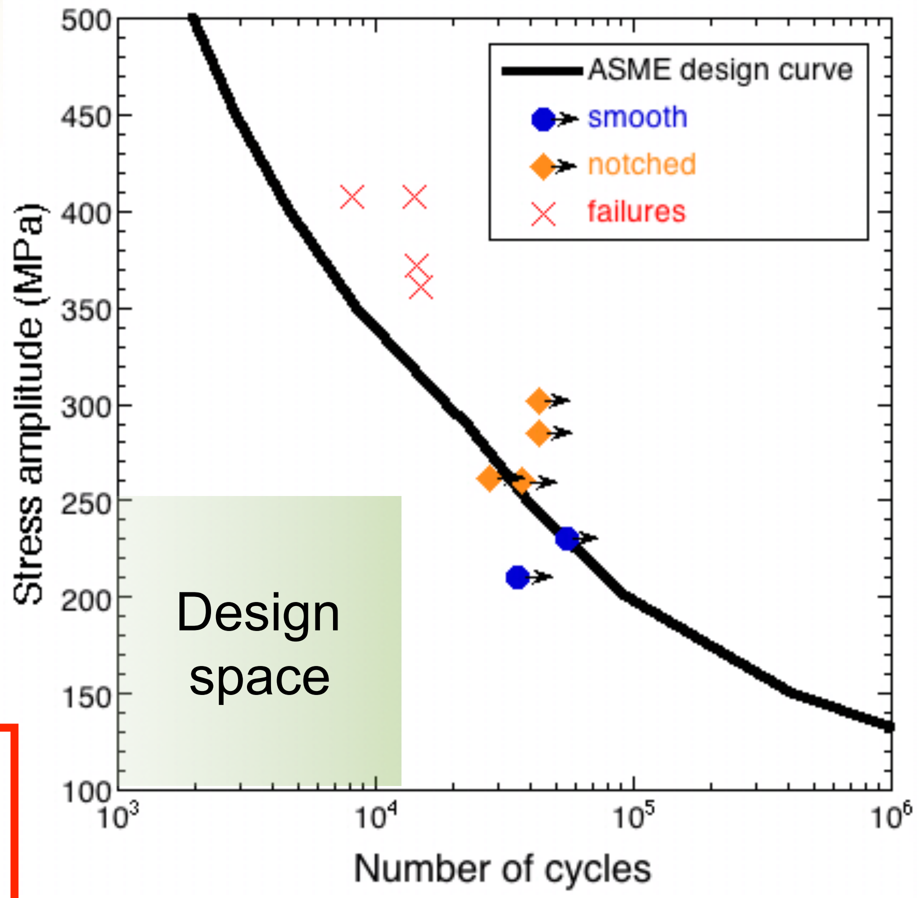
- $S_u < 890$ MPa
- hoop stress $\leq 0.4\ S_u = 356$ MPa

From ASME VIII.3 KD-3

- assume: $K_r = 1.25$
- T1 design
- $S_m \approx 260$ MPa & $S_a \approx 230$ MPa

<u>Engineering Significance</u> of these requirements

- Stress intensity < ~400 MPa
- Stress amplitude < ~250 MPa
- Design life > 40,000 cycles



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

Summary

- Vessels being used for hydrogen storage were subjected to more than 55,000 pressure cycles with gaseous hydrogen at a peak pressure of 43.5 MPa
- Engineered defects with depth >6% of the wall thickness failed between 8,000 and 15,000 cycles
- Leak-before-burst was observed for all failures
- Fatigue crack growth assessment is very conservative for idealized defects
  - Cycles to failure due to engineered defects is >4 times design calculation using ASME VIII.3
  - Crack initiation dominates the cycle life even with internal defects
- Fatigue life curves based on testing in air are being considered for design of hydrogen pressure vessels (CSA HPIT1)