SAND2011-6556C

Pressure Cycling of Type 1 Pressure Vessels with Gaseous Hydrogen

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September 14, 2011

Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000

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Outline and Objectives

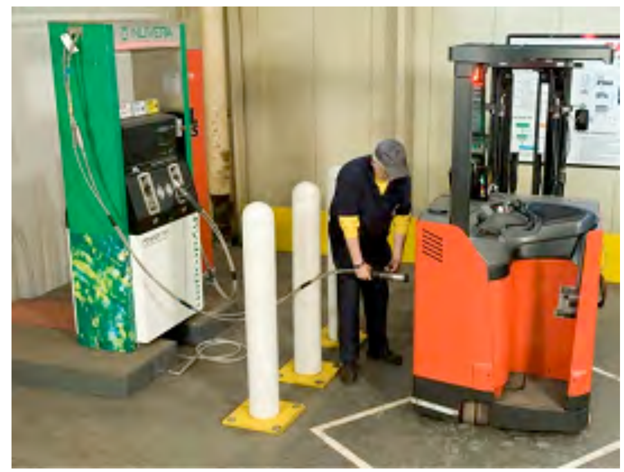
- Demonstrate performance test method for evaluating compatibility of pressure vessel with gaseous hydrogen
- Determine failure characteristics of pressure vessels
  - Do the pressure vessels leak-before-burst when cycled with gaseous hydrogen?
- Compare full-scale testing for steel (type 1) pressure vessels for gaseous hydrogen with engineering design methods
  - Fracture mechanics-based design
  - Stress-life design

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

Hydrogen-induced failure of transport cylinder

Ref.: *Barthélémy, 1st ESSHS, 2006*

<u>Motivation</u>:
innovative applications are expanding design space beyond engineering experience



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

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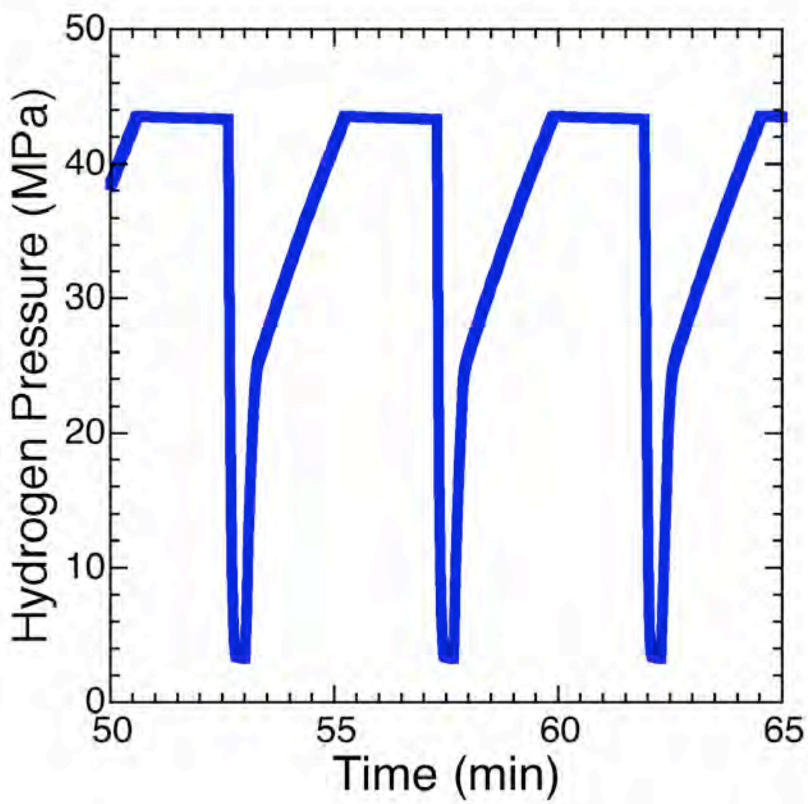
Pressure cycle designed for accelerated testing

Consider 350 bar gaseous hydrogen fuel system
- Nominal pressure of 35 MPa
- Allow 25% over-pressure during rapid filling
- Minimum system pressure of ~3.5 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)

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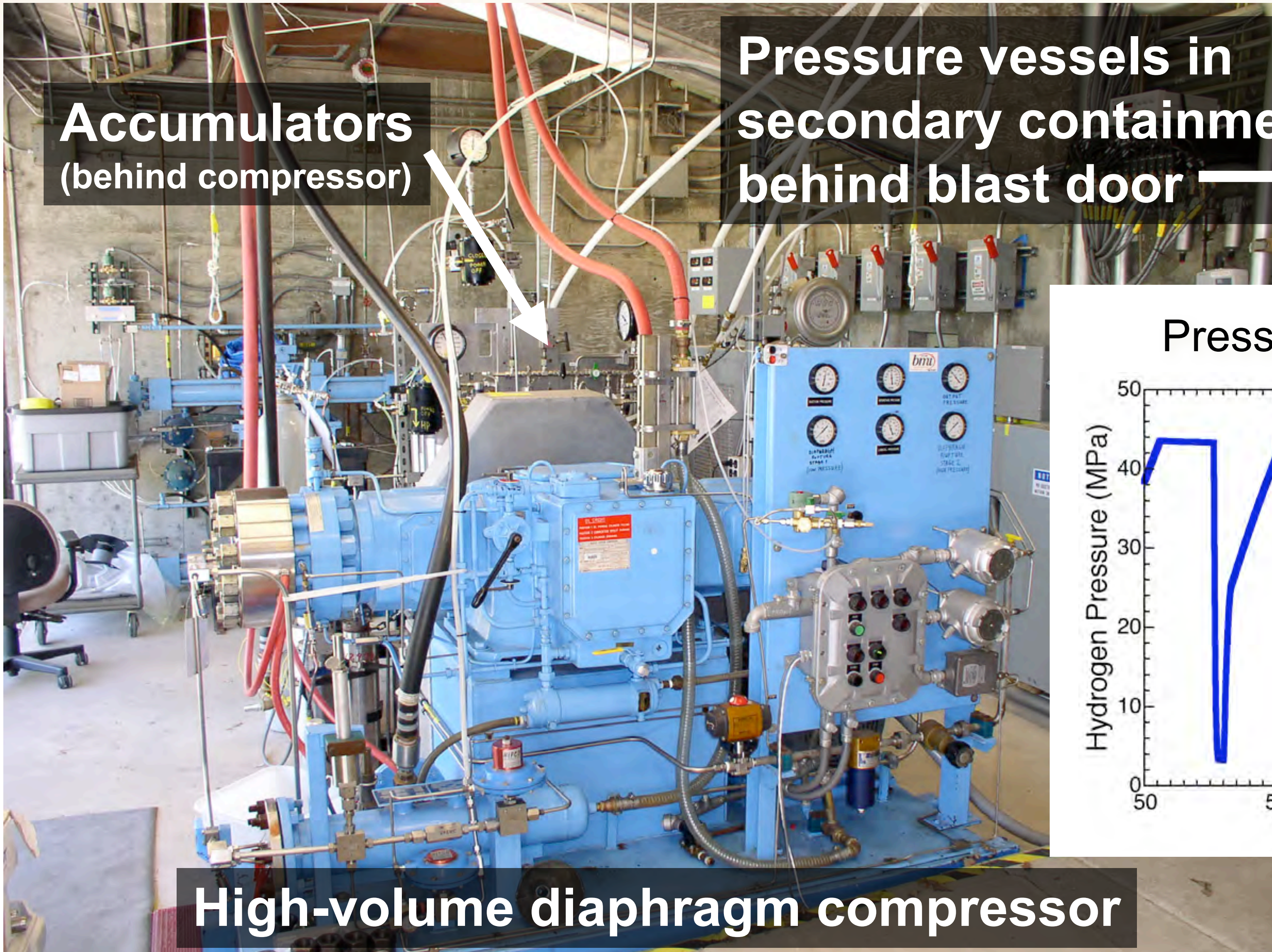
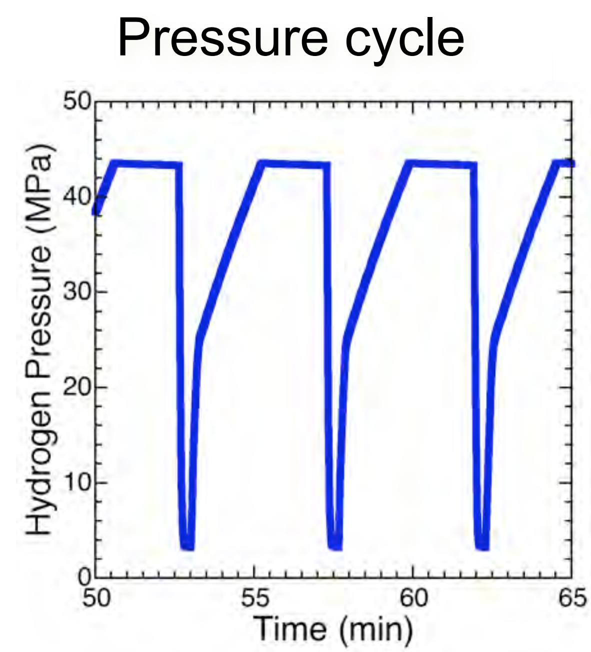
Closed-loop gas-handling system capable of simultaneously pressurizing 10 pressure vessels





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
  <u>typical analysis</u>
  - oxygen <2 ppm
  - hydrocarbons <5 ppm
  - water <5 ppm

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

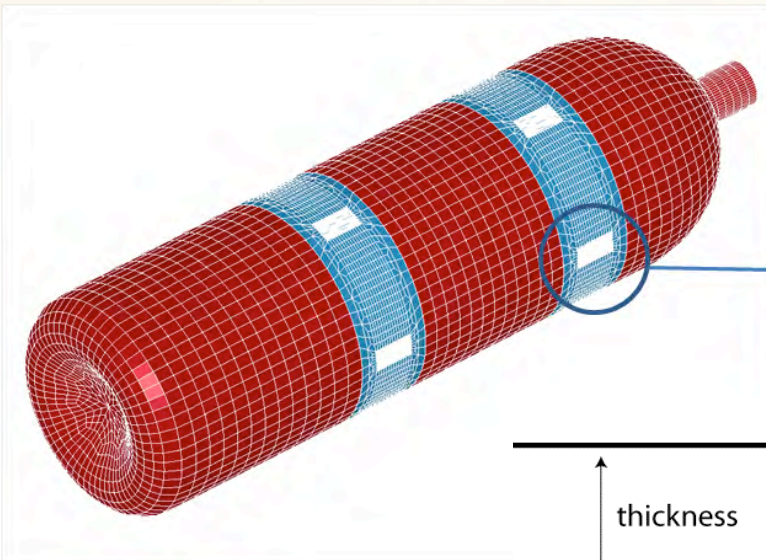
Pressure vessels consistent with design rules for transportable gas cylinders

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

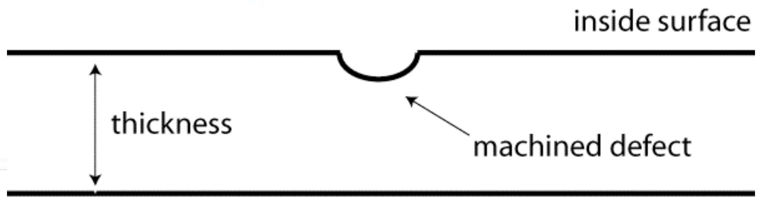
- Two pressure vessel designs from different manufacturers
  - Nominal hoop stress at P = 43.5 MPa
    - T1 design: ~340 MPa
    - T2 design: ~305 MPa

- 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

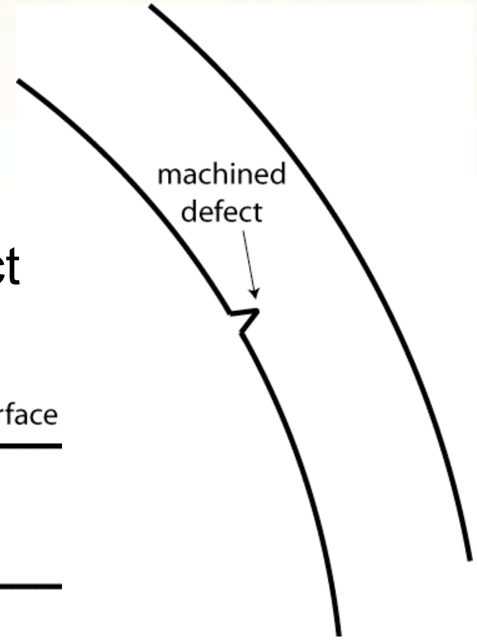
Engineered defects used to initiate failures



Engineered defect
(10 per vessel)



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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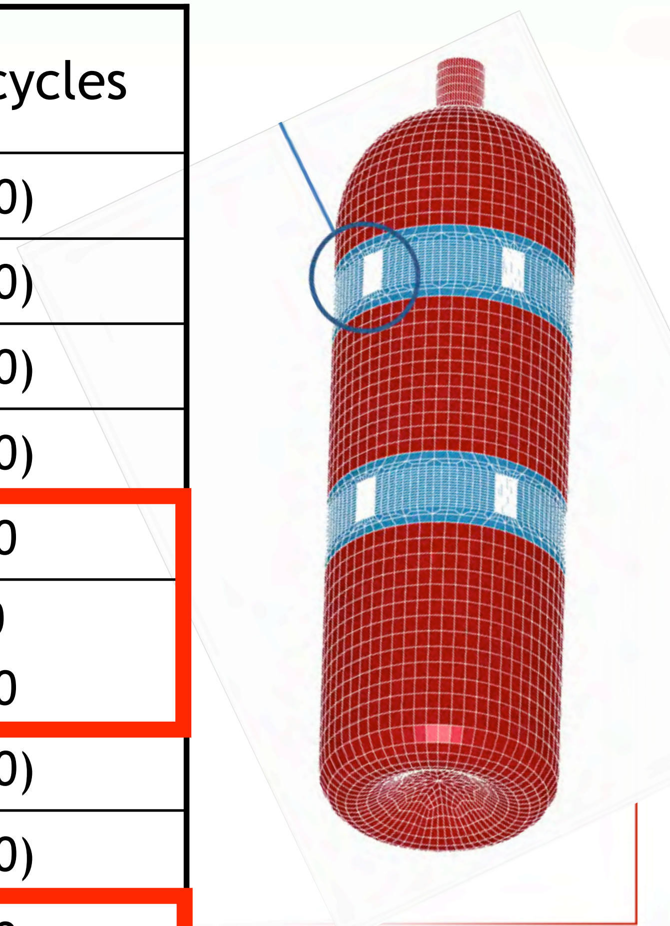
Large engineered defects initiated cracking and hydrogen-assisted failure

Summary of hydrogen pressure cycling and defect sizes

Pressure vessel	Nominal defect depth (%)	Pressure cycles
T1	0	(55,700)
	3 & 4	(27,800)
	4	(42,800)
	2 & 5	(42,800)
	7 & 8	15,000
	10	8,000 14,000
T2	0	(35,200)
	3	(36,900)
	8	14,300



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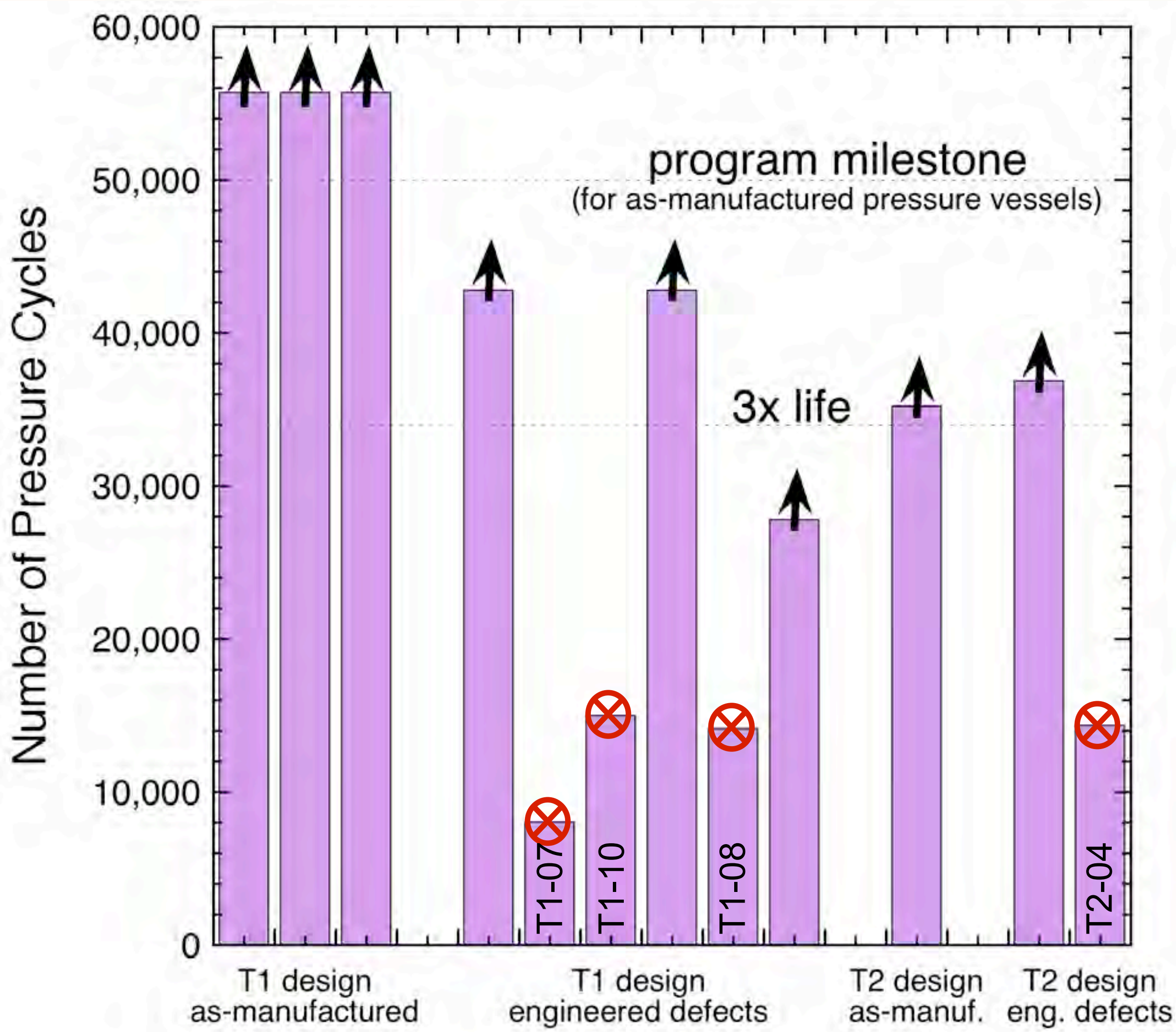
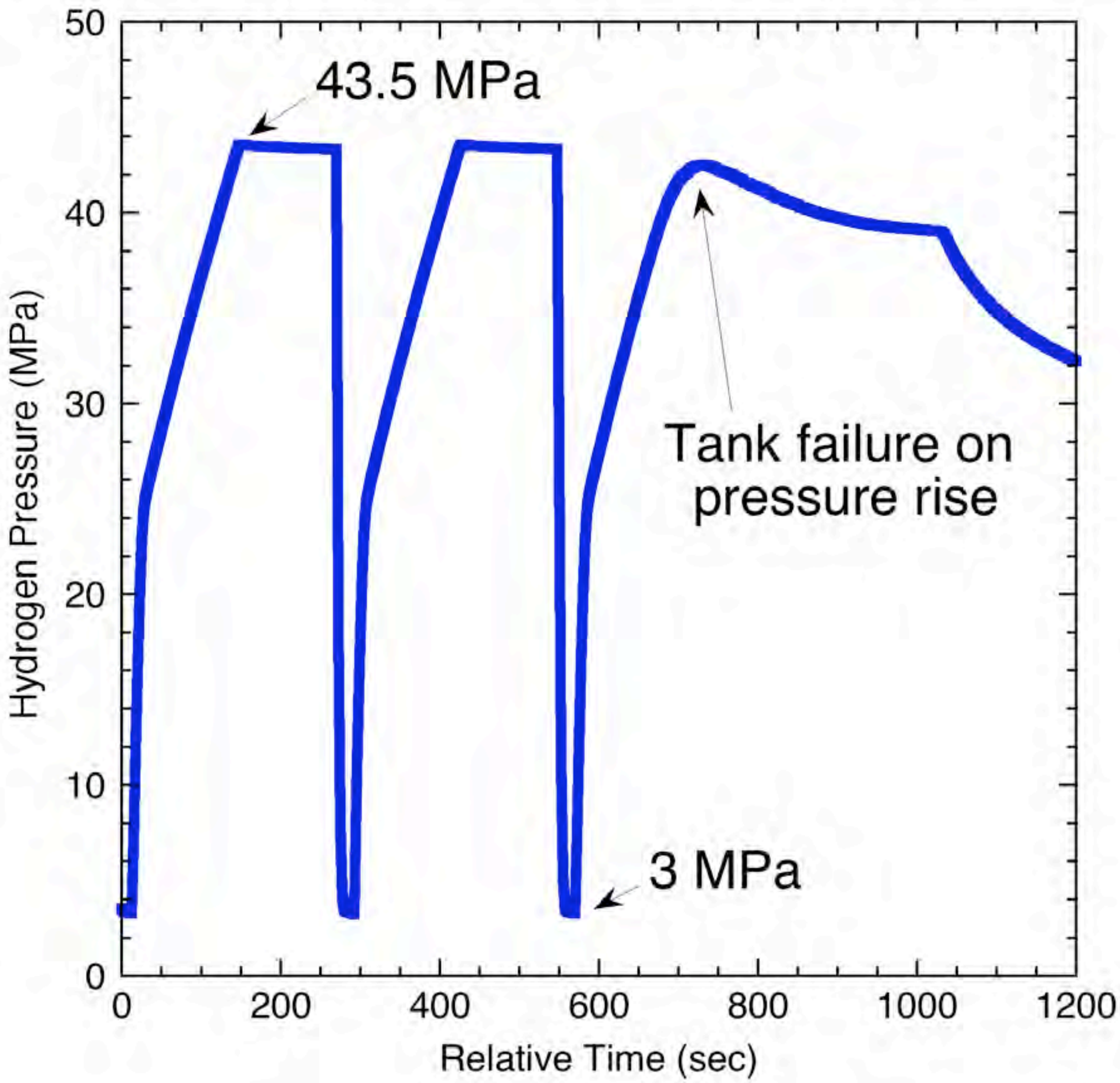
Commercial pressure vessels exceed lifetime target of 11,250 cycles by >3x



- 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 failures (4) are leak before burst

All observed failures are *leak-before-burst*



- All failures occur during pressure ramp
- At failure, pressure vessel “slowly” leaks gas into secondary containment
- After failure, vessels can be pressurized to ~10 MPa without leakage
- Through-wall crack cannot be detected visually

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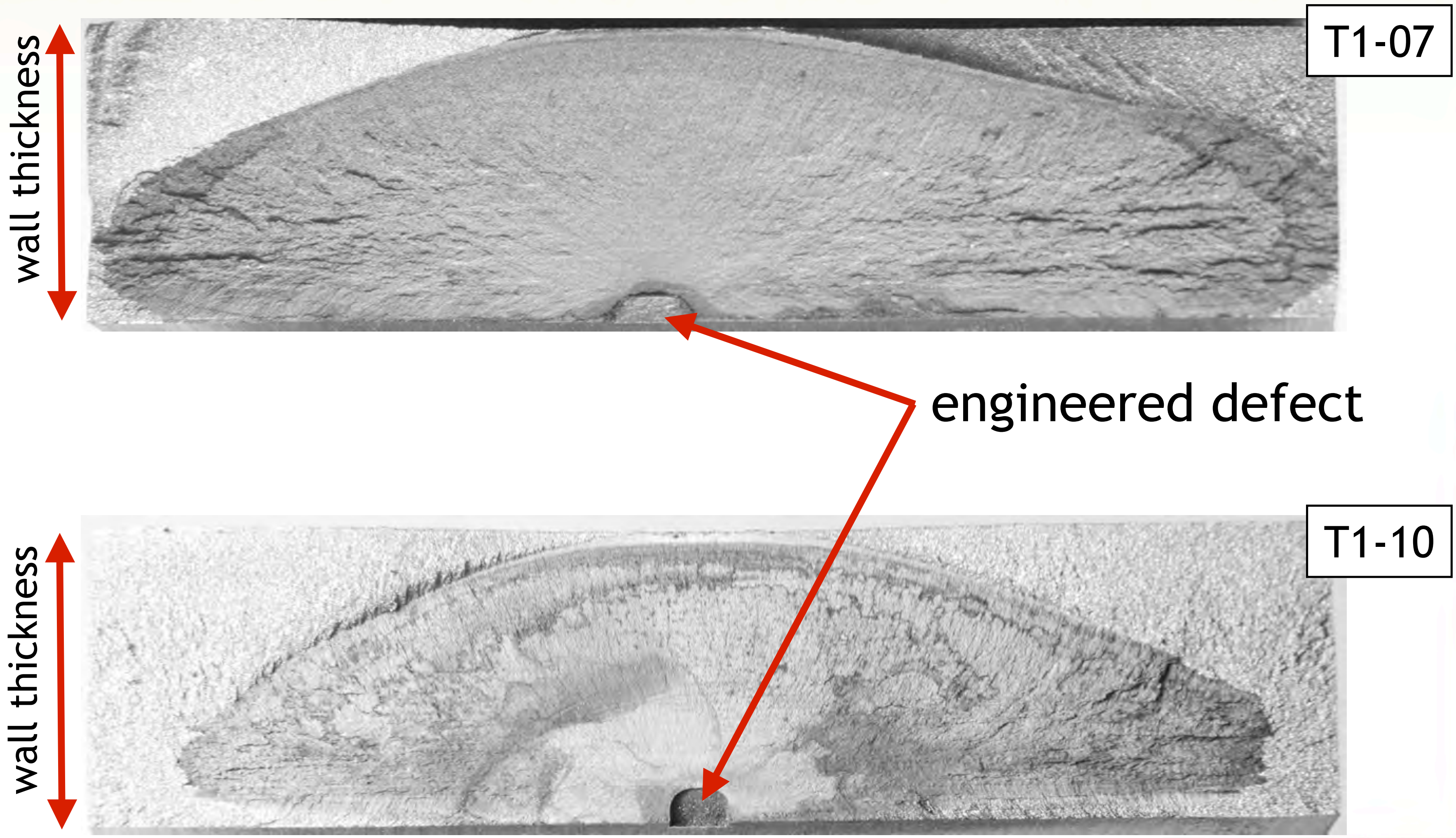
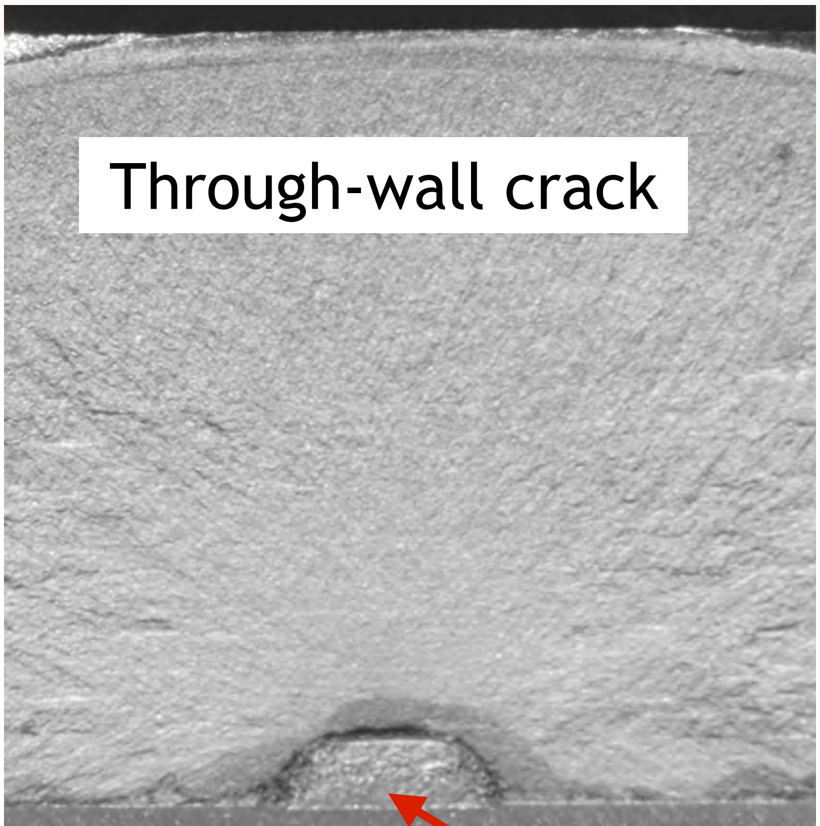
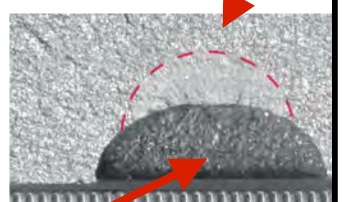
Through-wall cracks extend from "critical" engineered defect



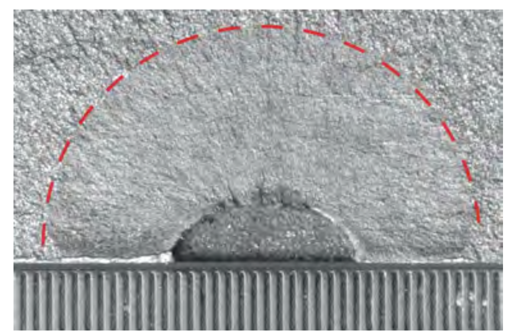
Cracks extend from all engineered defects



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

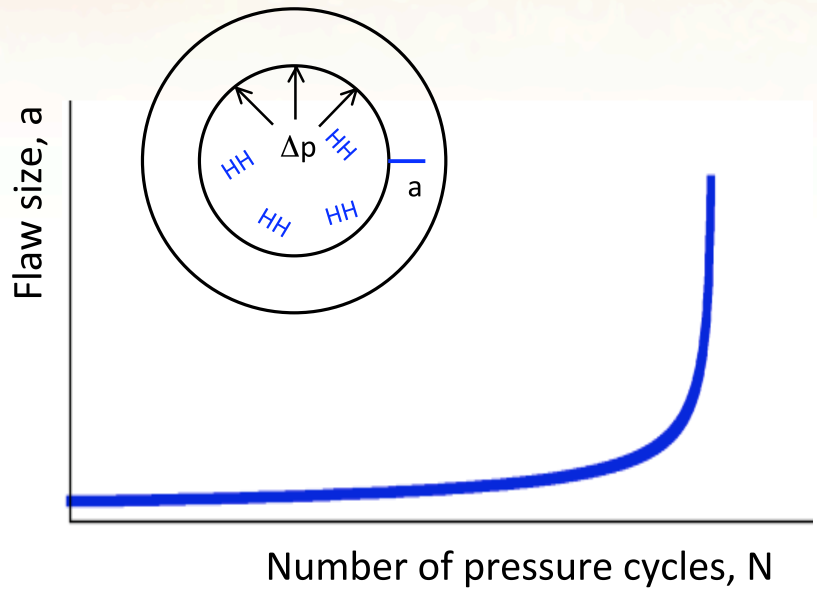


- Smaller engineered defect
- Greater number of cycles
  = more crack extension



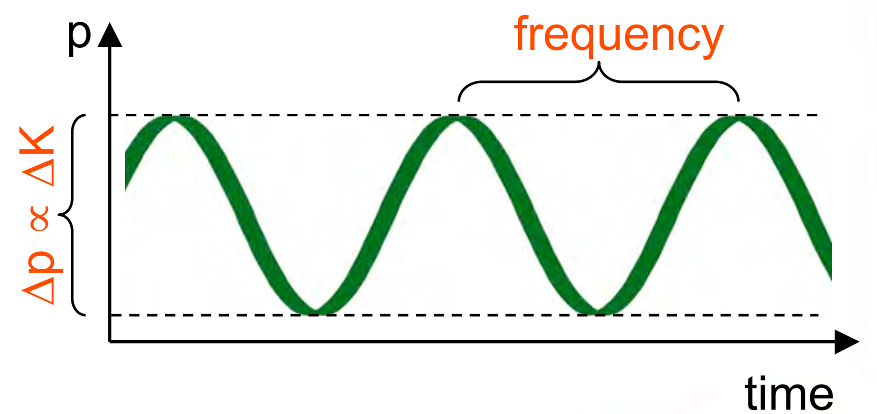
Same size engineered defect
(same vessel)

Fracture mechanics provides a methodology for predicting crack growth



Fracture mechanics implies that single parameter uniquely characterizes the cracking response

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



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

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

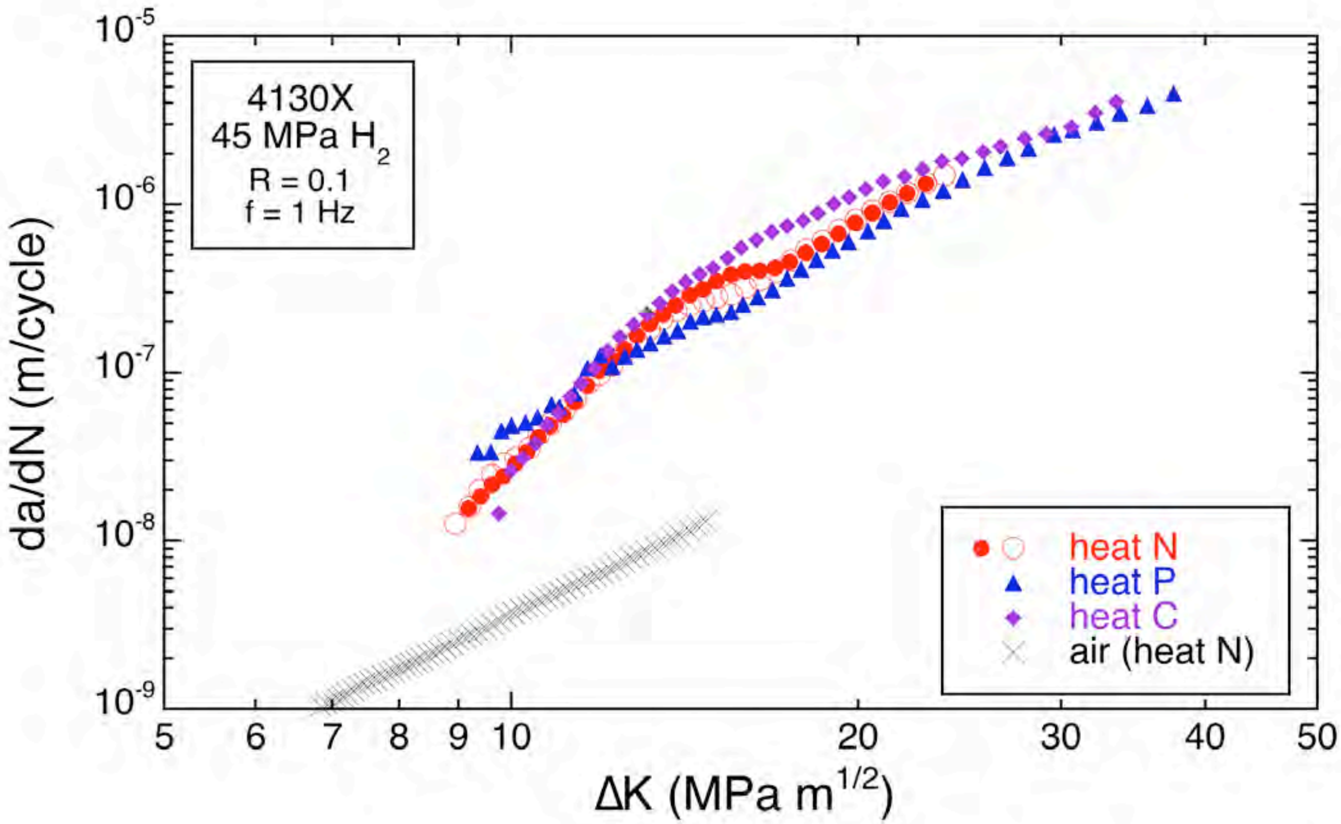
And integrate for a known geometry

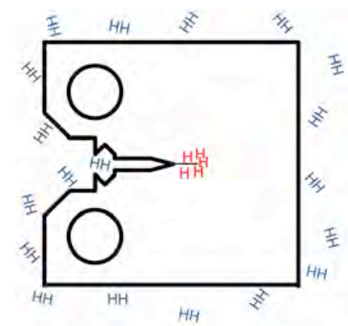
$$a_{i+1} = a_i + (da/dN)_i \, \Delta N$$

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

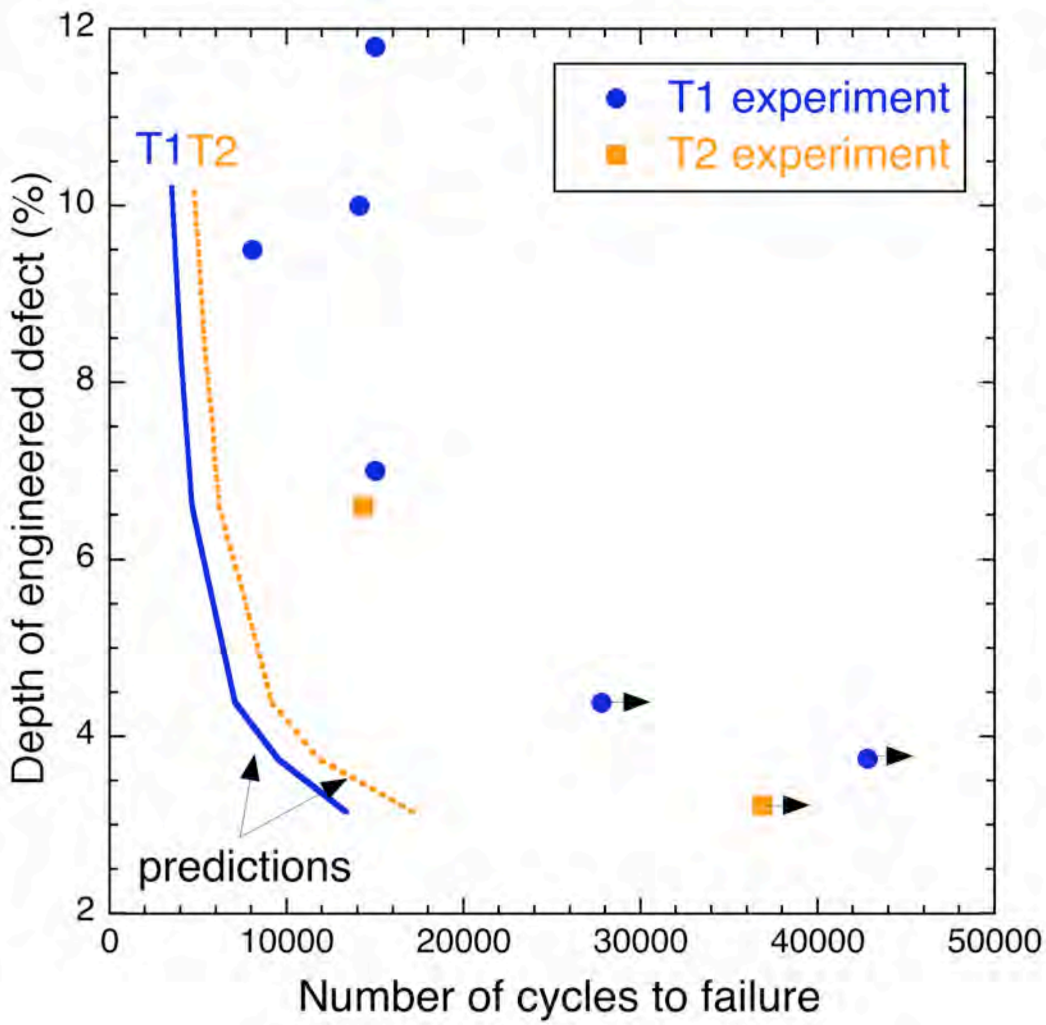
Fatigue crack growth rates measured in gaseous hydrogen at pressure of 45 MPa

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





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 (other assume nominal dimensions)

- Predictions underestimate experiments by >2x or more
- Size of vessel wall and size of propagating defect are relatively unimportant

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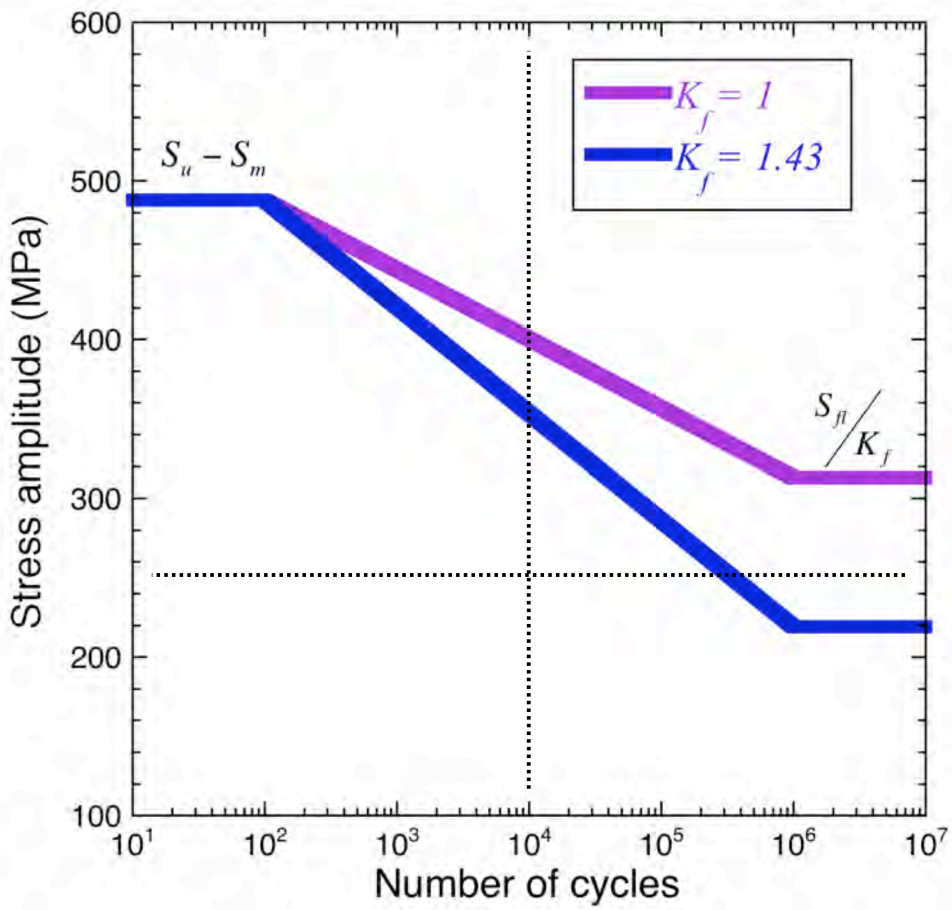
Fatigue life predictions offer more realistic estimates for design life



- Idealized S-N curves based on
  - Materials properties: S_u and S_{fl}
  - Geometry and loading: K_f and S_m
- Data for Cr-Mo steels *suggests* $S_{fl}(H_2) \approx S_{fl}(\text{air})$

- Stress amplitude for tested vessels <250 MPa
- K_f ~ 1.4 for engineered defect of ~5% depth
- Estimated number of cycles to failure >> 10^5

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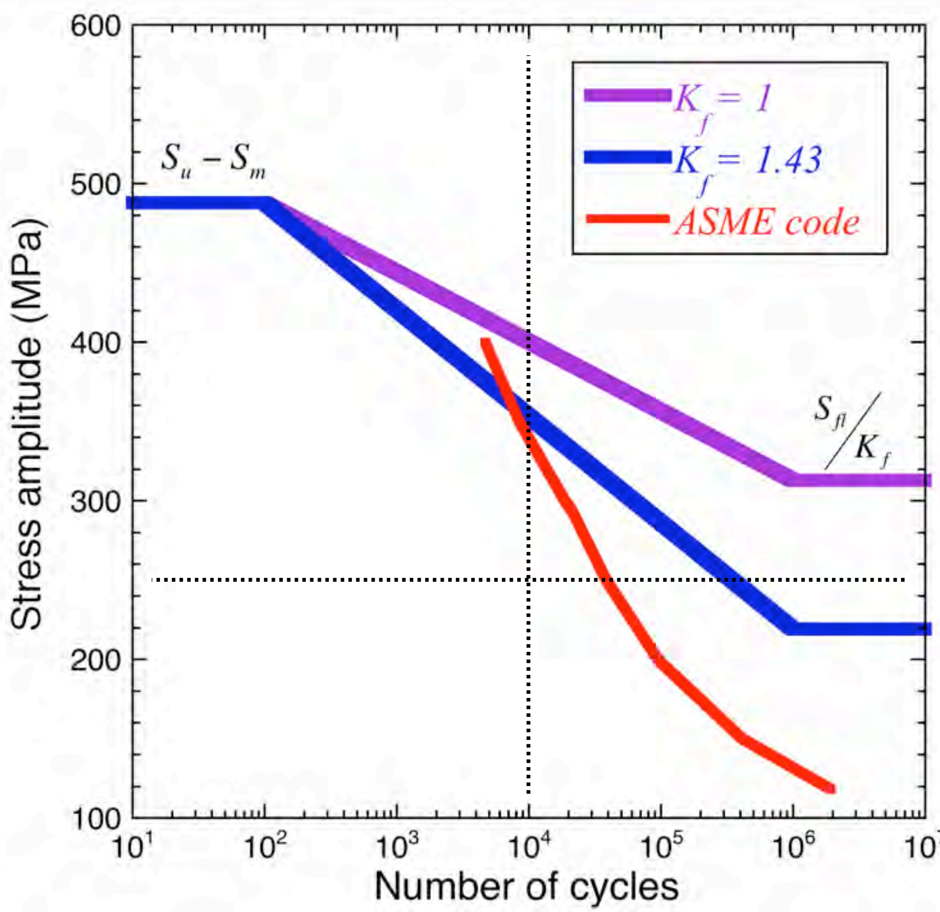
Fatigue life predictions offer more realistic estimates for design life



- ASME code provides design curves for pressure vessels
- Conservative with respect to measured S-N curves

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

- Cr-Mo steel with S_u < 875 MPa
- Wall stress < $0.4S_u$
- Use ASME code to predict design lifetime

Engineering Significance

- Wall stress < 350 MPa
- Stress amplitude generally < 250 MPa

Summary

- Vessels being used for hydrogen storage have been 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 initiated failure after 8,000 and 15,000 cycles
- Leak-before-burst was observed for all failures
- Fatigue crack growth assessment is overly conservative for idealized defects
  - Cycles to failure due to engineered defects is >2 times prediction
  - Crack initiation dominates the cycle life even with internal notches
- Fatigue life data using air data are being considered for design of hydrogen pressure vessels