Fatigue life prognosis for Type I hydrogen storage vessels

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Steel tanks have long history of successful use storing hydrogen

- Early failures (1960's-70's) of high strength steel tanks led to better awareness of hydrogen assisted cracking
- Lower strength (UTS<950 MPa) tanks have been in service for >30 years.
  - Very few failures
- Tanks see relatively few refilling cycles
  - Fatigue has not been well explored

All-steel Type I tanks are in use for hydrogen-fueled industrial trucks

- Economically advantageous compared to battery power in large indoor distribution warehouses
- >10,000 filling cycles anticipated over life
  - ~3 fillings per day and ~10 year life
- Steel tanks provide ballast
- CSA HPIT1 (Hydrogen powered industrial truck) required input for tank design rules

Background

- Fatigue crack growth rate measurements for relevant ferritic pressure vessel steels in gaseous hydrogen are an order of magnitude greater than those in air
- Flaw tolerant design methods based on fracture mechanics predict lifetimes less than the service life for forklifts
  - Assumes flaw detection limit around 5% of wall thickness
  - Crack initiation expected to be significant portion of actual total life
- Test program designed to evaluate life of steel tanks subjected to pressure cycling with gaseous hydrogen
- Primary object was to facilitate CSA HPIT1 development

Outline

- 12 Full size tanks cycled with gaseous hydrogen
  - With and w/o engineered defects
- Results were used to inform the development of sections CSA HPIT1 (Hydrogen Powered Industrial Trucks) which define requirements for Type 1 all-steel hydrogen tanks
- Ongoing and future efforts to develop total life prognosis (initiation + propagation) for hydrogen tanks

12 full size tanks cycled with gaseous hydrogen

- Tanks from two different manufacturers
  - Some left in as-received condition, other contained engineered defects
- Free volume reduced to facilitate pressure cycling

Only one other similar test program in last 30 years (Kesten *etal)*

- 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

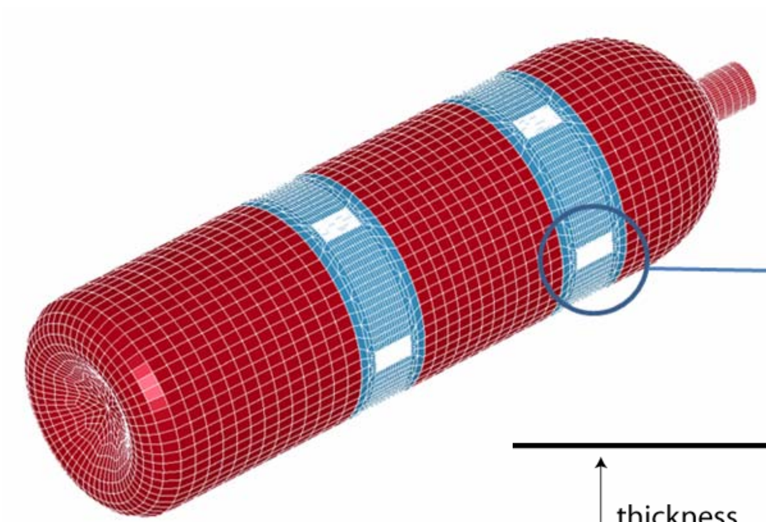
Pressure vessels consistent with design rules for 4130X transportable gas cylinders (e.g. DOT-3AA)

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

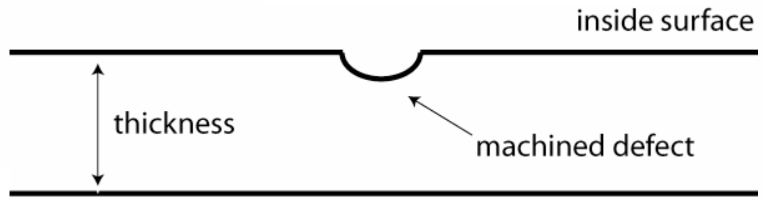
- Two pressure vessel designs from different manufacturers
  - Nominal hoop stress at P = 43.5 MPa
    - T1 design: ~340 MPa
    - T2 design: ~305 MPa

- 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

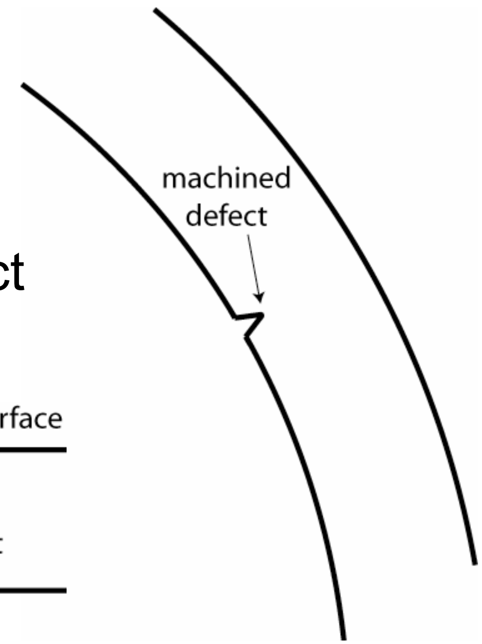
EDM machined defects used to initiate failures



Engineered defect
(10 per vessel)



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

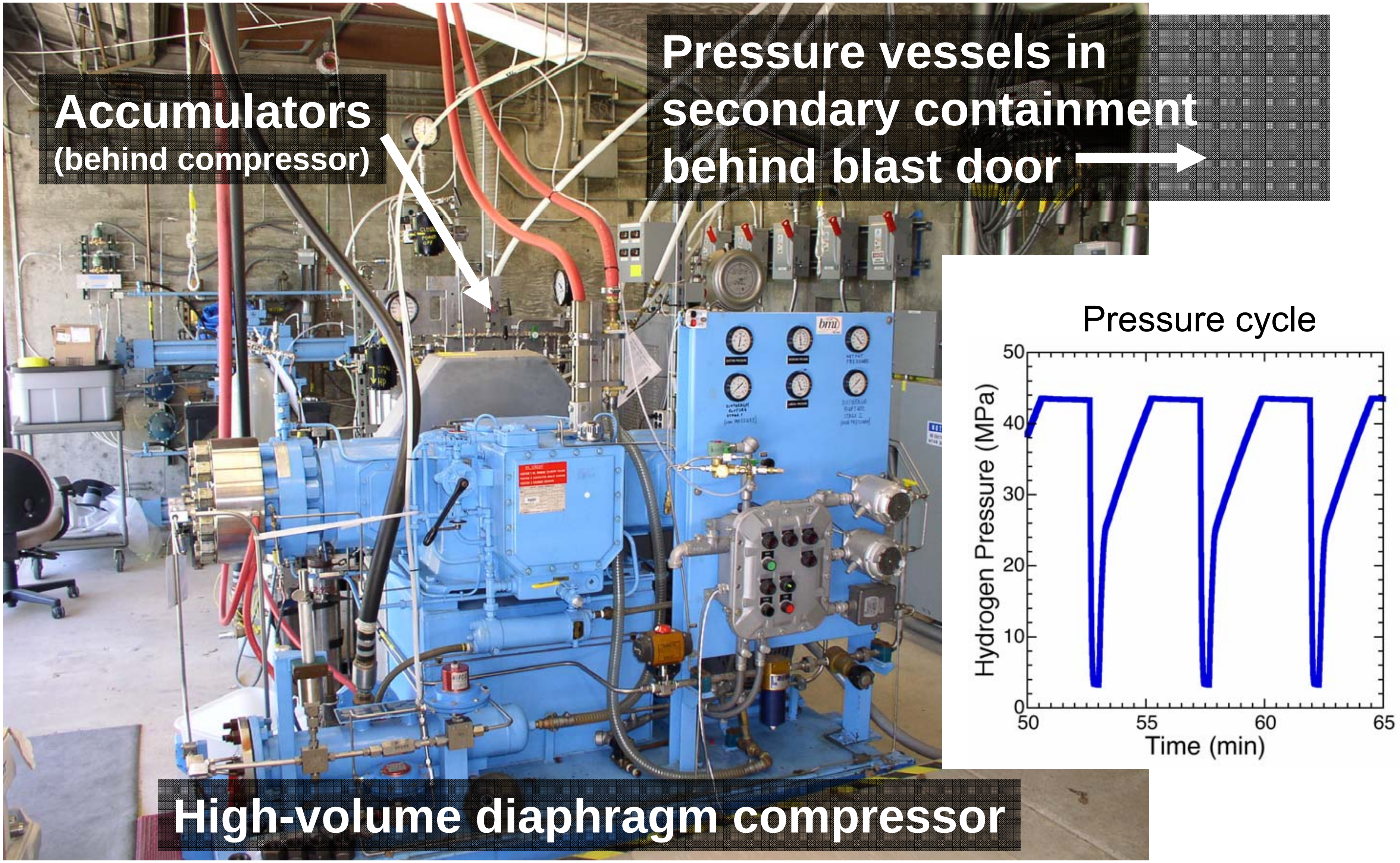


V-notch in profile
Nominal root
radius 0.05mm
(actual ~0.12mm)

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

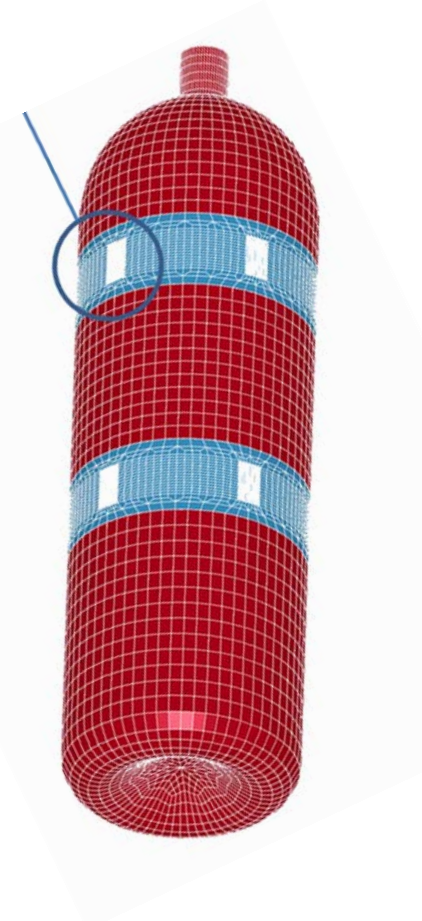
Closed-loop gas-handling system capable of simultaneously pressurizing 10 pressure vessels



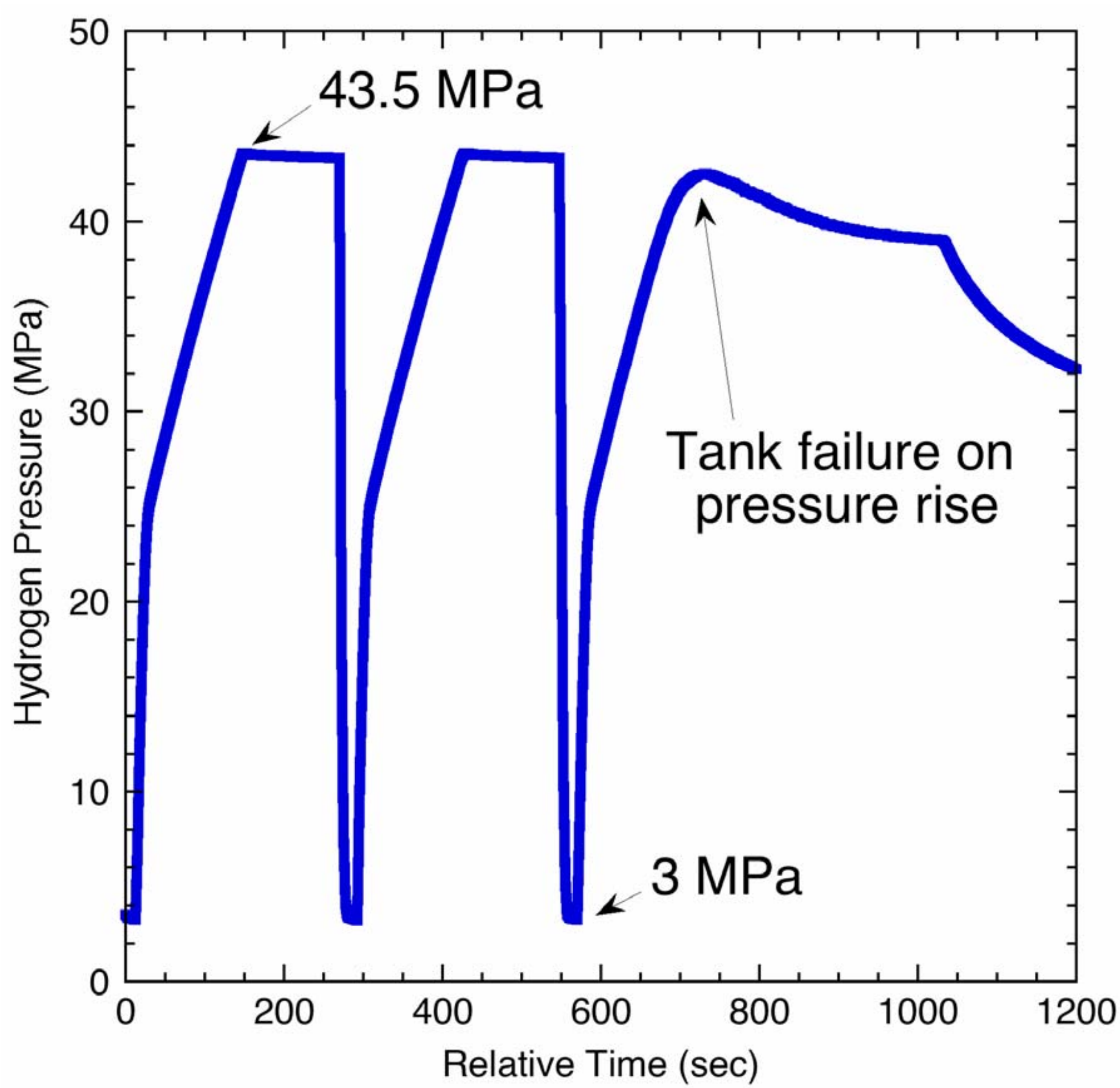
Failure occurred only for tanks with large machined defects

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



All observed failures are *leak-before-burst*

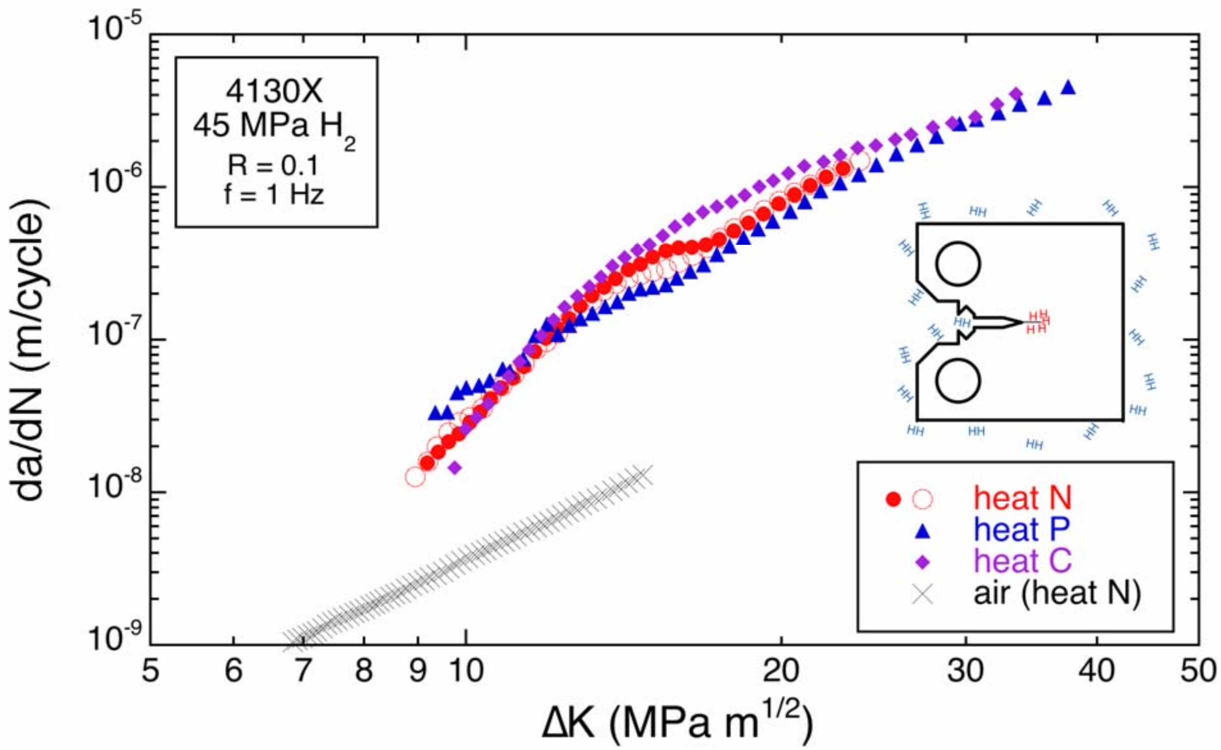


- All failures occur during pressure ramp
- At failure, pressure vessel "slowly" leaks gas into secondary containment
- After failure, vessels can be pressurized to ~10 MPa without leakage
- Through-wall crack cannot be detected visually

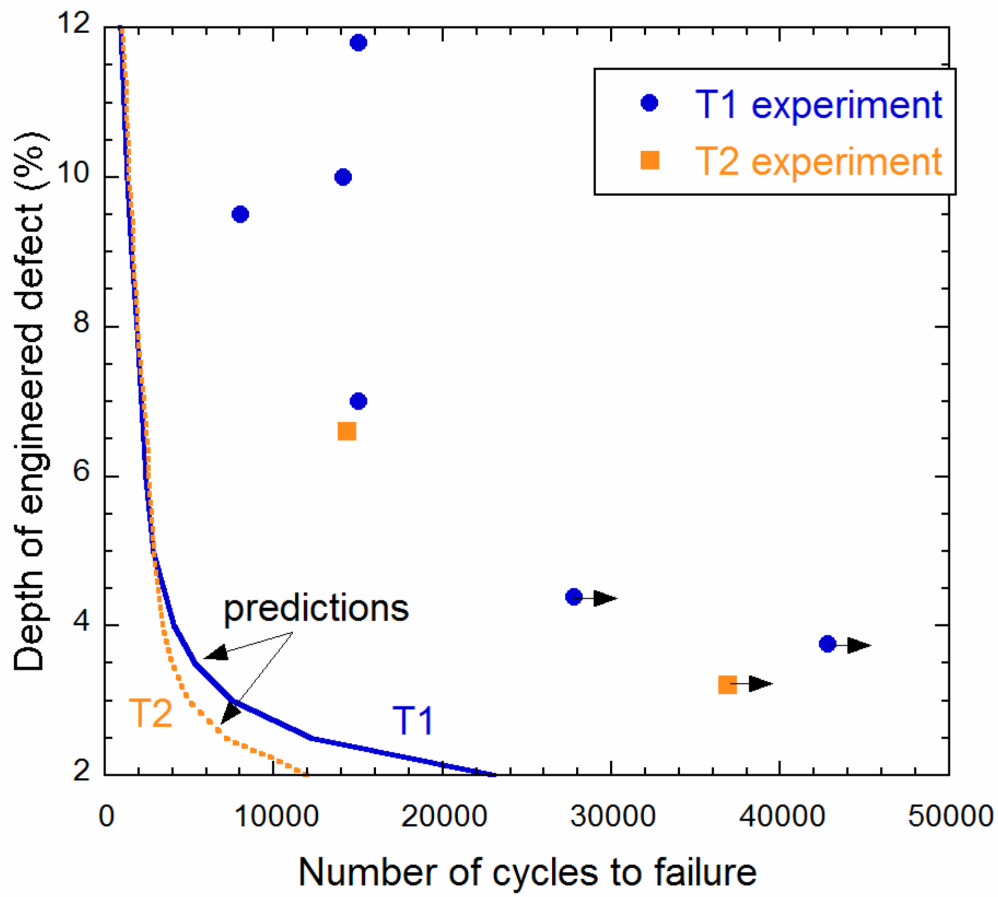
Fatigue crack in gaseous hydrogen is an order of magnitude greater than in air

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

- 3 heats of 4130X steel from pressure vessels



Crack growth assuming LEFM does not account for total life observed from tanks with defects



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

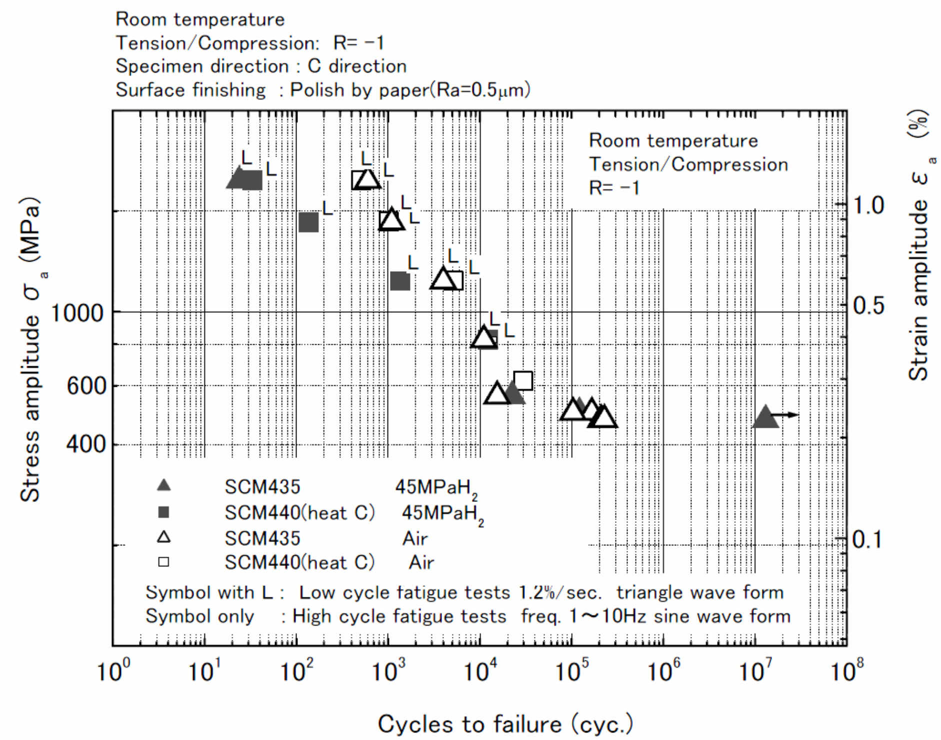
- LEFM predictions underestimate experiments by for all defect sizes

- conservativeness of LEFM is restrictive for small defects

Crack initiation is significant at long life!

Fatigue life approach may be more appropriate that damage tolerant approach

- ASME BPV code provides guidance and design curves for fatigue life analysis of steel pressure vessels
- KD-3 (Section VIII, Div 3) provides conservative design parameters, but does not account for effect of gaseous hydrogen
- Limited data suggests hydrogen does not accelerate crack initiation at long life

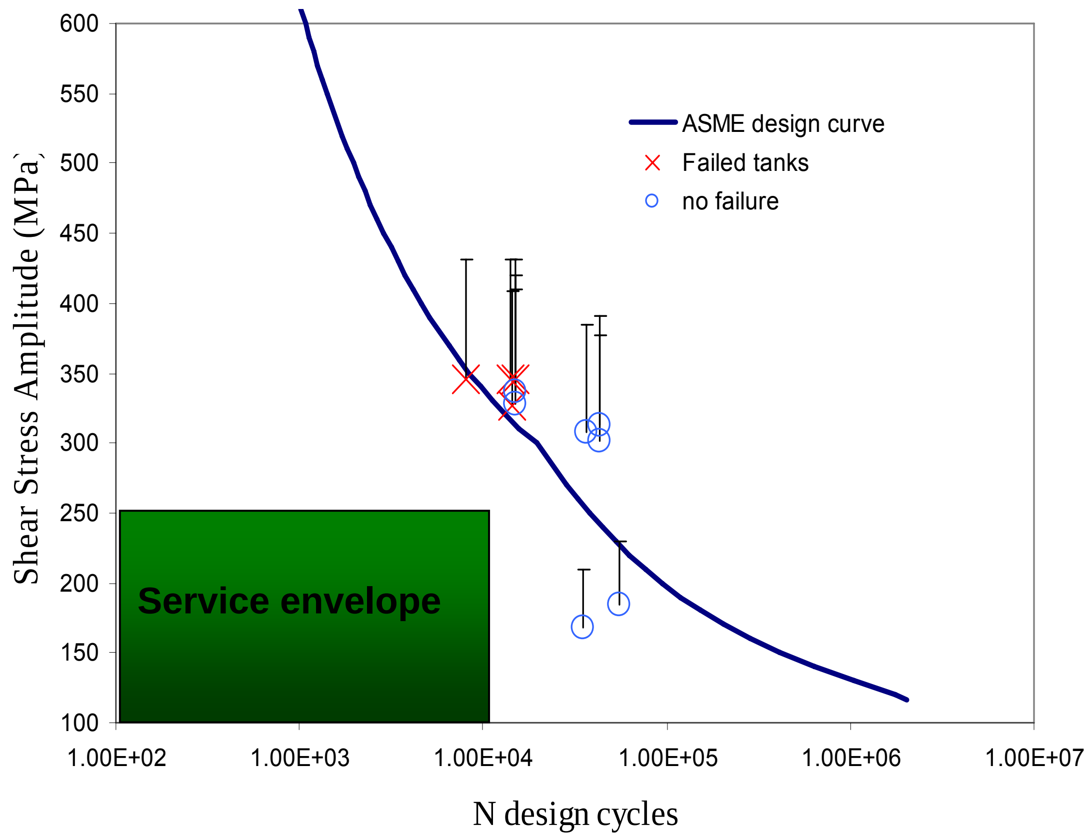


Ref. Wada ICHS proceedings

Solution for CSA HPIT1 tank design rules

- Option 1: Verify fatigue life by testing actual tanks

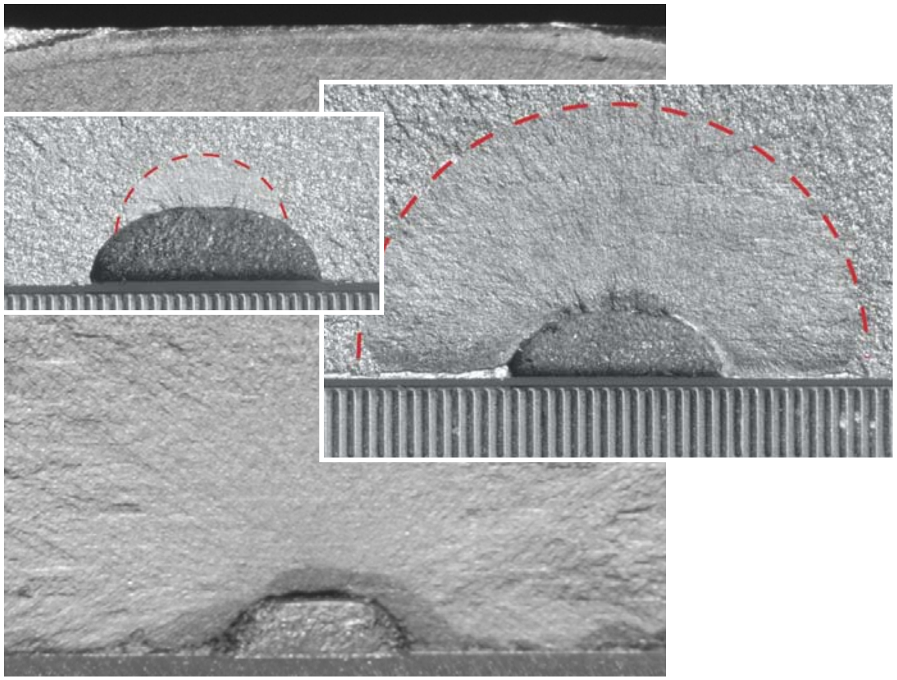
- Option 2: design by analysis
- Follows ASME Division 3 Section VIII Article KD-3 rules for fatigue evaluation
- Special requirements ensure tanks operate in long-life regime:
  - DOT3AA 4130X or ASME SA-372 (Cr-Mo) steels
  - S_u<890 MPa
  - Hoop stress < 0.4 S_u
  - Surface roughness: Ra < 6.4 µm and Rmax < 20 µm
  - NDE inspection for 5% defect



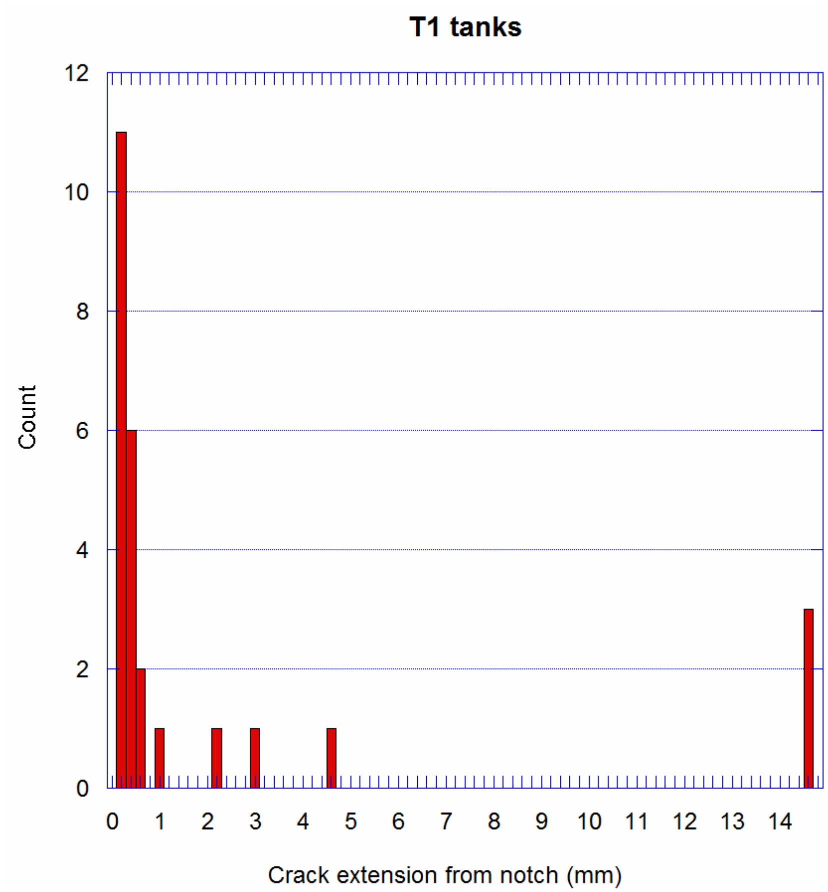
Future improvements

- Current rules in HPIT1 provide an acceptable engineering solution
- Forced to limit application to narrow window of material and operation variables that have been studied in test program
  - Inhibits innovation
- Total life prognosis methods could provide more universal guidance for life prediction of hydrogen tanks

Crack initiation observed at all machined defects



- Crack-length distribution suggests cracks initiate quickly, decelerate and then accelerate to failure
- Significant portion of life may occur during this crack “incubation” period which is not accounted for in flaw tolerant analyses



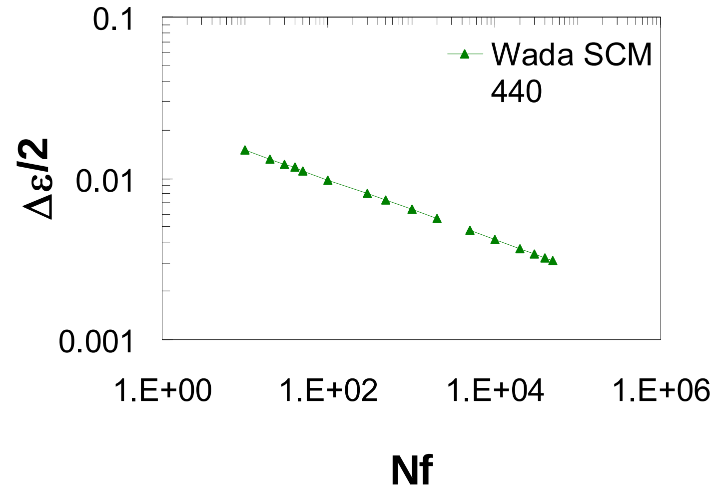
3 tanks, 8,000-15,000 cycles per vessel

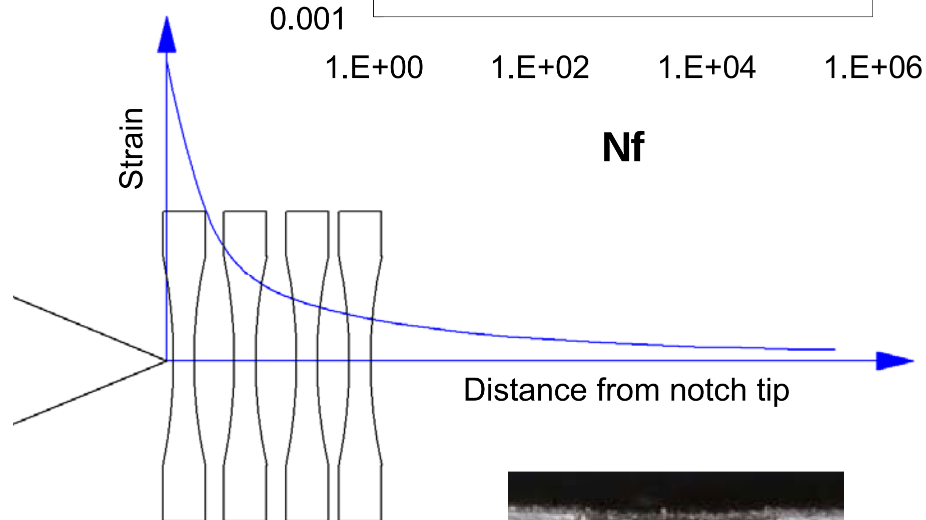
7,8 and 10% defect depth

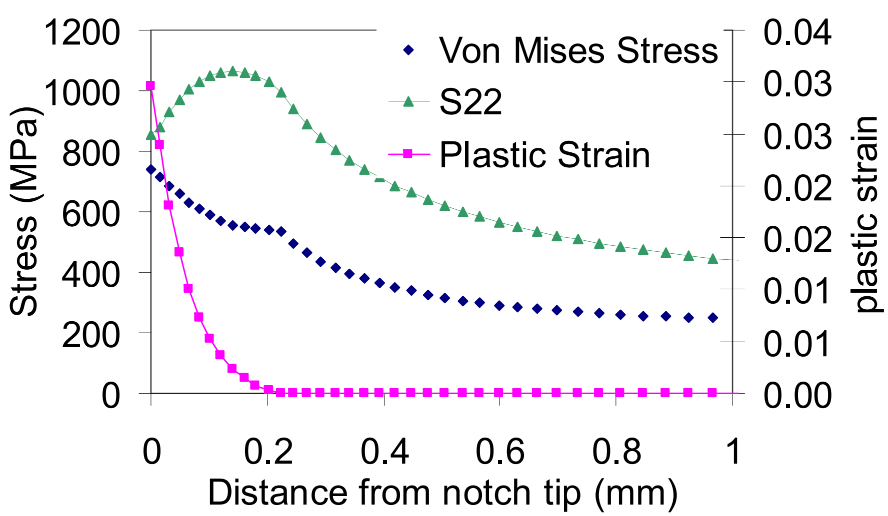
Total life methods utilizing strain-life data and crack propagation data

- Strain life data can be mapped to notch-tip strain profiles to infer crack initiation life
  (e.g. Socie etal Eng Frac. Mech. 1979)

- Indicates rapid crack initiation

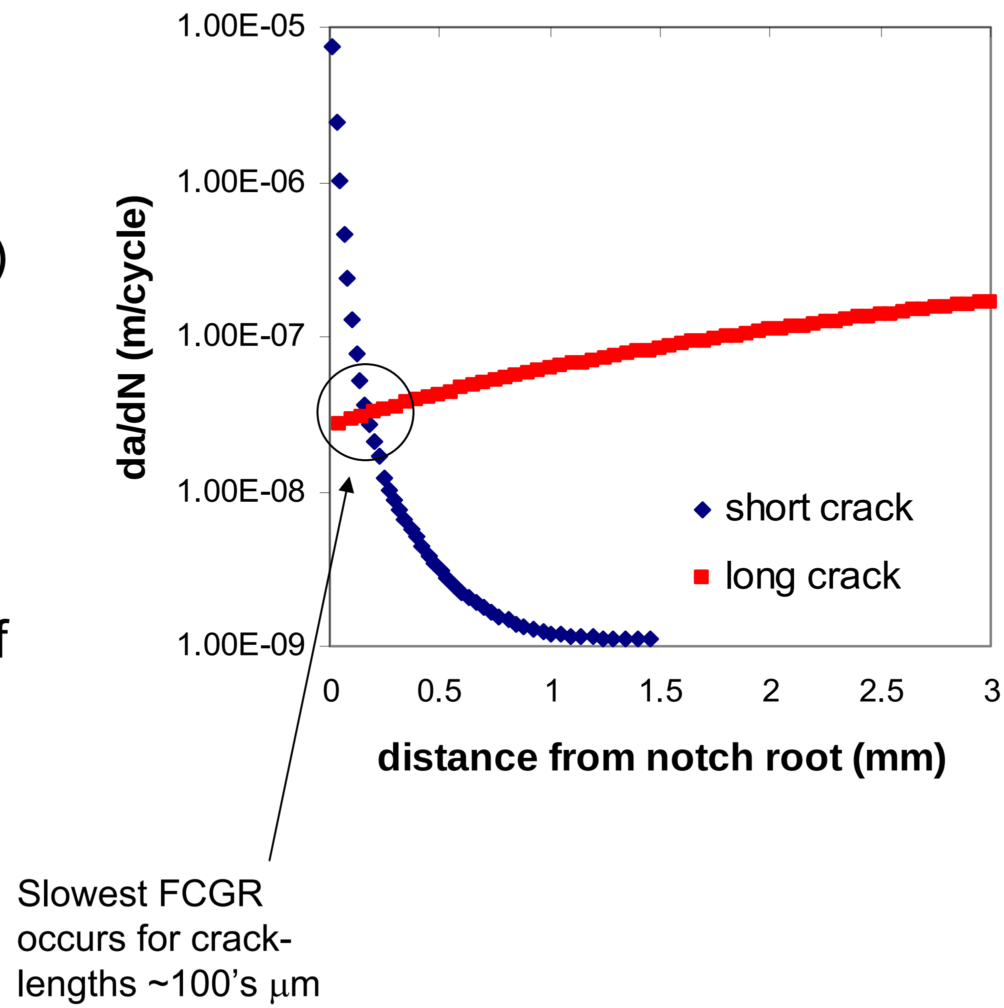






Total life prediction methods explain observed crack length distributions

- Construct is consistent with observed distribution of crack lengths at notches (0.1 and 0.3 mm)
- Need improved strain life data
- Is long crack da/dn appropriate for cracks <1mm
- Need to consider effect of frequency on fatigue crack propagation rates in gaseous hydrogen



Summary

- Hydrogen storage tanks have been subjected to more than 55,000 cycles with 43.5 MPa gaseous hydrogen without failure
- Engineered defects instigated failure of the tanks only when deeper than ~6%
- Flaw tolerant designs are restrictively conservative for forklift tank applications
- Interim solution involves fatigue life analysis using published design curves and prescriptive limits on design
- Total life (initiation plus propagation) needed to facilitate widespread application of steel hydrogen tanks