Pressure Cycling of Type 1 Pressure Vessels with Gaseous Hydrogen

Chris San Marchi and Brian Somerday

Sandia National Laboratories

Kevin Nibur

Hy-Performance Materials Testing

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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 (type 1) pressure vessels for gaseous hydrogen with engineering design methods
  - Fracture mechanics-based design
  - Stress-life design

- Described method proposed in CSA standard

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

Motivation:
innovative applications are expanding design space beyond engineering experience

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

Hydrogen-induced failure of transport cylinder

Ref.: *Barthélémy, 1st ESSHS, 2006*

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
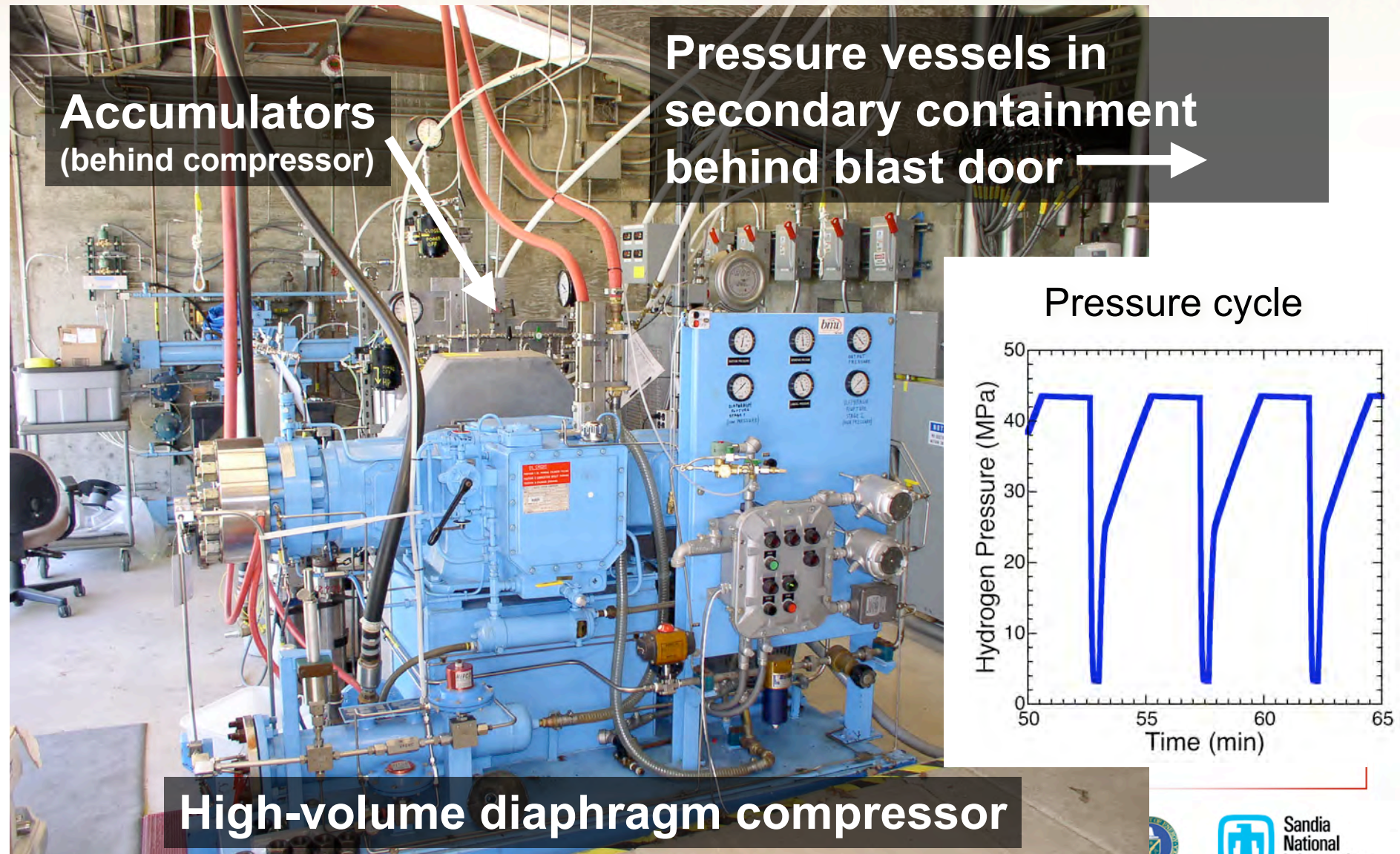- Minimum system pressure of ~3 MPa

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

Pressure cycle

High-volume diaphragm compressor

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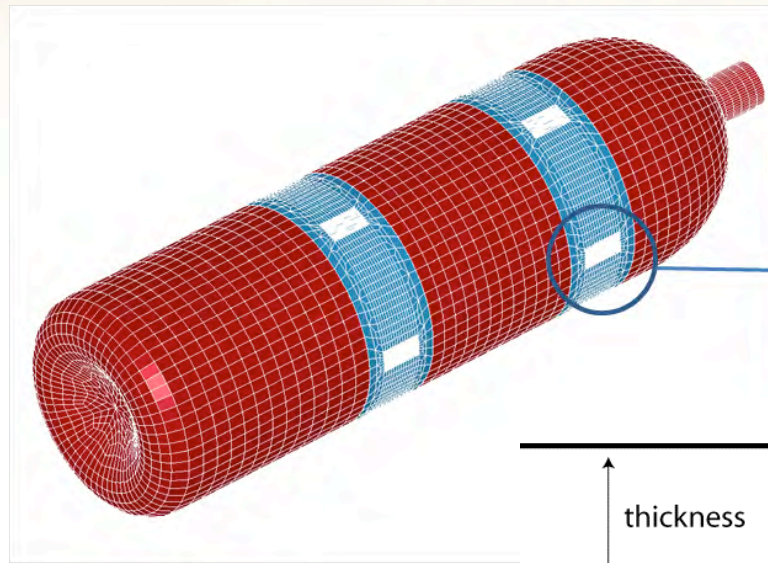
- Two pressure vessel designs from different manufacturers
  - Nominal hoop stress at P = 43.5 MPa
    - T1 design: ~340 MPa
    - T2 design: ~305 MPa

- 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
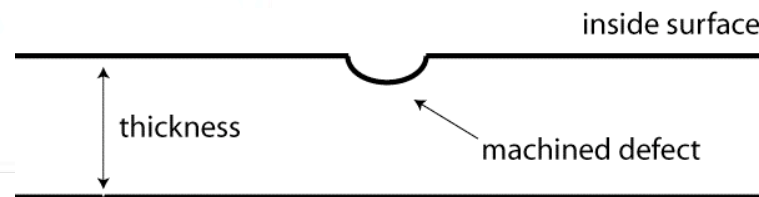T2 design: 340 MPa

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Engineered defects used to initiate failures

Engineered defect
(10 per vessel)

machined defect

inside surface

thickness

machined defect

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
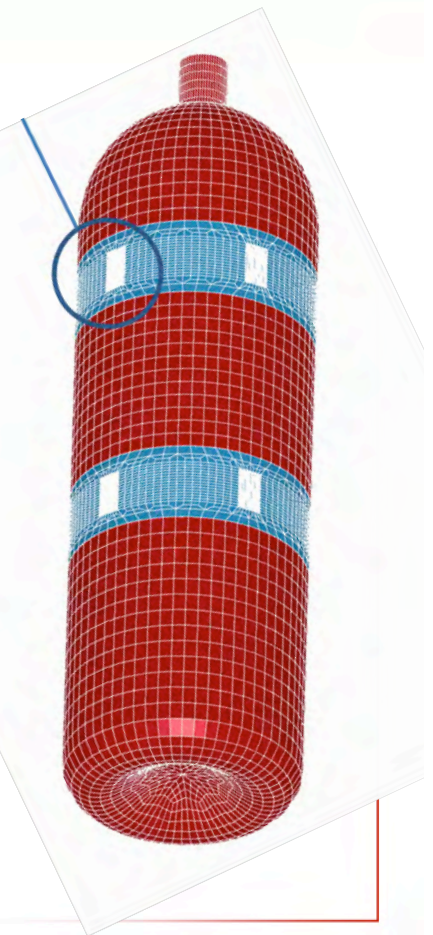
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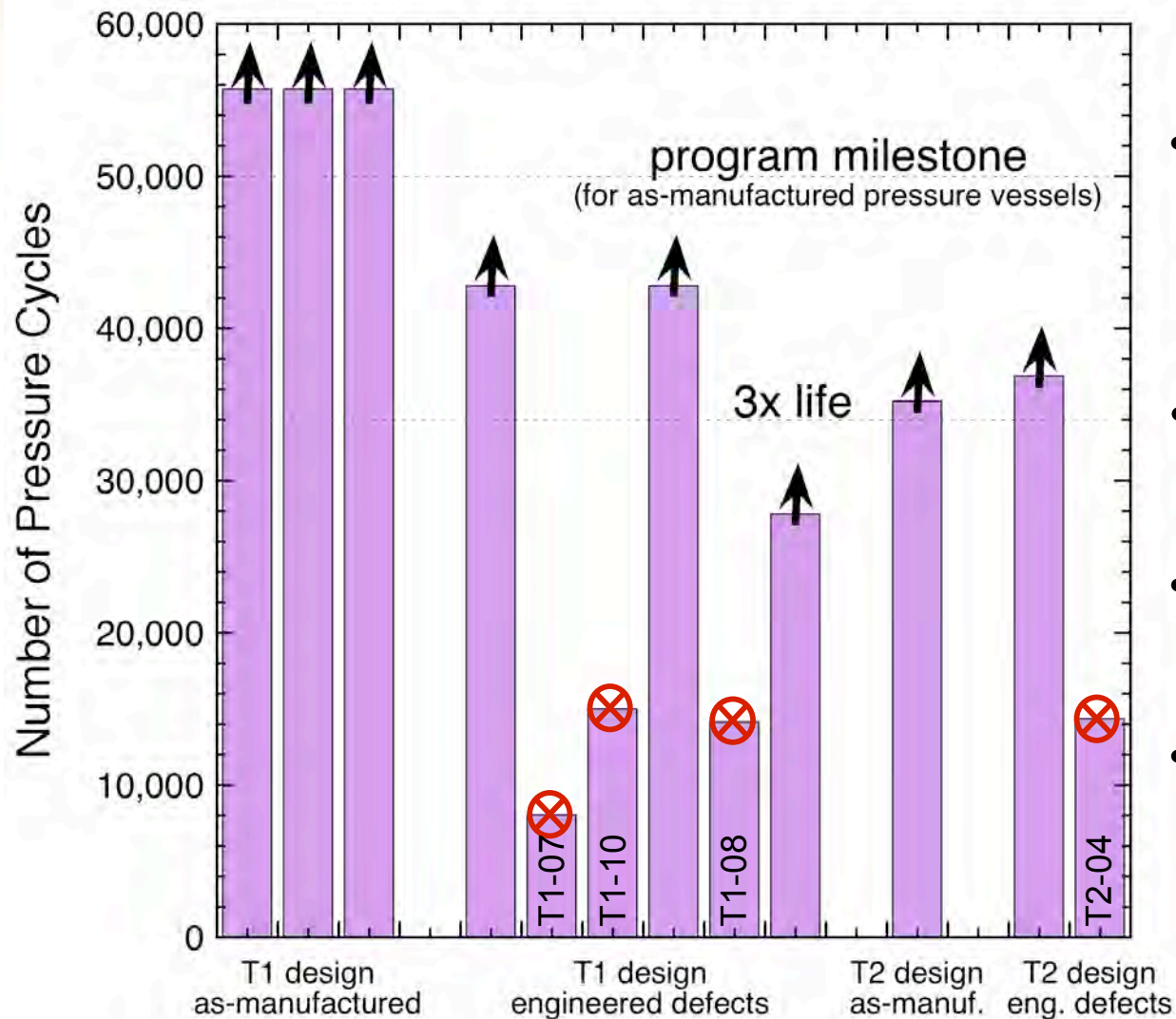- Described method proposed in CSA standard

9

Large engineered defects initiated cracking and hydrogen-assisted failure

Summary of hydrogen pressure cycling and defect sizes

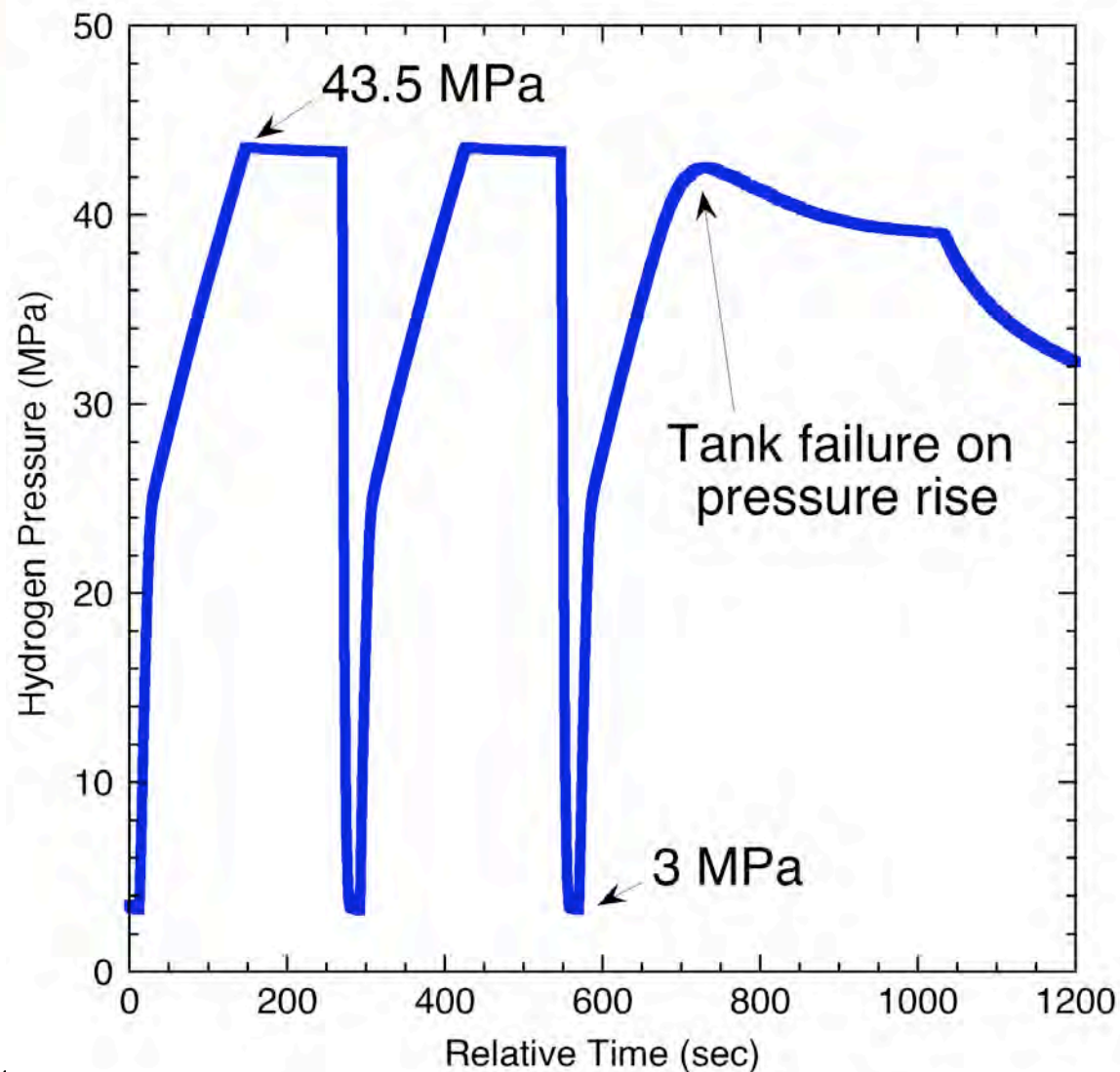| Pressure vessel	Nominal defect depth (%)	Pressure cycles
T1	0	(55,700)
	3 & 4	(27,800)
	4	(42,800)
	2 & 5	(42,800)
	7 & 8	15,000
	10	8,000 14,000
T2	0	(35,200)
	3	(36,900)
	8	14,300

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

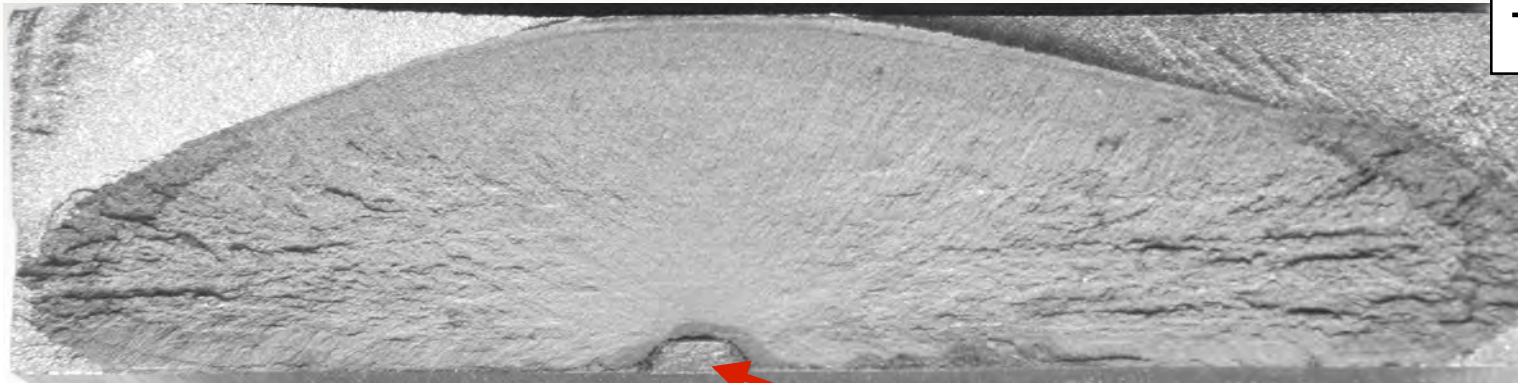- All failures (4) are leak before burst

All observed failures are *leak-before-burst*

43.5 MPa

Tank failure on pressure rise

3 MPa

Hydrogen Pressure (MPa) vs *Relative Time (sec)*

- 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

T1-07

T1-10

wall thickness
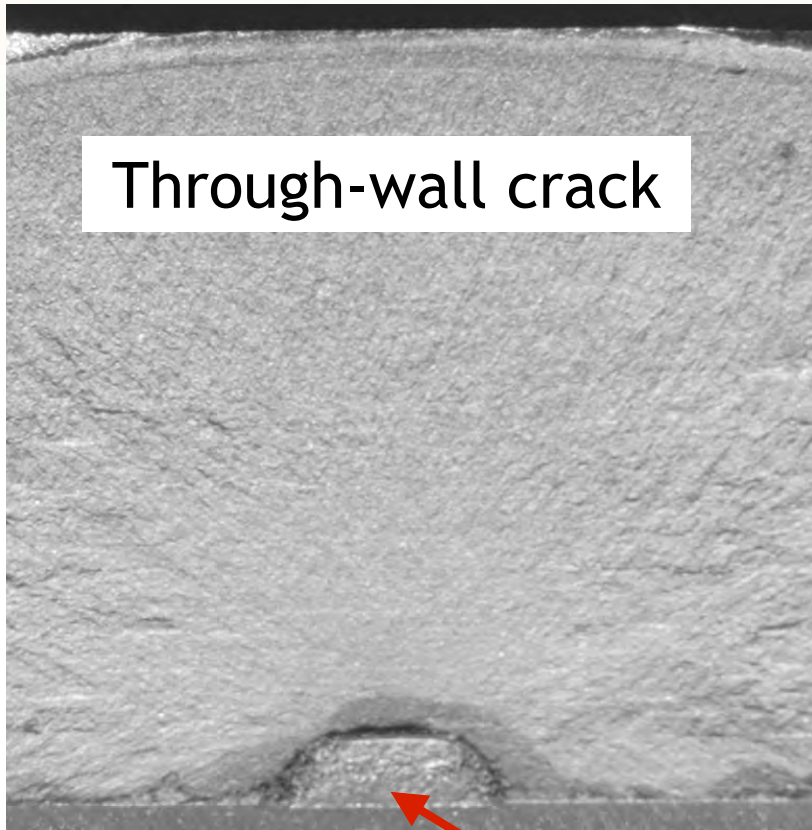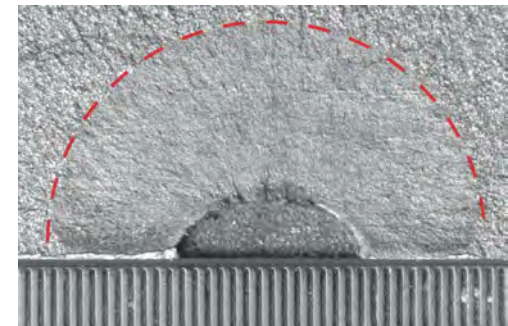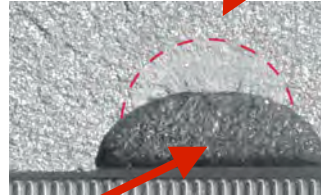
wall thickness

engineered defect

Through-wall crack

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

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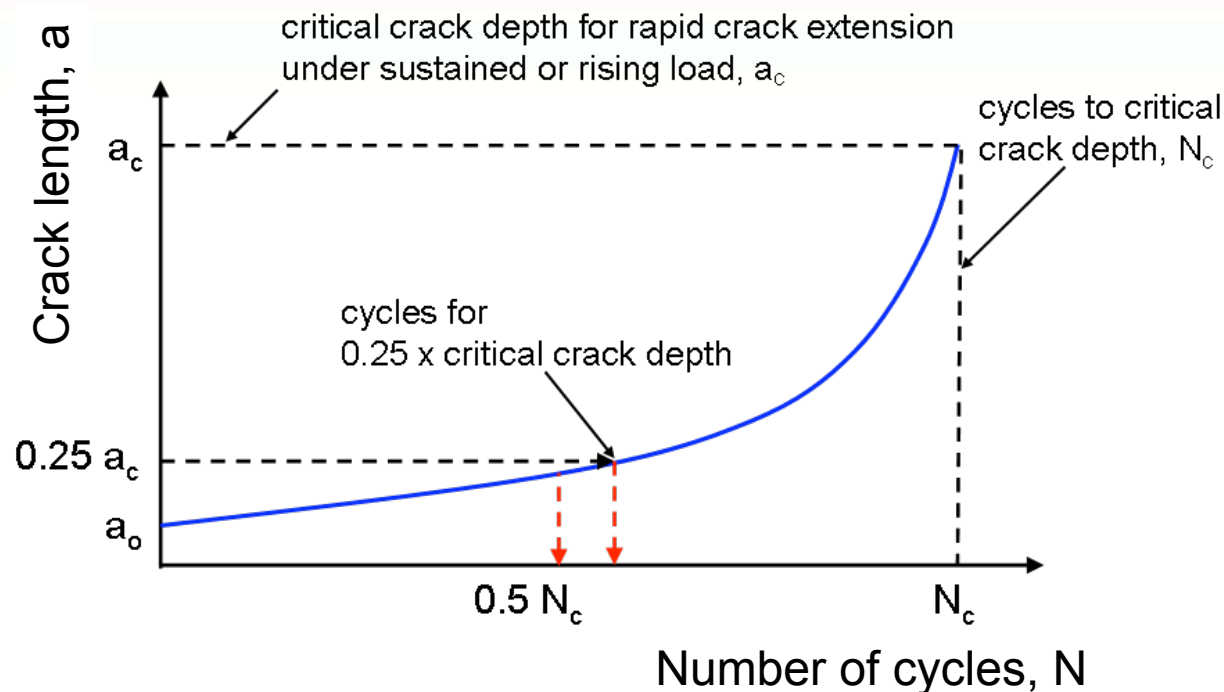- Greater number of cycles
  = more crack extension

Same size engineered defect
(same vessel)

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- Described method proposed in CSA standard

Fatigue life qualification by fracture mechanics (crack growth methodology)

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

Stress intensity
at a/t = 0.8

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

$^{\dagger}K_{JIH}$ = 59 MPa m$^{1/2}$

Assumptions:
- a_c = 0.8 x thickness
- semicircular propagating cracks
- use data[†] for R = 0.1 and f = 0.1 Hz

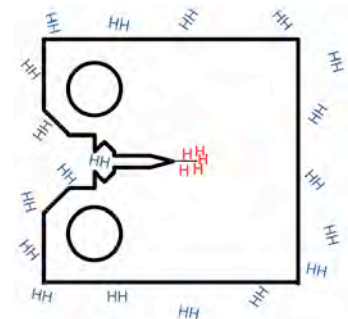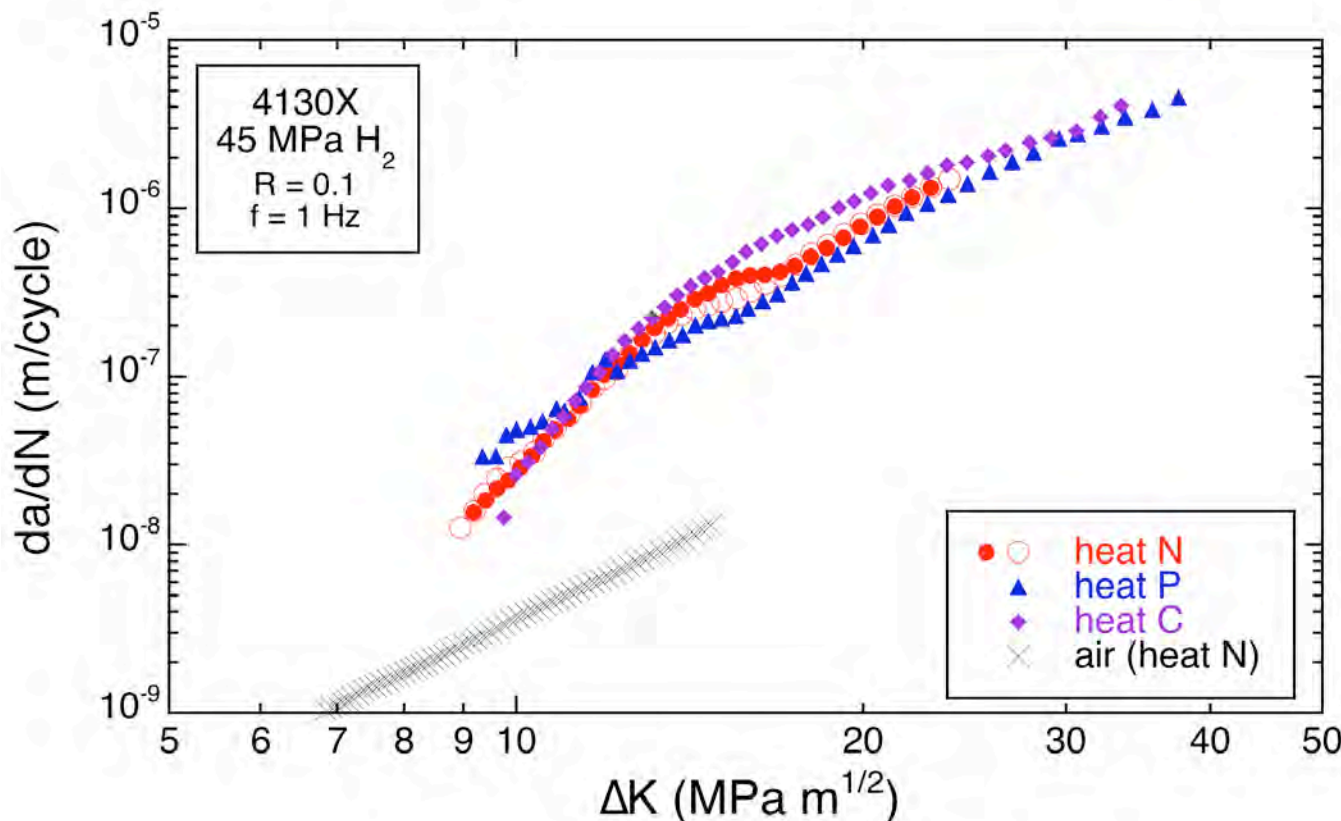[†] 4130X steel measured in gaseous H_2 at pressure of 45 MPa Nibur et al. (PVP2010-25827)
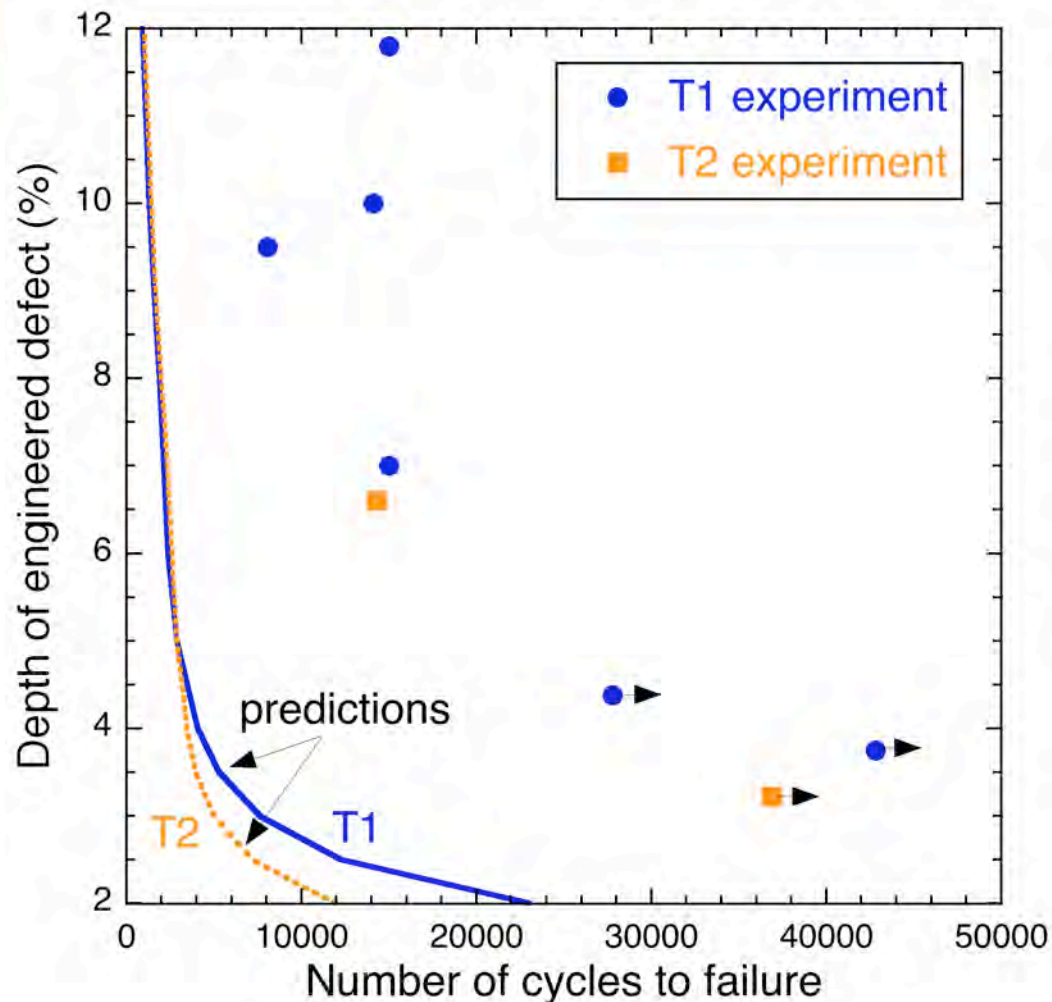
Fatigue crack in gaseous hydrogen is an order of magnitude greater than in air

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)

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

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:

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

Effect of notch:

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

Data for Cr-Mo steels in tension-compression fatigue *suggests*
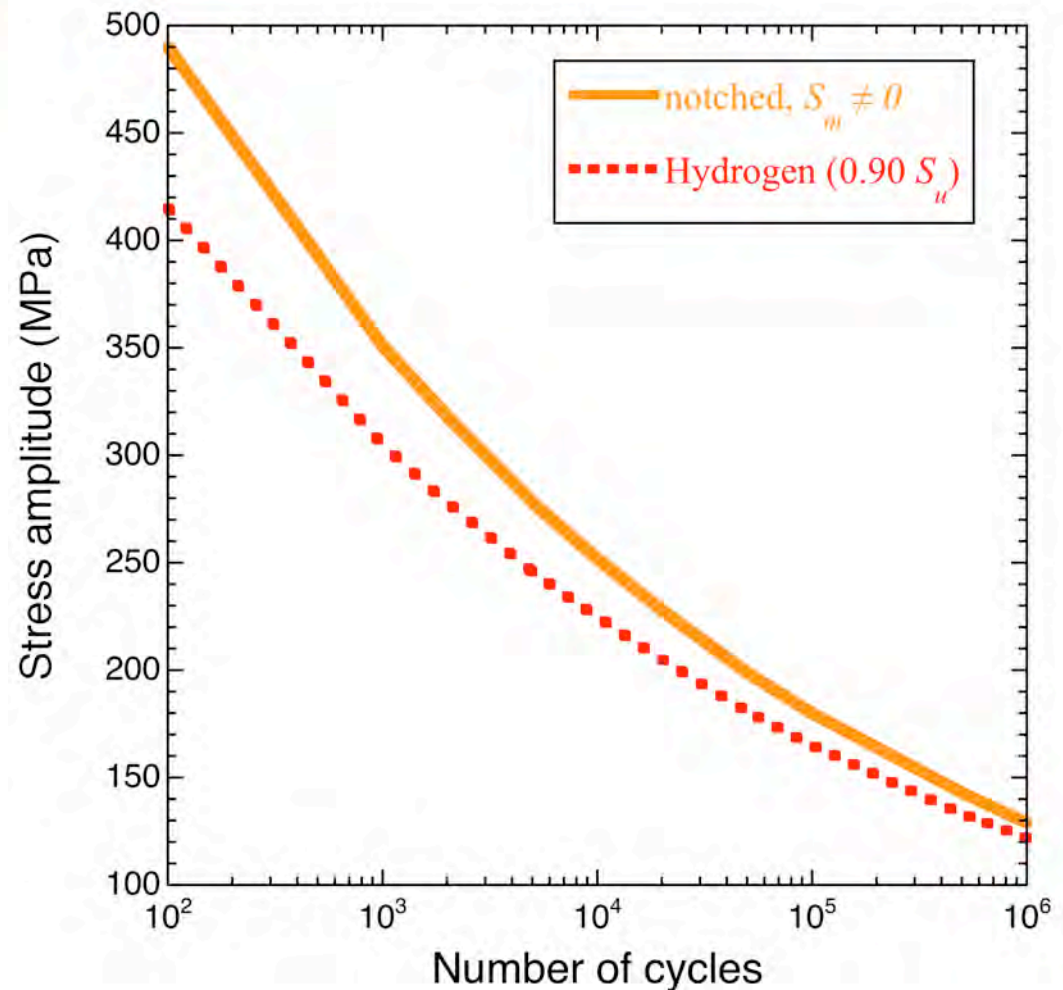
$$S_f(H_2) \approx S_f(air)\dagger$$

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)

20

Fatigue of pressure vessels with engineered defects compare favorably with predictions

Legend:
- $S_m = 260$ MPa ($K_f = 1.77$)
- Hydrogen ($0.90\,S_u$)
- $\times$ Pressure vessel failures ($K_r = 1.25$)

X-axis: Number of cycles

Y-axis: Stress amplitude (MPa)

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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- **Described method proposed in CSA standard**

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

Performance requirements

- Leak-before-break requirements (31.1)
    - 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* (31.3)
    OR
    - Fatigue life qualification by *analysis* (30.5)

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

- Fatigue life verification by *testing* (31.3)

  <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* (30.5)

  <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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Proposed requirements for type 1 steel pressure vessels in gaseous hydrogen service
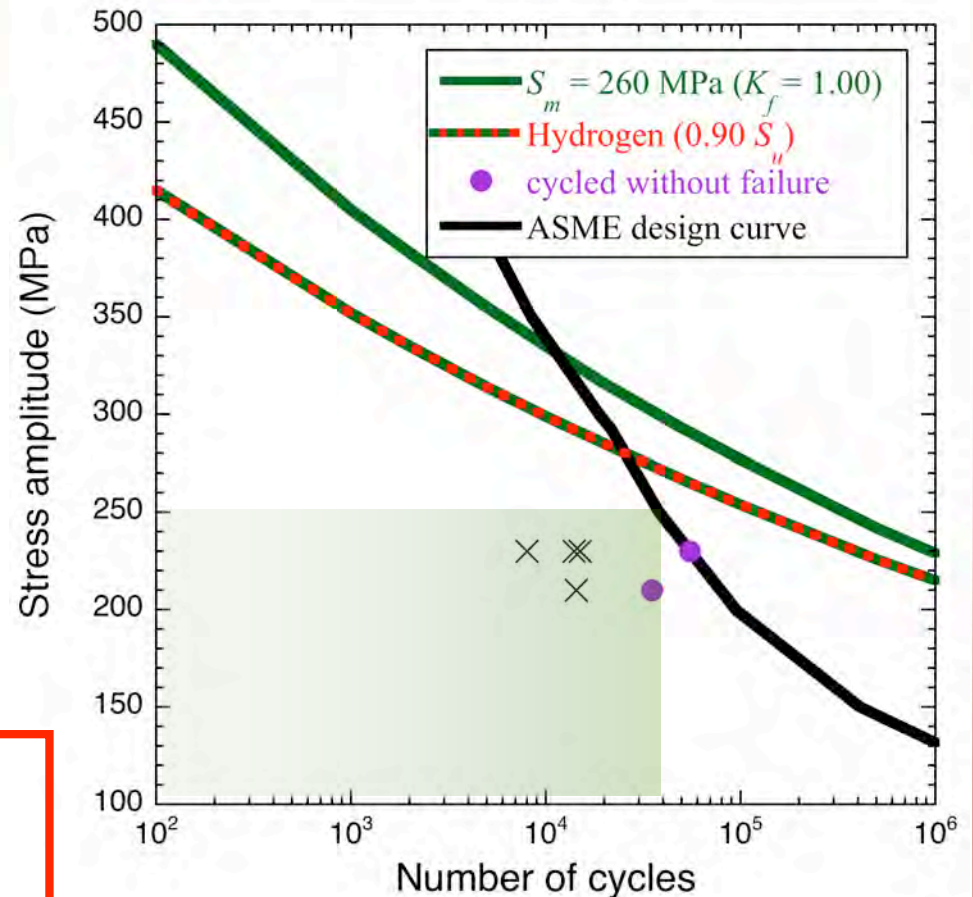
- $S_u \leq 890$ MPa
- hoop stress $\leq 0.4\, S_u = 356$ MPa

From ASME VIII.3 KD-3
- assume: $K_r = 1.25$
- T1 design
- $S_m \approx 260$ MPa & $S_a \approx 250$ MPa

Engineering Significance of these requirements
- Stress intensity < ~400 MPa
- Stress amplitude < ~250 MPa
- Design life > 40,000 cycles

Legend:
- $S_m = 260$ MPa ($K_f = 1.00$)
- Hydrogen (0.90 S_u)
- cycled without failure
- ASME design curve

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

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