

Life Extension of Tanks for High Pressure Hydrogen Storage Vessels

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Agenda

- 1) Updated status of project (10 min total)
 - Low ΔK data appear to match ASME Code Case 2938
 - NDE plans with NASA-WSTF and Digital Wave
 - Case studies suggest significant usable life left on tanks if partial fills
 - Obtained field data of both Type 2 tanks (2015-2018)
- 2) What does life-extension require for Type 2 tanks?
 - Is it just the ability to size flaws? Then ASME PCC-3?
- 3) What role do Codes play in maximization of design life?
 - Is this left up to individual customer?
 - Is there general guidance that can be provided through ASME on how to account for pressure cycles?

Invitation List

Sandia	Joe Ronevich Chris San Marchi John Emery
Fiba Tech	John Felbaum
Air Products	Dave Farese
Praxair/Linde	Kang Xu Mahendra Rana
Becht Eng.	Eileen Chant Bob Sims Greg Epremian
Digital Wave	Brian Burks
NASA-WSTF	Charles Nichols Tommy Yoder
Luna Inc.	Matt Webster
UC Davis	Prof. Mike Hill

Accomplishment: Low ΔK fatigue crack growth rates in high pressure H_2 are bound by master design curves

Test conditions

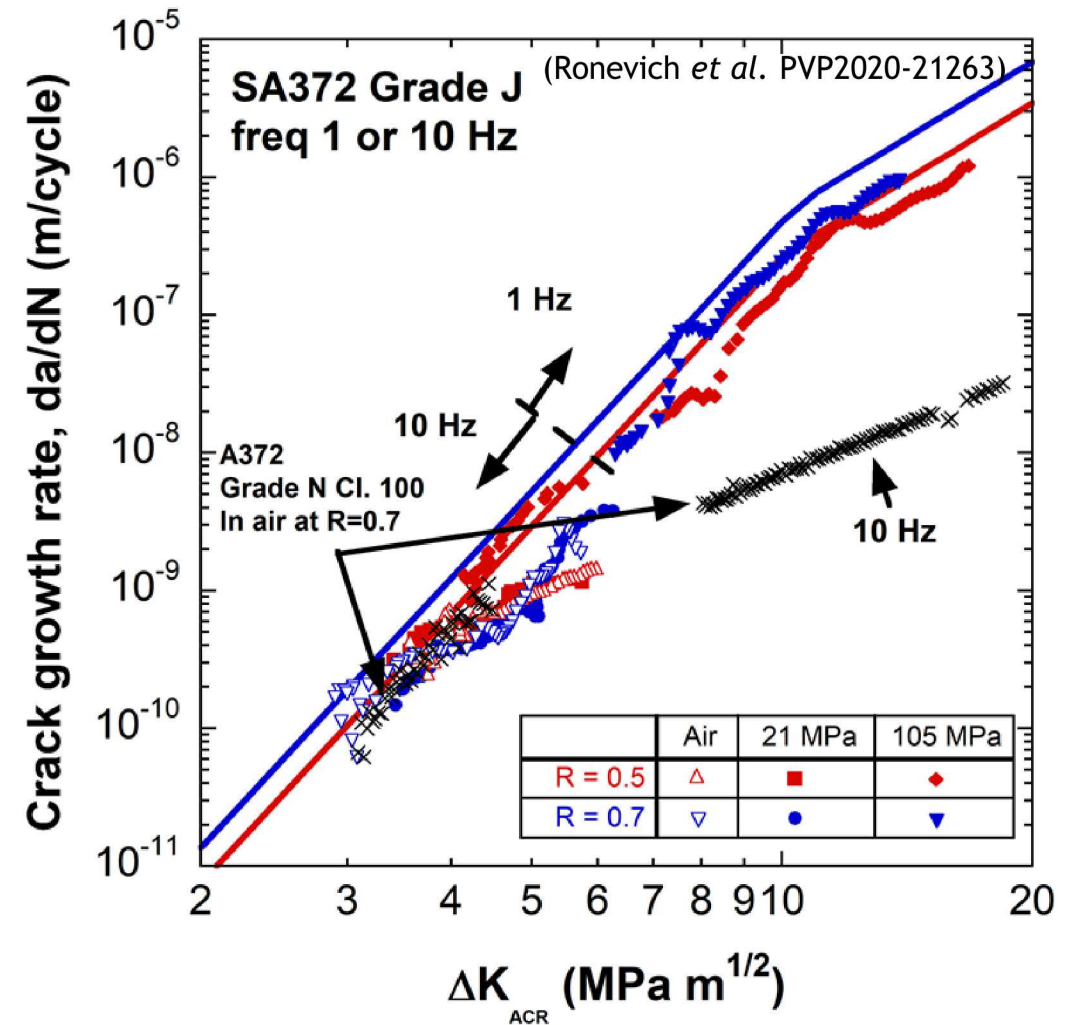
$P = 21$ or 105 MPa

$R = 0.5$ or 0.7

Freq = 1 or 10 Hz

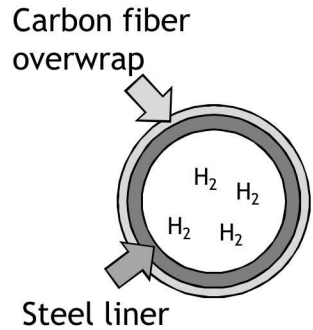
Master design curves from ASME Code Case 2938
established from data $\Delta K > 6$ MPa $m^{1/2}$

- Data in H_2 appear to overlap data in air at low ΔK
- Crack closure was corrected for via adjusted compliance ratio method (ΔK_{ACR}) resulting in better overlap of air and H_2 curves



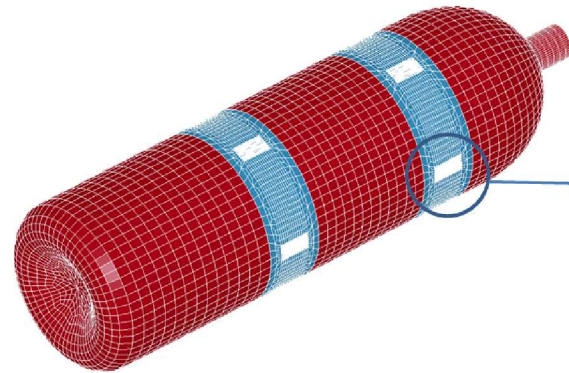
- Operational ΔK_{th} (thresholds) were established to be between 3 and 4 MPa $m^{1/2}$ meaning da/dN values $\sim 10^{-10}$ m/cycle \rightarrow Practical engineering limits for infinite design life
- More testing is needed before these trends can be generalized for behavior in low ΔK range

Approach: Explore feasibility of eddy current NDE techniques for re-assessment of metal liner (Type 2 tanks)



Access to metal liner is limited in Type 2 tanks
 → Perform internal inspection through bore using eddy current technique

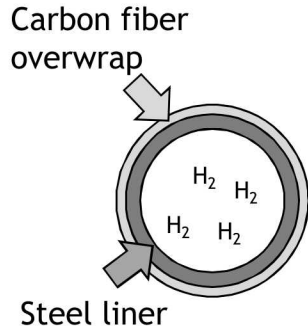
Task 1: Demonstrate feasibility of Eddy Current (EC) technique at detecting flaws



Calibration block of manufactured defects

- Utilize type 1 tanks with manufactured defects on inner surface for proof of principle for EC technique
- Partnering with Hexagon Digital Wave and NASA-White Sands Test Facility for NDE development and measurements (contracts are pending)

Approach: Explore feasibility of eddy current NDE techniques for re-assessment of metal liner (Type 2 tanks)



Task 2: Demonstrate flaw detection capability on full-scale Type 2 tanks



14'6" Length / O.D. = 17 in / Steel liner ~ 1.5" / Access port = 1.5" NPT

- Eddy current detection of flaws in metal liner through end ports
- Modal Acoustic Emission (MAE) on carbon fiber overwrap
- Partnering with Hexagon Digital Wave (contracts pending)

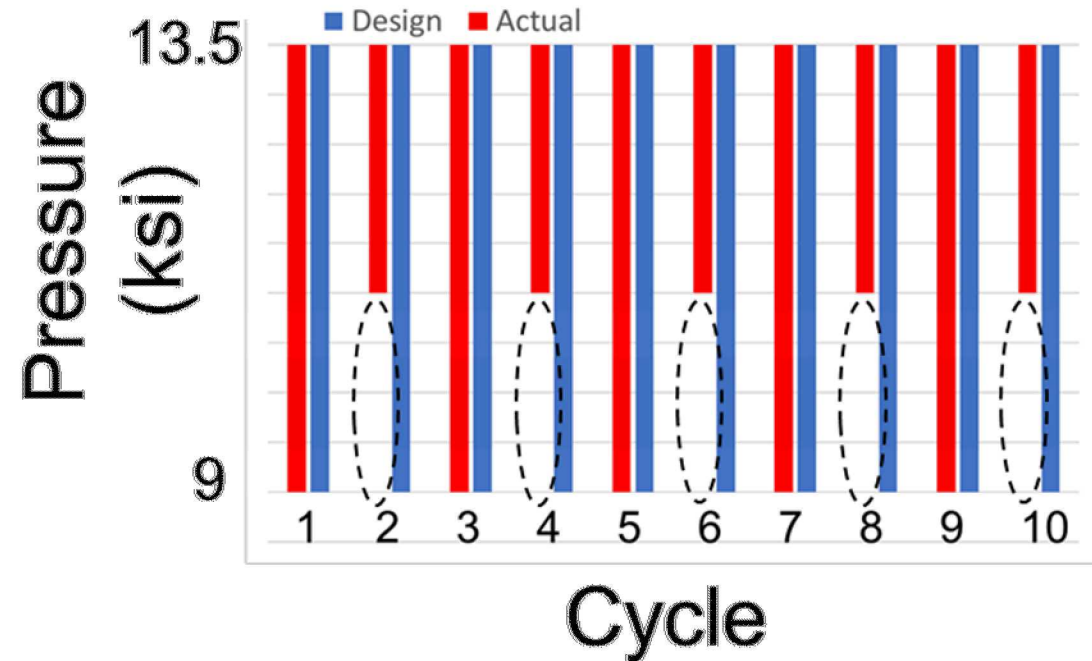


Benefits if Successful - Demonstration of a NDE technique capable of detecting flaws in metal liners of full-scale Type 2 tanks will facilitate life-extension via conventional life-extension practices (such as ASME PCC-3)

Approach: Assess how accounting of pressure cycles can affect life of tanks

Industry is conservative and counts every refill of tanks = 1 cycle

- Should *partial* cycles be counted the same as *full* cycles?



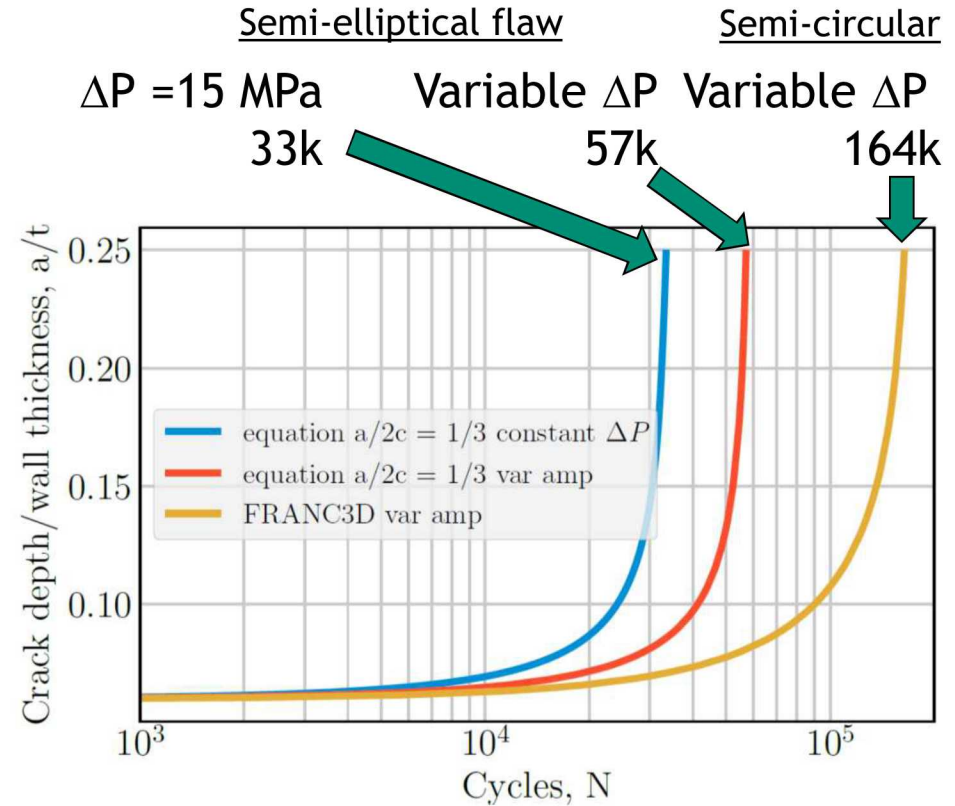
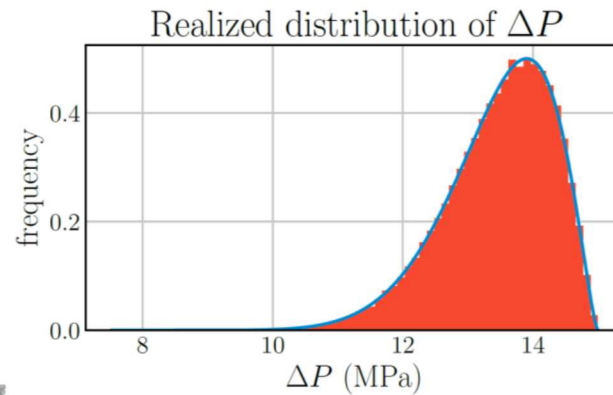
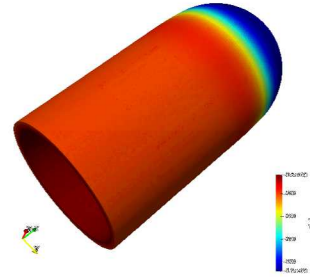
Identify margins through rigorous analysis of pressure cycles

- Incorporate pressure variations in fatigue life assessment
 - Actively pursuing in-field pressure cycle data from HRS
- Incorporate autofrettage effects
- Identify gaps in experimental fatigue data needed to assess design life
 - Low ΔK
 - Variable amplitude testing (load-cycle history effects)

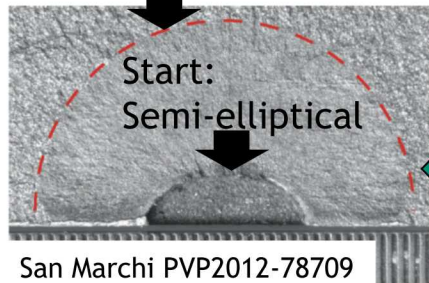
7 Accomplishments: Performed simulations of estimated tank life assuming variations in pressure cycles

Assumptions:

- ▮ Type 1 tank
- ▮ $P_{max} = 45 \text{ MPa}$
- ▮ $\Delta P = 15 \text{ MPa}$ or variable
- ▮ End of life ($a/t = 0.25$)
- ▮ $a_o = 0.86 \text{ mm}$
- ▮ OD= 238 mm
- ▮ $t = 14.4 \text{ mm}$



Finish:
Semi-circular



San Marchi PVP2012-78709

- ASME assumes conservative flaw shape (semi-elliptical) $a/2c = 1/3$
- Experimental evidence suggests flaws are semi-circular $a/2c=1/2$
 - Means reduced driving force which equal longer life

- Accounting for actual pressure ranges extends useful life of the tank by more than 1.7X (extends by ~ 5X if you account for flaw evolution)

Analysis of Type 2 tanks assuming 50% full pressure cycles



Table 1-2. Summary of Design Calculation Cases

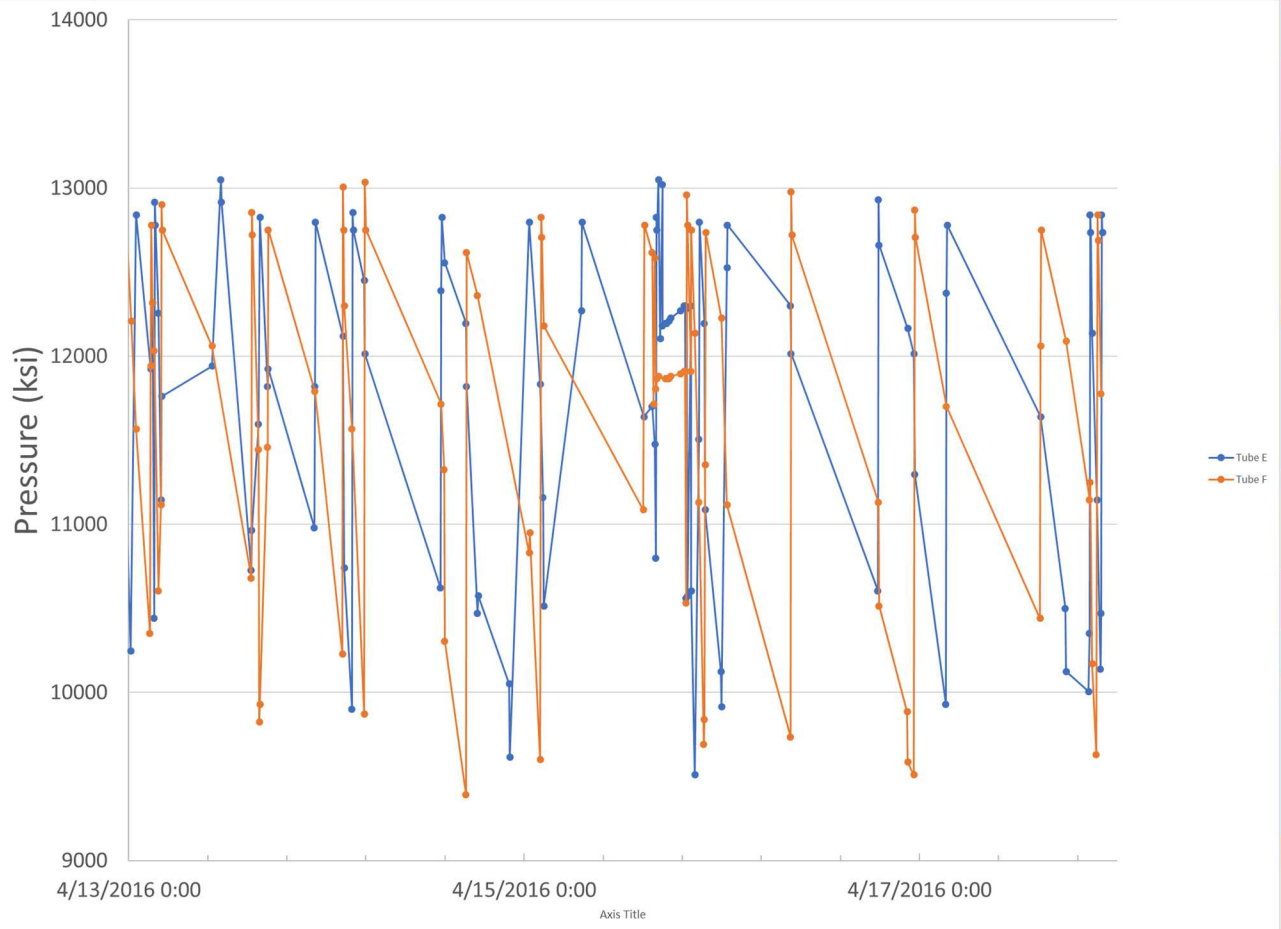
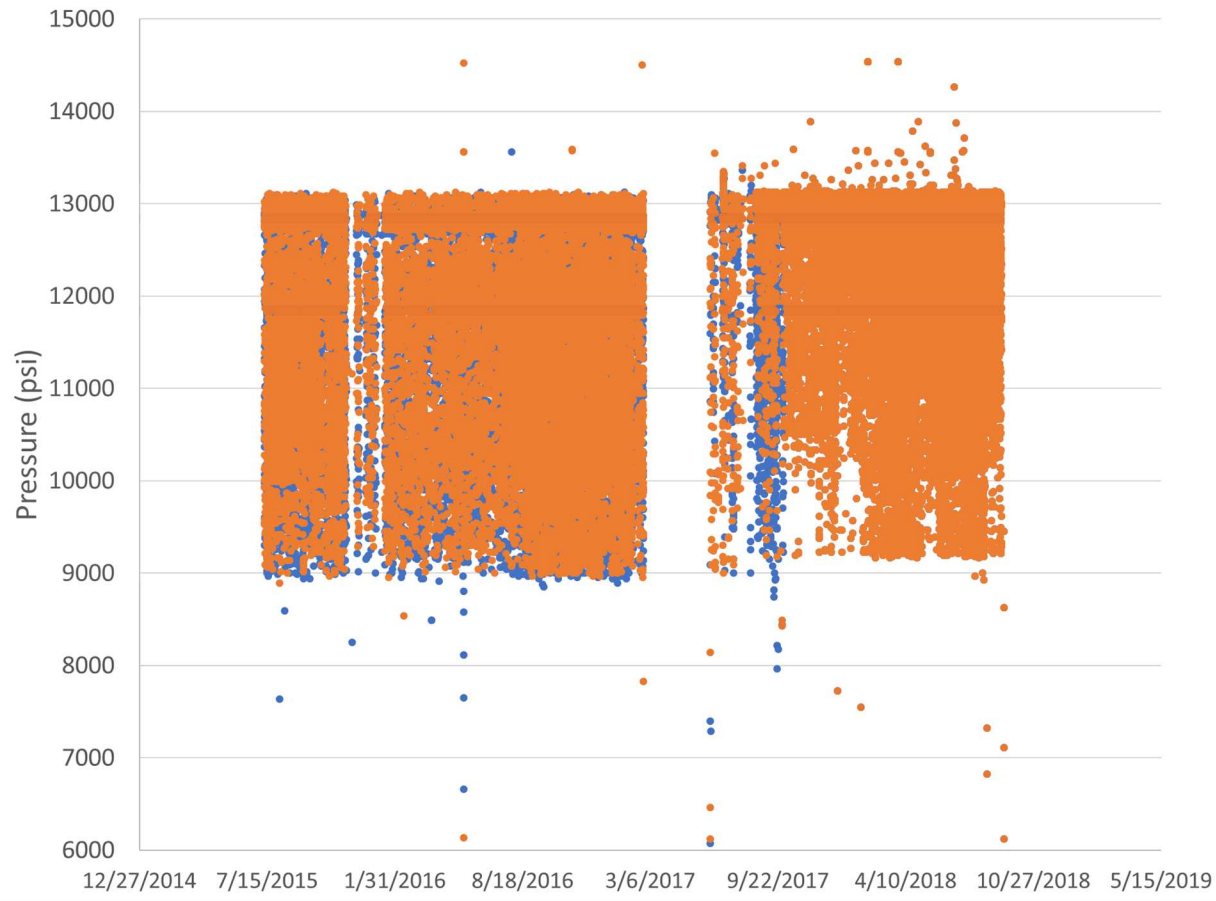
Case	Code	Primary Pressure Cycles	FAD Pressure	Total Design cycles
1. Original Design Basis (2010)	ASME VIII Div 3 2009	100% @ 8,900-13,500	14,850 psi	37,540
2. Rerun of 2010 Case in Becht web software (BechtFFS)	ASME VIII Div 3 2019	100% @ 8,900-13,500	14,850 psi	37,313
3. Updated with full pressure cycles	ASME VIII Div 3 2019 Code Case 2938	100% @ 8,900-13,500	16,500 psi	99,000
4. Updated with full and half cycles	ASME VIII Div 3 2019 Code Case 2938	50% @8,900-13,500 50% @ 11,000 – 13,500	16,500 psi	190,800

Diff due to design curves in Code Case 2938

Obtained Type 2 Hydrogen Refueling Station Data of two tanks



Tube E & F



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Issue: Type 2 composite-wrapped tanks reaching end of life criteria far sooner than anticipated

Design life: 37,500 cycles or 20 year (whichever comes first)

Pressure range: 13,500 psi (93 MPa) to 8,900 psi (61.3 MPa)

Reached cycle life in ~ 7 years



17"OD, 14'6" length with bores of 1.5" or 2-3/4".

No current NDE method to inspect metal liner of type 2 tanks, therefore tanks are retired

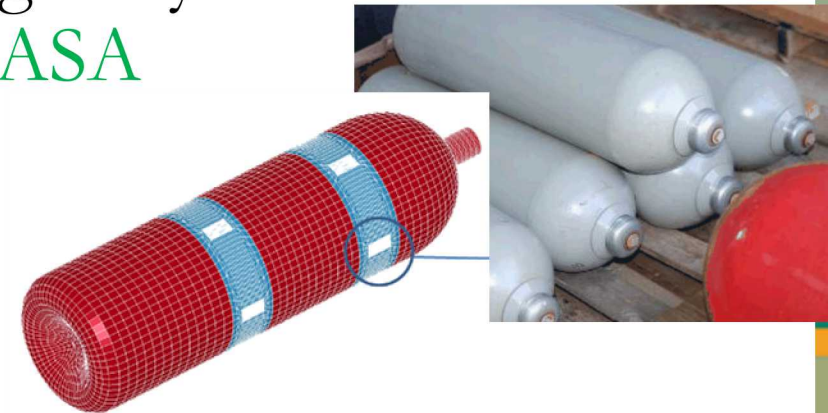
Project Objectives / Plan

1) Develop understanding of opportunity space for life extension:

- Influence of cycle range on estimated life – [Sandia & Becht](#)
- Perform ΔK_{th} testing in high pressure H₂ – [Sandia](#)
- Obtain industry data - ???

2) Assess defect population in end of life vessels

- Develop techniques for NDE for Type II tanks – [Digital Wave & NASA](#)
- Proof of principal - metal liner measurements using eddy current on Type 1 tanks with internal manufactured defects - [NASA](#)
- Inspection of Type 2 carbon-fiber – [Digital Wave](#)



3) Develop guidelines and protocols for life extension

- Could range from predictive tool that operators could employ to generic guidance on what cycles can be dismissed

→ Oversight/Input needed from industry on what this would look like

4) (*Stretch goal*) Experimental validation of life extension practice

- Pressure cycling of miniature vessels with engineered defects followed by NDE?

Result of this effort will be science-based justification for tank life-extension which can be adopted by industry and standards.

Other items to consider

Does spectrum loading have a measurable effect on tank life?

How do we capture evolution of residual stress in these vessels?

→ How does it evolve or diminish with cycling, with crack extension?

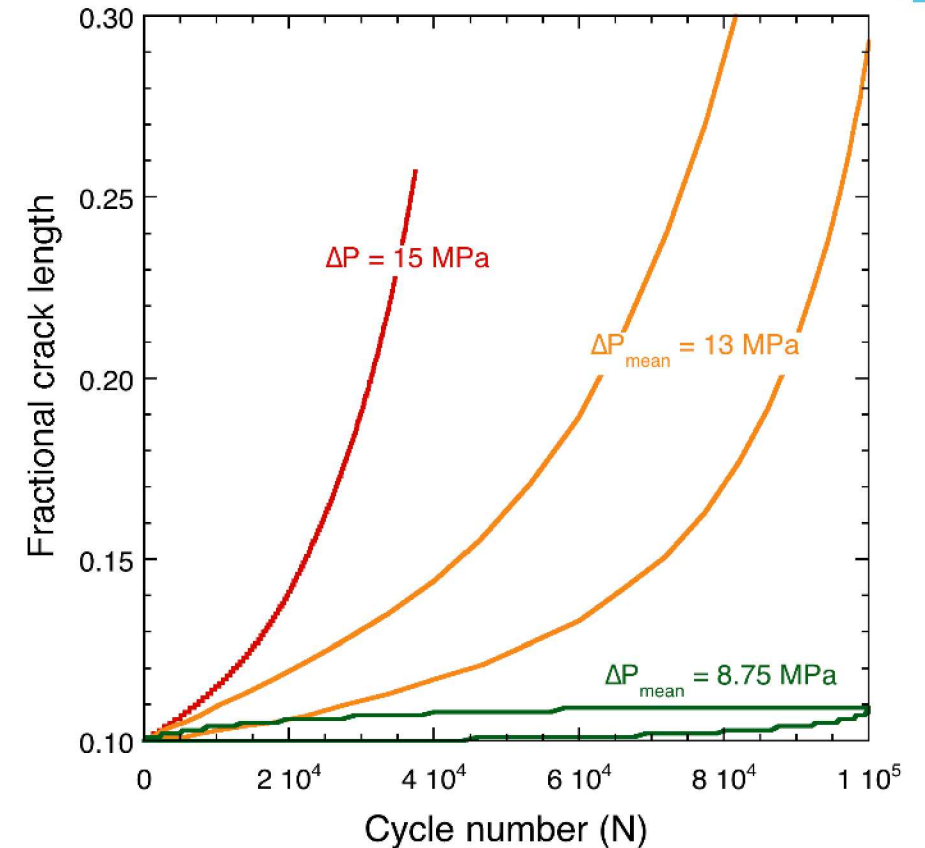
Lower mean = longer life AND lower ΔP earlier = longer life

Assumption:

- Cylinder: 238 x 15.9 mm (OD x t)
- Maximum pressure = 45 MPa
- ΔP is determined from distributions provided
- Initial defect is 6% of wall ($a/t = 0.06$)
- Life = cycles to grow defect to $a/t = 0.25$
- da/dN follows “master curves” for H2

Outcome:

- Red curve represents constant $\Delta P = 15$ MPa
- Two curves are shown for each distribution (estimated to be bounding behavior)
- Crack extension is strongly dependent on ΔP and its distribution
- In this case, worst case = ~34k cycles (constant ΔP), but cycle life is 2 to >5 (?) times greater for lower ΔP



Notes:

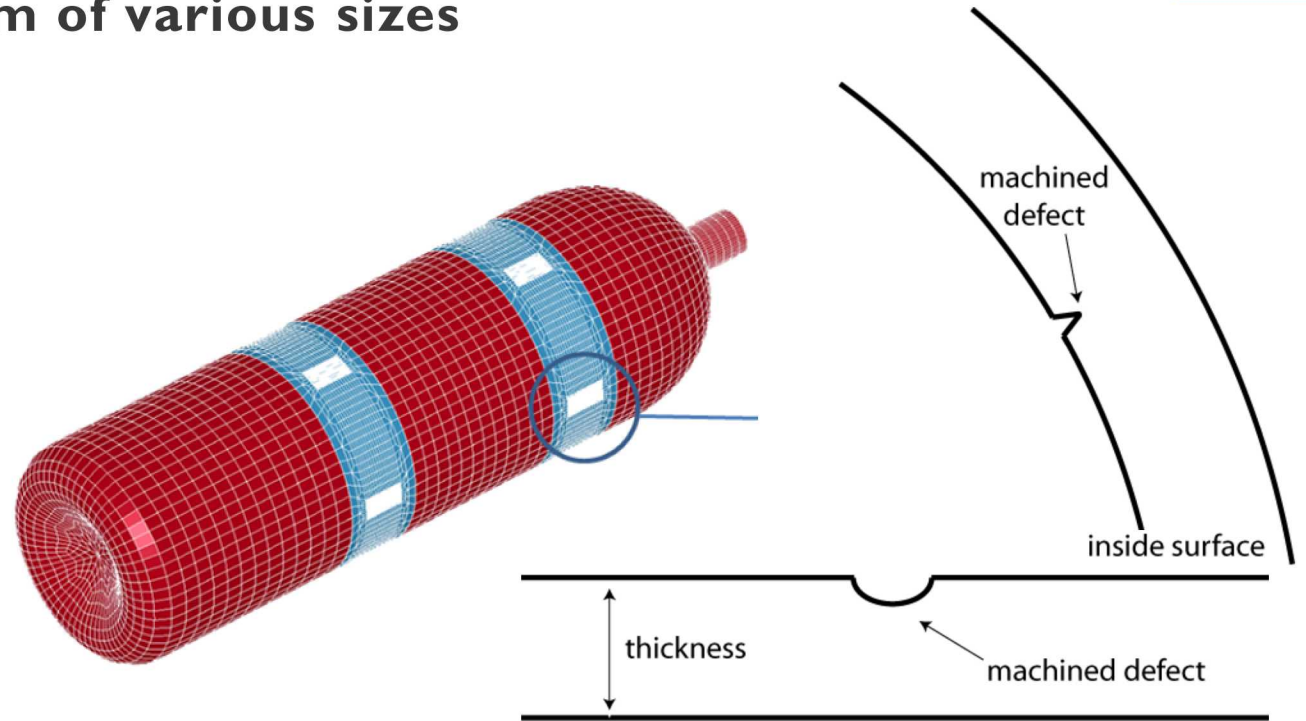
- Crack growth is dependent on order of application of pressure cycles
 - Here we assumed either accumulation of cycles from low to high ΔP (slower), or from high to low ΔP (faster)
 - Planning to calculate with random application of ΔP (within an assumed distribution)

Additional tanks could be used for development work – all steel (no overwrap)

9 tanks with machined defects in them of various sizes



Steel pressure vessels



Calibration block with machined defects

