SAND2020-6938PE

Tank Life Extension

Team: Joe Ronevich, Chris San Marchi, John Emery, Dusty Brooks

Sandia National Laboratories, Livermore, CA

Partners/Subcontracts with:

FIBA Technologies, Air Products, Linde/Praxair, Becht Engineering, Hexagon Digital Wave, NASA-WSTF, Luna Innovations

SCS Tech Team Meeting

July 9th, 2020

Overview

Timeline

- Project start date: Oct 2019
- Project end date: Sept 2021*

* Project continuation and direction determined by DOE annually

Technical Barriers

A. Safety Data and Information: Limited Access and Availability

G. Insufficient technical data to revise standards

Budget

FY20 DOE Funding: $600K

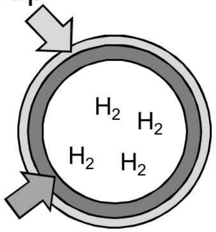
FY21 DOE Funding: $600K

Partners

- **SDO/CDO participation:** ASME committee members from industry
- **Industry:** Air Products, Linde/Praxair, Luna Innovations, FIBA Technologies
- **Subcontracts:** NASA-WSTF, Hexagon Digital Wave, Becht Engineering

Background / Approach:

Develop an understanding of opportunity space for life extension of high-pressure hydrogen vessels, initially focusing on Type 2 pressure vessels



Type 2 tanks are used at Hydrogen Refueling Stations (HRS)

Background:

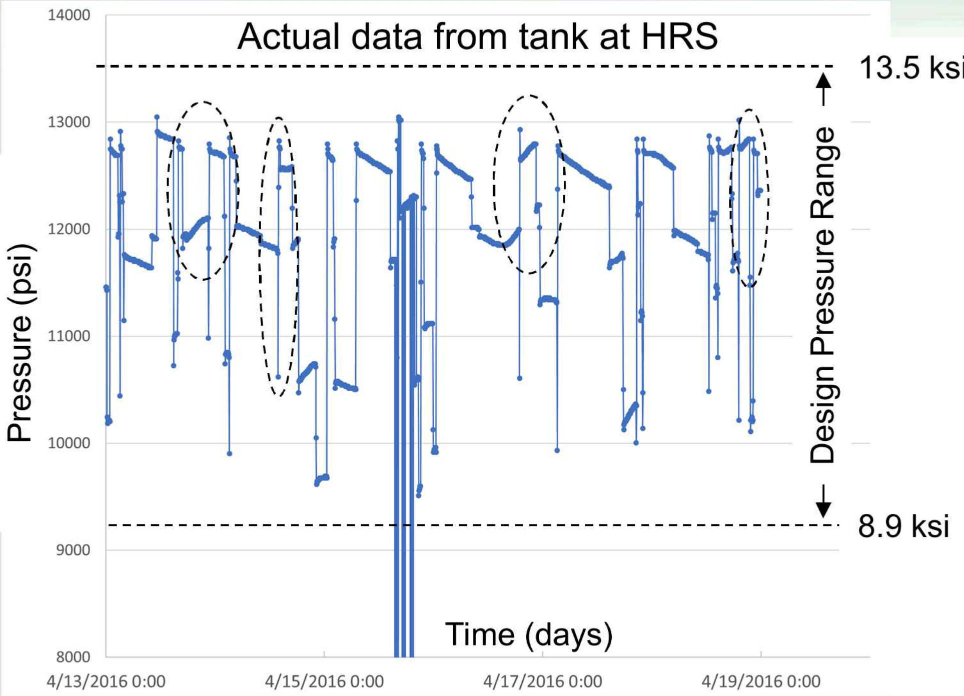
- Type 2 tanks have finite design life over certain pressure range
  - e.g. Pressure range 13,500 psi to 8,900 psi, Design Life = **37,540 cycles** or **20 yr**
- Tanks are reaching cycle limit *much sooner* than expected (e.g. 7 yr)
- Conventional non-destructive evaluation (NDE) methods to inspect metal liner are incompatible with overwrap; therefore no means to inspect, recertify, and extend life of tank → ***Result = tanks are retired***

Substantial savings can be achieved if:
1) Design methods can show longer life of tanks (***Design Methods***)
2) Tanks can be inspected to re-assess remaining life (***Inspection***)

Approach: Design Methods
Assessment of variable pressure cycles on projected design life of tanks

Industry is conservative and counts every refill of a tank = 1 cycle

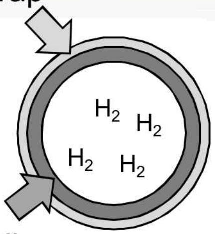
- Should ***partial*** cycles be counted the same as ***full*** cycles?



Identify margins through rigorous analysis of pressure cycles

- Analyze simulated pressure variations in fatigue life assessment
  - If available, incorporate in-field pressure cycle data from HRS
- Identify gaps in experimental fatigue data needed to assess design life
  - Low ΔK in gaseous H_2
  - Variable amplitude testing (load-cycle history effects) in gaseous H_2

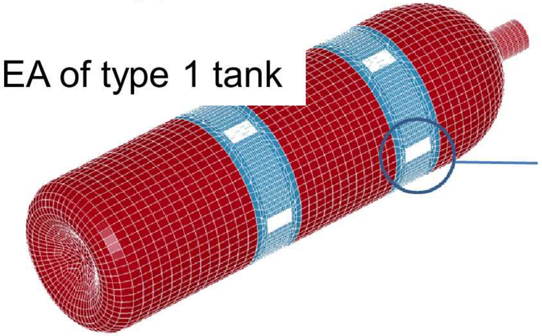
Approach: Inspection
NDE techniques for life assessment of metal liner (Type 2 tanks)



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 for detecting flaws in type 2 vessels


Type 1 tanks with internal flaws


FEA of type 1 tank


Calibration block of manufactured defects

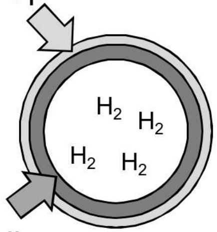
- Utilize type 1 tanks with manufactured defects on inner surface for proof of principle for EC technique
- Partnering with Hexagon Digital Wave and NASA-White Sands Test Facility for NDE development and measurements (subcontracts initiated in FY20 Q2-Q3)

NASA White Sands Test Facility

DIGITAL WAVE

Approach: Inspection
NDE techniques for life 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

DIGITAL WAVE

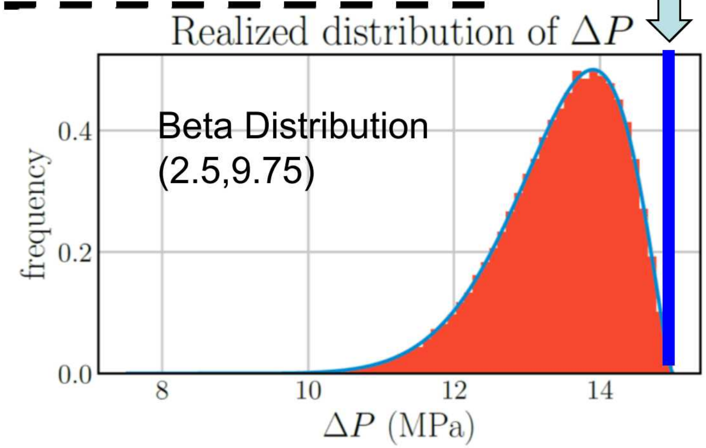
Benefits if Successful – Demonstration of a NDE technique capable of detecting flaws in metal liners of full-scale Type 2 tanks will facilitate life-extension via conventional life-extension practices (such as ASME PCC-3)

Task	Owner	FY 2020 Q1	FY 2020 Q2	FY 2020 Q3	FY 2020 Q4	FY 2021 Q1	FY 2021 Q2	FY 2021 Q3	FY 2021 Q4	Deliverable date
Design Methods										
Report evaluating fatigue life extension of Type 2 tanks using in-service operating data	Becht Engineering									6/30/2020
Provide in-service operation data (if available)	Air Products									On-going, more is welcome
Identify margins through data analysis of pressure cycles	Sandia									
Measure & document crack growth rates at low ΔK to provide guidance for cycle counting	Sandia									Complete
Identify gaps & perform experimental fatigue tests needed to assess design life	Sandia									6/30/2021
Document guidance for life extension based on cycle counting	Sandia									9/30/2021
Inspection										
Develop proof of principle non-destructive evaluation technique on Type 1 tanks with manufactured defects	NASA-WSTF									9/30/2020
Perform modal acoustic emission (MAE) on two type 2 tanks to inspect composite overwrap.	Hexagon Digital Wave									9/30/2020
Integrate internal Eddy Current (EC) inspection technology to inspect Type 1 tank	Hexagon Digital Wave									10/31/2020
Design and integrate internal Eddy Current to interface with Type 2 (14'6" long) tank.	Hexagon Digital Wave									3/31/2021
Develop & fabricate test coupons with fatigue cracks consistent with flaws in Type 2 tanks for NDE inspection	Sandia									3/31/2021
Perform NDE inspection on fatigue precracked coupons	TBD									9/30/2021

Accomplishments: Design Methods
Simulations show extended life for variable pressure cycles

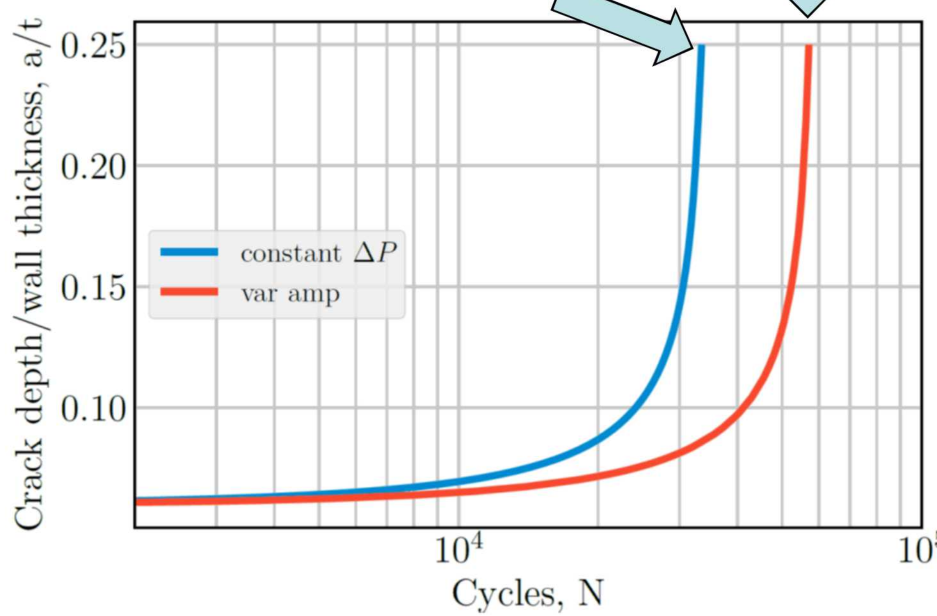
Assumptions:
- Type 1 tank
- P_{max} = 45 MPa
- ΔP = 15 MPa or variable
- End of life (a/t =0.25)
- a_o = 0.86 mm
- OD= 238 mm
- t = 14.4 mm

ΔP =15



ΔP =15 MPa
33k

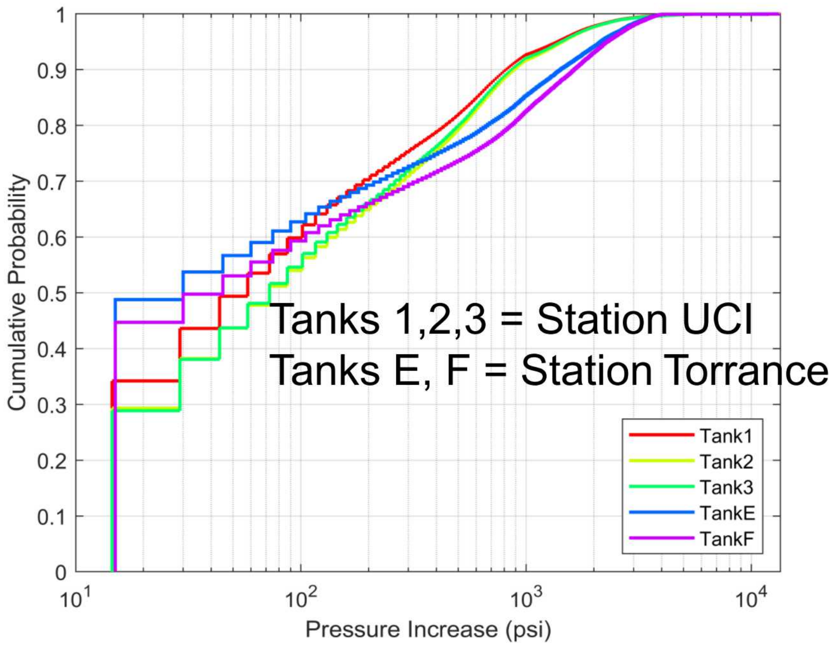
Variable ΔP
57k



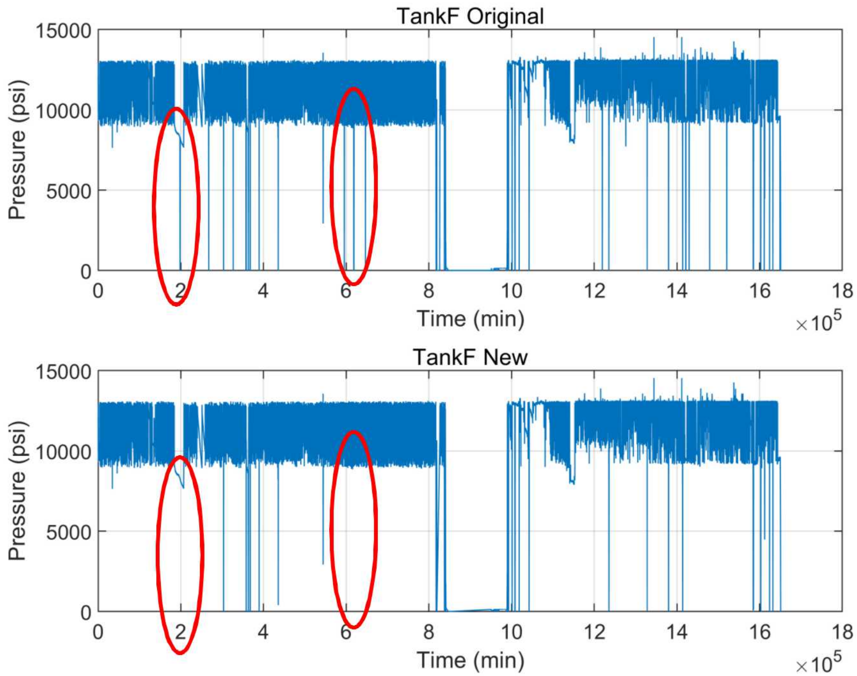
Design life of the tank is improved by a factor of more than 1.7X by incorporating variable pressure swings

In Progress: Design Methods
Acquired service data from two different HRS

Tanks within HRS appear self-similar



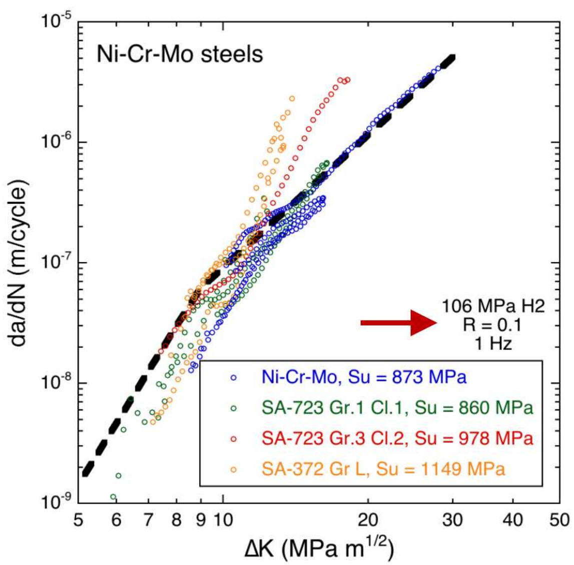
Data analysis to remove erroneous 0 psi (which can have large effect on estimated design life)

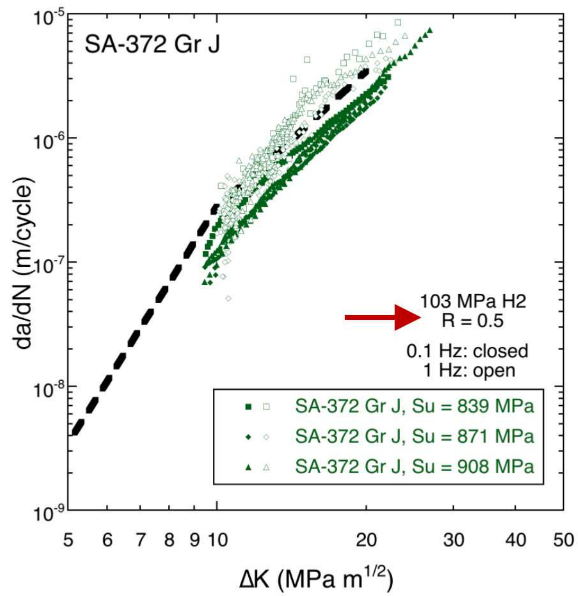


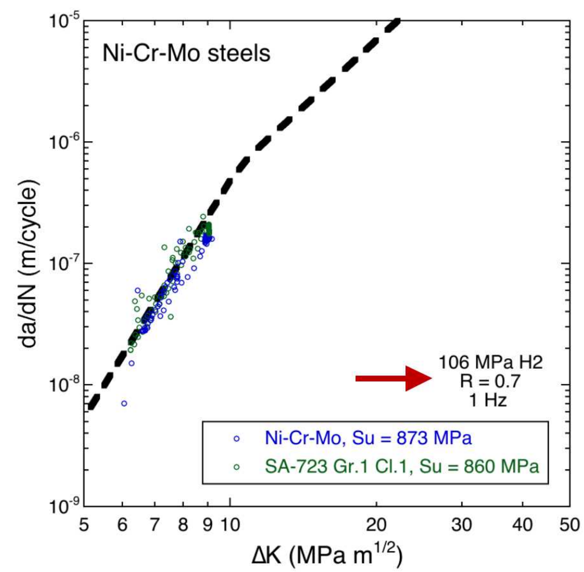
- Design life may be improved just by better accounting of the data
- By analyzing the data from multiple HRS, we hope to provide guidance on:
  - Sensitivity of design life to full blowdowns to 0 psi
  - Largest margins for improved design life

2019 Accomplishment (…but paying dividends): ASME Code Case 2938 approved

"Technical basis for proposed master curve for fatigue crack growth of ferritic steels in high-pressure gaseous hydrogen in ASME section VIII-3 code" (PVP2019-93907), Proceedings of the 2019 ASME Pressure Vessels & Piping Conference, 14-19 July 2019, San Antonio TX.



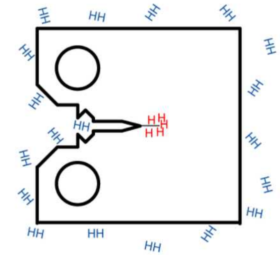




- **Provides design curve**

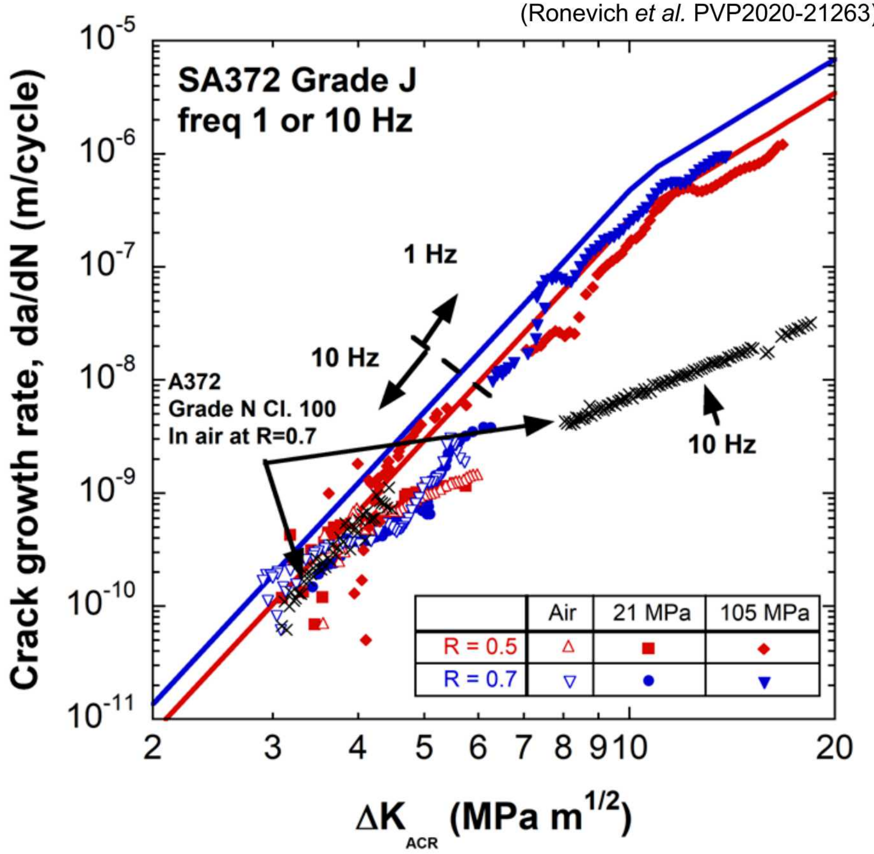
$$\frac{da}{dN} = C\left[\frac{1 + C_H R}{1 - R}\right]\Delta K^m$$

based on data and analysis from this program



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

(Ronevich *et al.* PVP2020-21263)



Operational ΔK_{th} (thresholds) were established to be between 3 and 4 MPa $m^{1/2}$ meaning da/dN values ~ 10^{-10} m/cycle → Practical engineering limits for infinite design life

Accomplishments: Design Methods
Code Case 2938 results in nearly 3X increase in design life

Subcontracted Becht Engineering to assess design life based for 2 different scenarios.

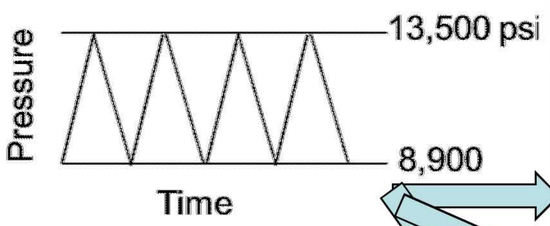
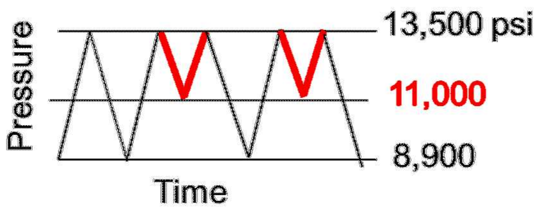


Table 1-2. Summary of Design Calculation Cases

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**

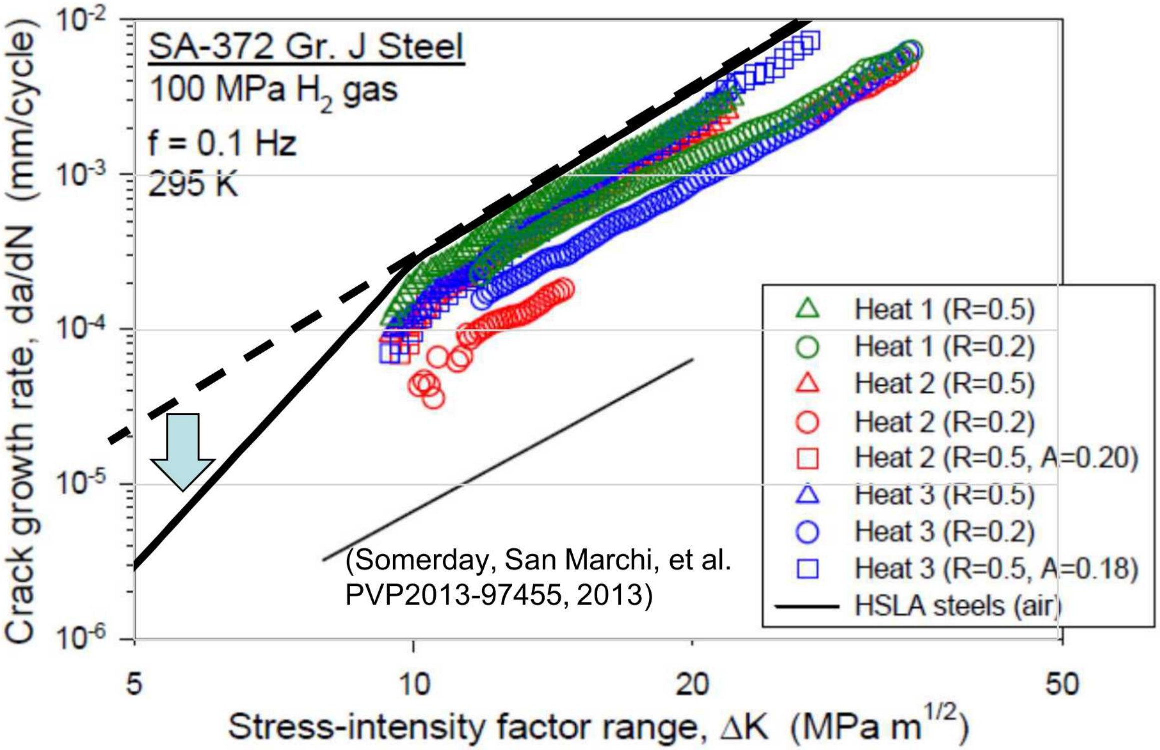
3X



Ref: E. Chant. Becht. "Evaluation of Fatigue Life Extension of High Pressure Hydrogen Cylinders using In-service Operating Data – Status Report 28901" (April 8th, 2020)

Reasons for extended design life: 1) Better data (Code Case 2938)
2) Reduced pressure swings (Assume 100% & 50% fills)

Accomplishments: Design Methods
More complete data sets have improved fidelity of design life predictions



- Designs in early 2010s needed to extrapolate data to lower ΔK
  - Unnecessary Conservatism
- Data were incorporated into ASME Code Case 2938 showed distinct ‘knee’ in curve and allows more accurate design.

Code Case 2938 results in more accurate design resulting in longer design life

Summary

- ***Design Methods***
  - Using ASME Code Case 2938 results in longer design life up to 3X compared to 2010 designs.
  - Analysis shows that more accurate accounting of simulated pressure cycles can extend useable life an additional 2X using simulated pressure cycles
  - Field operating data are currently being analyzed to perform similar evaluations of life extension
    - Analyzing trends among tank operating conditions at same HRS compared to different HRS to inform guidance of how to better account for pressure cycles
- ***Inspection***
  - Eddy current is being pursued as possible NDE technique for flaw inspection of Type 2 metal liners in partnership with NASA-WSTF, Hexagon Digital Wave
    - Both Type 1 and Type 2 tanks are being inspected
    - Composite overwrap is being inspected on Type 2 tank
- ***Extensive Industry Partnerships***

- FIBA Technologies- Material, tank fabricator
- Air Products – Type 2 tanks, in-field data
- Becht Eng – engineering analysis, ASME
- Linde/Praxair – ASME guidance, experience
- Hexagon Digital Wave – NDE measurements
- NASA-WSTF – NDE measurements
- Luna Innovations – NDE developer

Proposed Future Work

Remainder of FY20

- ***Design Methods***
  - Becht Engineering will provide report contrasting design life using design pressure range versus actual pressure ranges
  - Perform parametric studies to identify margins in design life
  - Identify gaps in experimental fatigue data necessary to improve design guidance
- ***Inspections***
  - Modal Acoustic Emissions (MAE) of Type 2 tanks to evaluate overwrap integrity
  - Establish proof of principle that eddy current technique is a viable means of detecting flaws on metal liner in Type 2 tanks (NASA-WSTF, Digital Wave)
  - Identify coupon geometry for evaluating NDE techniques on fatigue precracked coupons.

Proposed Future Work

FY21 (Likely carryover several items from FY20)

- ***Design Methods***
  - Parametric studies to identify margins for design life extension
  - Document guidance for life extension based on cycle counting
  - Perform fatigue testing to address experimental gaps identified
- ***Inspections***
  - Design and integrate internal Eddy Current system for measurements of large scale Type 2 tanks (Hexagon Digital Wave)
  - Produce test coupons with fatigue precracks to demonstrated that NDE technique can detect fatigue cracks

Remaining Challenges and Barriers

- Stationary pressure vessels remain a design challenge
  - Design strategies are conservative with limited allowance for life extension
- Consensus on codes and standards
  - Consensus has always been a significant challenge and requires patience and sustained interaction
  - Identifying most impactful avenue for getting acceptance in codes
    - ASME is very conservative
    - Identifying trends based on limited data sets, uncertain if we can build sufficient case to satisfy a code change.

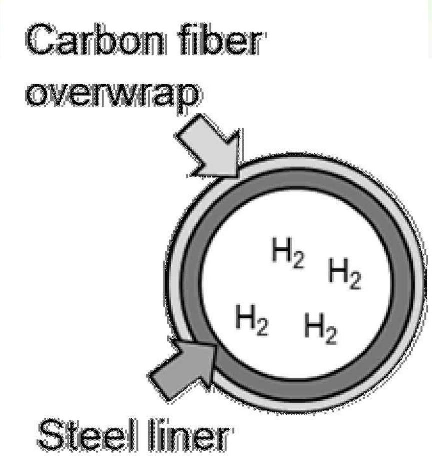
Publications and Presentations (selected)

Publications

- J. Ronevich, C. San Marchi, K. Nibur, P. Bortot, G. Bassanini, M. Sileo, "Measuring fatigue crack growth behavior of ferritic steels near threshold in high pressure hydrogen gas," (PVP2020-21263), Proceedings of the 2020 ASME Pressure Vessels & Piping Conference, 19-24th July 2020, Minneapolis, MN.
- C. San Marchi, J. Ronevich, P. Bortot, Y. Wada, J. Felbaum, M. Rana: "Technical basis for proposed master curve for fatigue crack growth of ferritic steels in high-pressure gaseous hydrogen in ASME section VIII-3 code" (PVP2019-93907), Proceedings of the 2019 ASME Pressure Vessels & Piping Conference, 14-19 July 2019, San Antonio TX.

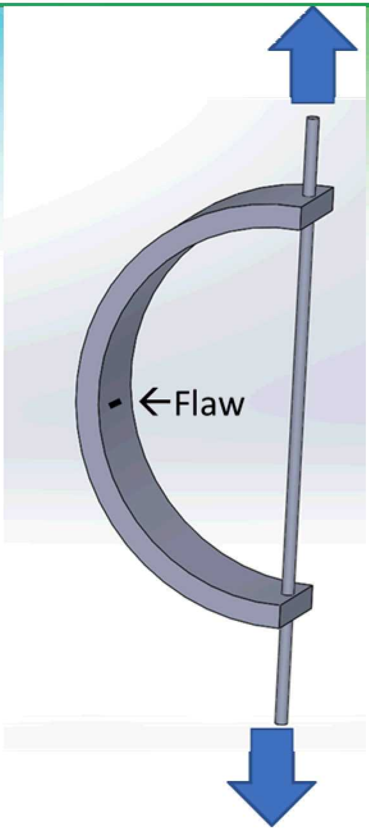
Back up slides

Evaluate NDE ability to detect fatigue precracked flaw



Autofrettage – puts steel liner under compressive loads to reduce crack nucleation/propagation

Challenge: detecting crack while faces are under compression might be more difficult

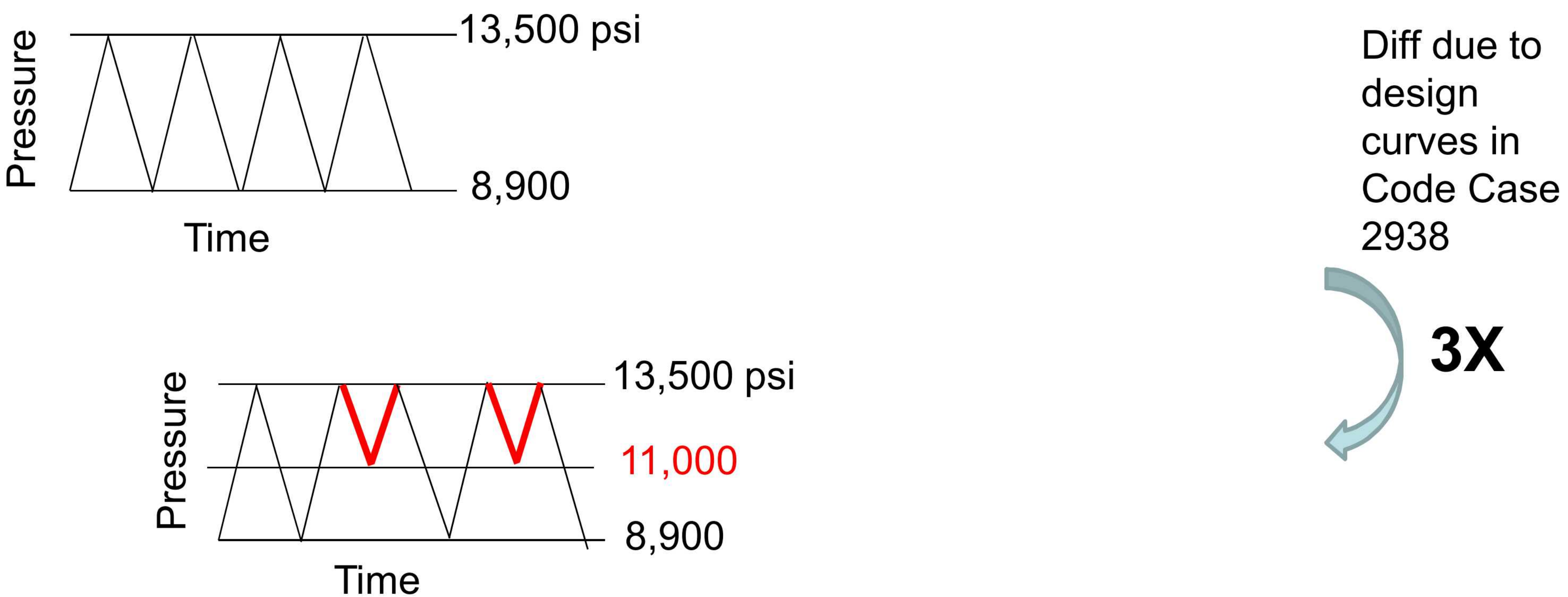


Approach

- Remove a C-section of tank and machine small starter flaw
- Put threaded bolt through ends to place ring under compression using bolts.
- Cycle under tensile fatigue to grow a fatigue precrack
- Leave tank under compression and inspect flaw

Accomplishments: Design Methods
Code Case 2938 results in nearly 3X increase in design life

Subcontracted Becht Engineering to assess design life based for 3 different scenarios.



Ref: E. Chant. Becht. "Evaluation of Fatigue Life Extension of High Pressure Hydrogen Cylinders using In-service Operating Data – Status Report 28901" (April 8th, 2020)