



Lift-Truck Tank Testing and Analysis

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Project ID # SCS012

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Overview

Timeline

- Project start date: Jan. 2010
- Project end date: May 2011
- Percent complete: 80%

Budget

Total project funding (to date)

DOE share: \$1.6M

FY10 Funding: \$1.3M

FY11 Planned Funding: \$0.3M

Barriers & Targets

- Barriers & targets addressed
 - Materials reference guide for design and installation
 - Hydrogen storage tank standards for portable, stationary, and vehicular use
 - Insufficient technical data to revise standards

Partners

- Collaborators
 - CSA (HPIT1 working group)
 - Nuvera
 - Plug Power
 - Norris Cylinder



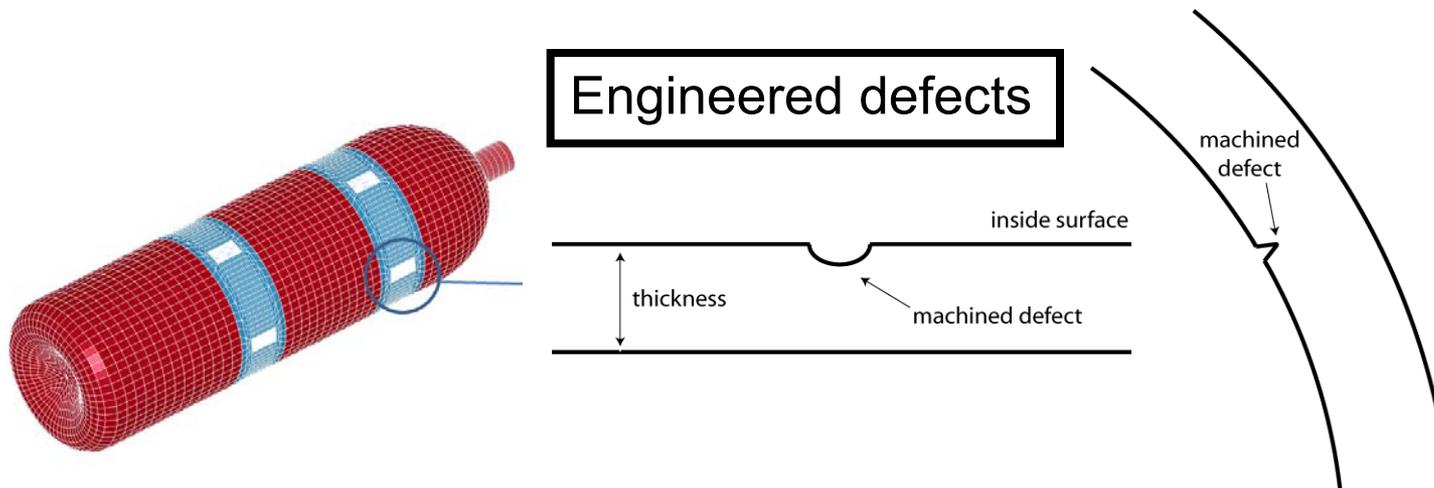
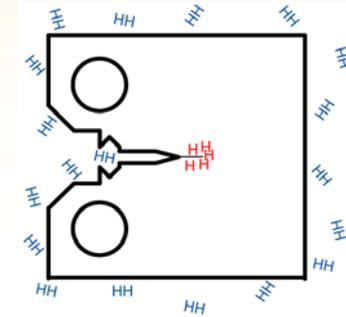
Objectives/Relevance

- Provide technical basis for the development of standards defining the use of steel (type 1) storage tanks
 - **Engineering Analysis Method**: validate fracture mechanics-based design approach in ASME BPVC Sec VIII, Div 3, Article KD-10
 - **Performance Evaluation Method**: provide data to help determine if time for crack initiation can be reliably credited in design qualification process
 - Quantify failure characteristics, such as *leak-before-break*
- Participate directly in standards development
 - Component design standards
 - ASME BPVC Sec VIII, Div 3, Article KD-10
 - CSA Hydrogen-Powered Industrial Trucks (HPIT1) working group



Approach: Full-scale tank testing including tanks with engineered defects to inform failure criteria

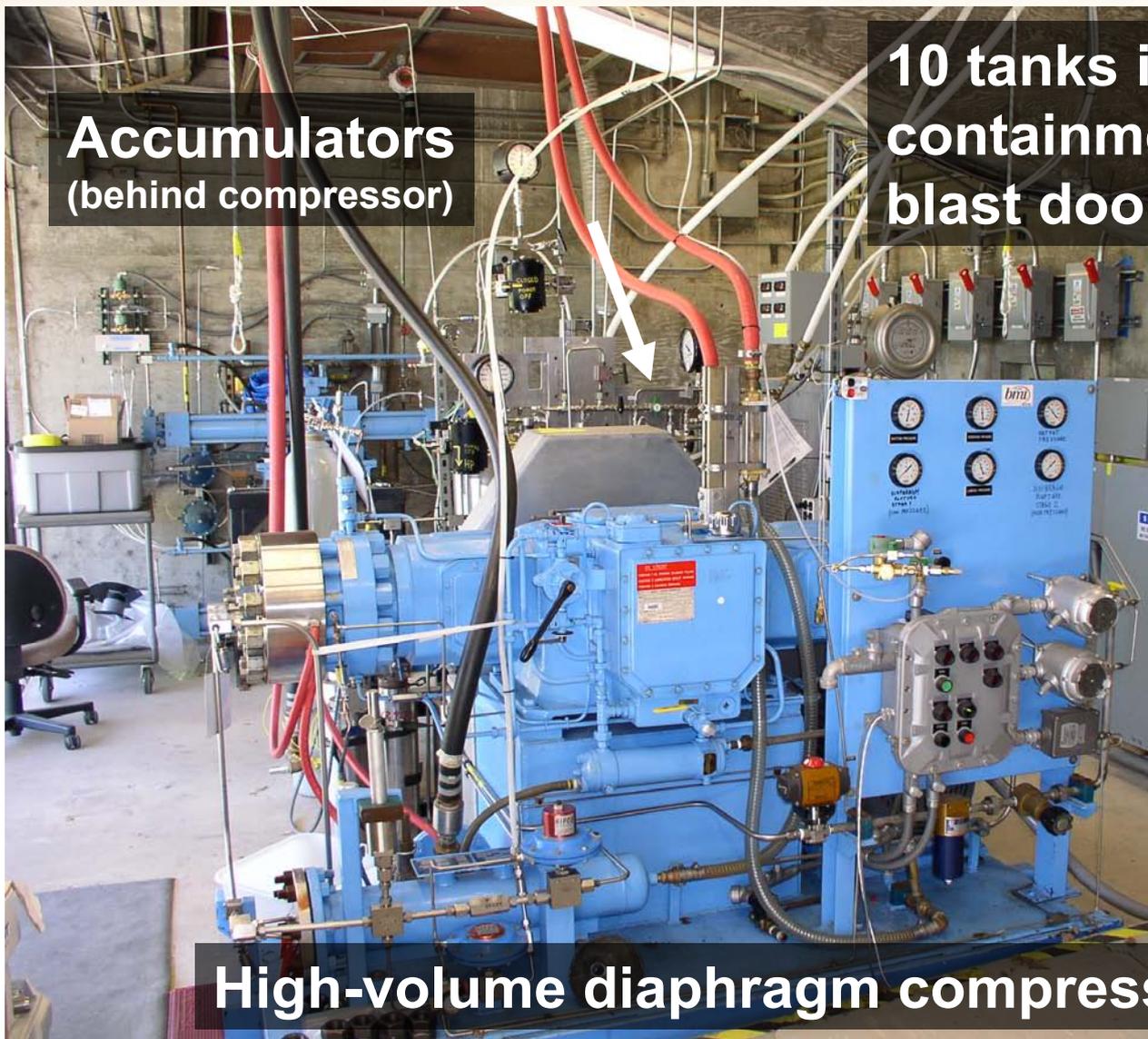
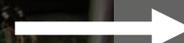
- **Materials testing**
 - Measure rate of crack growth
 - Inform engineering analysis method
- **Full-scale tank testing**
 - Develop methods for performance evaluation
 - Assess crack initiation (using engineered defects)
 - Evaluate leak-before-break
- **Contribute to codes and standards writing processes**



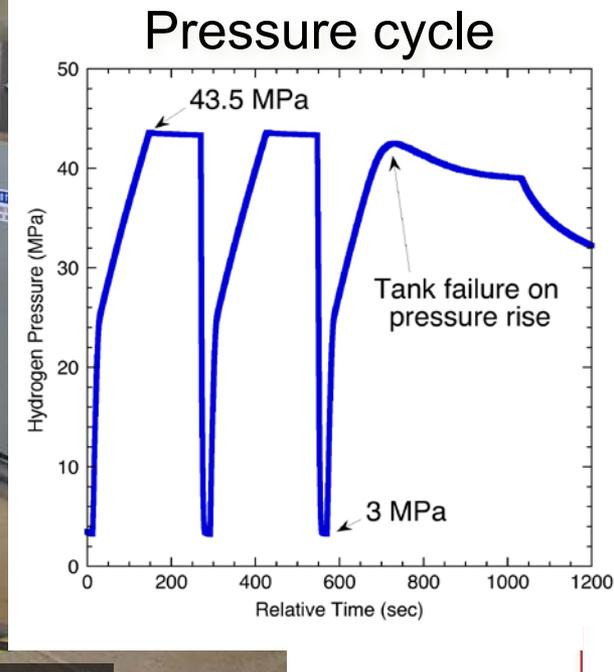
Approach: Full-scale testing requires significant infrastructure and maintenance

Accumulators
(behind compressor)

10 tanks in secondary containment behind blast door



High-volume diaphragm compressor



Technical Accomplishments and Progress

Applied research

- Fatigue crack growth testing of tank materials shows engineering predictions to be conservative relative to tank testing results
- Built infrastructure for accelerated pressure cycling of steel hydrogen storage tanks
- Pressure cycling of **two tank designs** is still in progress
 - T1 design: >29,000 cycles and counting (3 tanks)
 - T2 design: >8,600 cycles and counting (1 tank)
- Pressure cycling with **engineered defects** to quantify effects of existing flaws
 - Two failures observed (stable through-wall cracks)
 - Greater number of cycles to failure than predictions

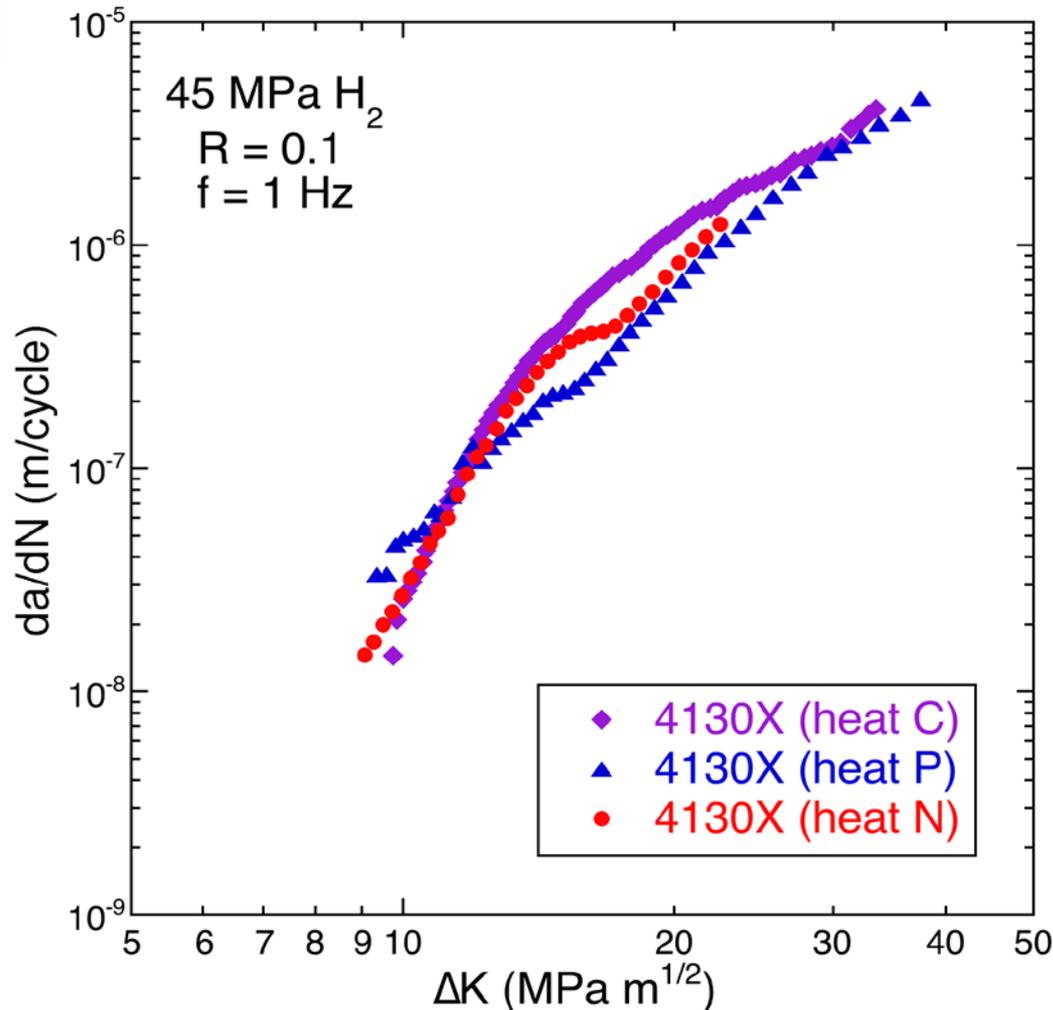
Standards development activities

- Procedures for tank testing are being included in **CSA HPIT1** and **SAE J2579** working documents for performance testing



Technical Accomplishments and Progress

Fatigue crack growth rates measured in gaseous hydrogen are used for *engineering analysis*

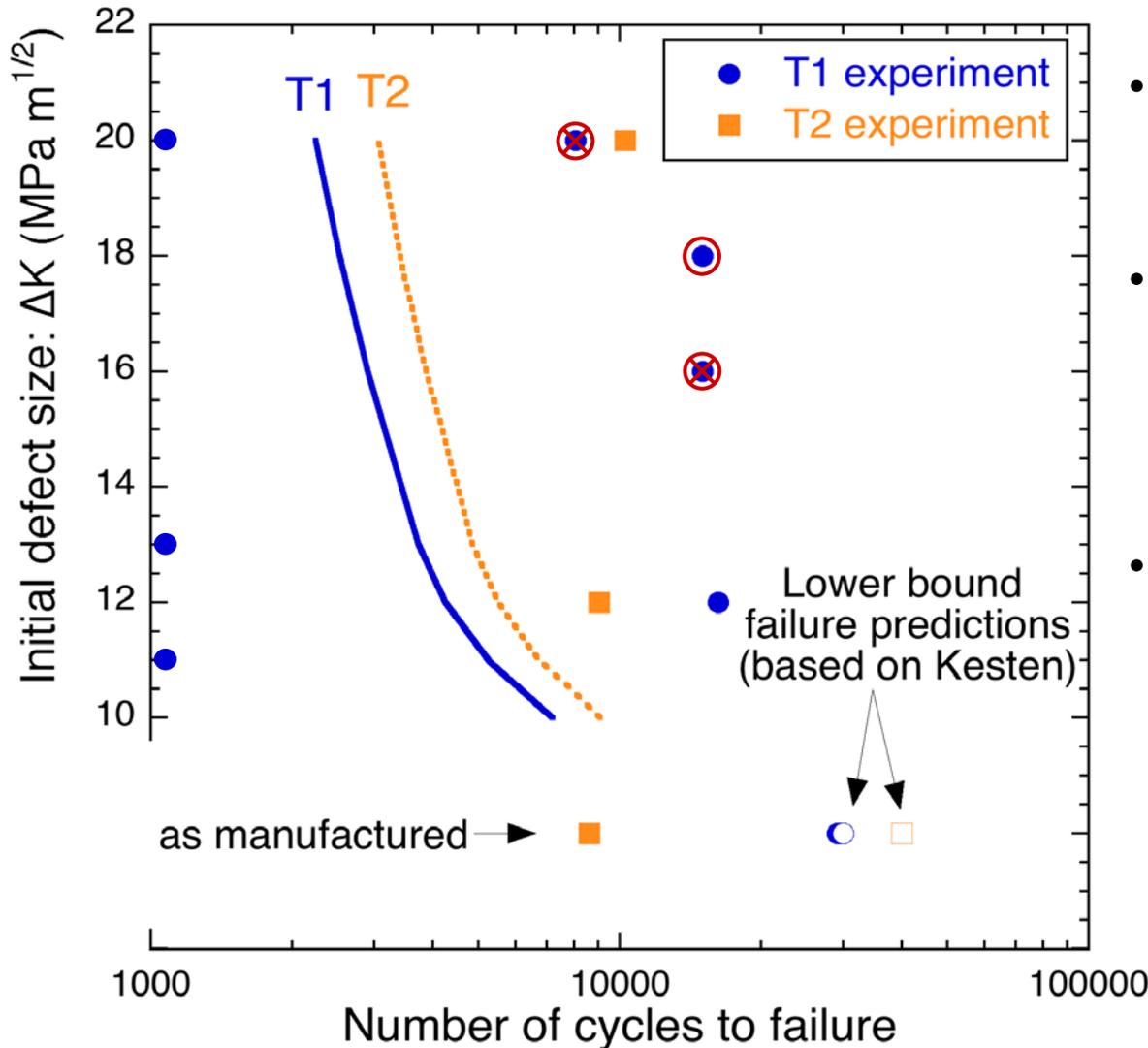


- Fatigue crack rates for 4130 steel from 3 different sources show similar response
- Results can be used to quantitatively predict *crack growth*
- Currently, there is no broadly accepted way to account for crack initiation (depends on many variables that are difficult to quantify)



Technical Accomplishments and Progress

Engineering analysis can be very conservative



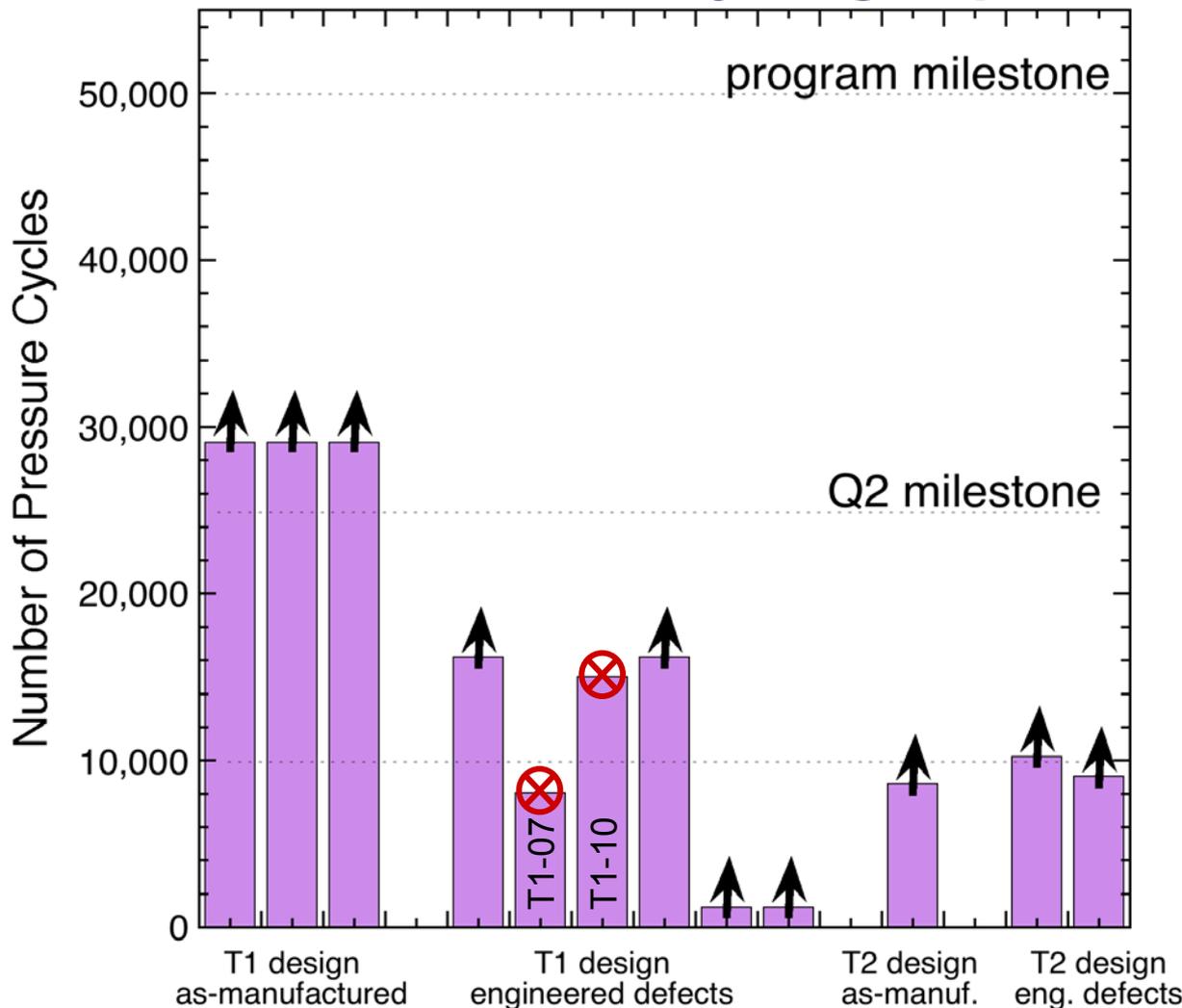
- failure = *initiation* + *crack growth*
- curves are predictions based on *crack growth* only (engineering analysis)
- lower bound failure prediction for as-manufactured vessels based on literature results (performance evaluation)

Kesten & Windgassen: in *Hydrogen Effects in Metals*, The Metallurgical Society of AIME (1981) p. 1017-1025.



Technical Accomplishments and Progress

Commercial vessels have been subjected to a large number of hydrogen pressure cycles



- Arrows indicate tanks that are currently cycling

- Cycles as of April 10, 2011

T1-07

- failure after 8,000 cycles
- prediction: ~2,250 cycles

T1-10

- failure after 15,000 cycles
- prediction: 2,500 to 2,900 cycles



Technical Accomplishments and Progress

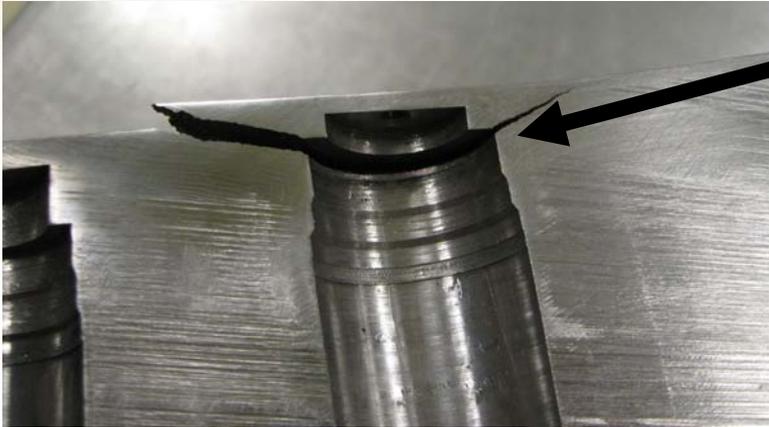
Maintaining infrastructure for tank cycling has been challenging

- Free-piston compressors have limited life (impractical)
- Diaphragm compressor head failed due to hydrogen embrittlement
 - resolution:* compressor successfully re-engineered
- Structural failure of compressor due to heavy duty cycle
 - resolution:* compressor rebuilt
- Internal components in ball valves continue to fail, causing unacceptable leakage of hydrogen
 - resolution:* re-engineer or replace frequently
- O-ring closure on vessels can be problematic leading to o-ring extrusion and loss of contents
 - resolution:* appropriate materials selection and “gap management”
- Leakage around fittings on bottles (presumably due to large strains associated with large pressure amplitude)



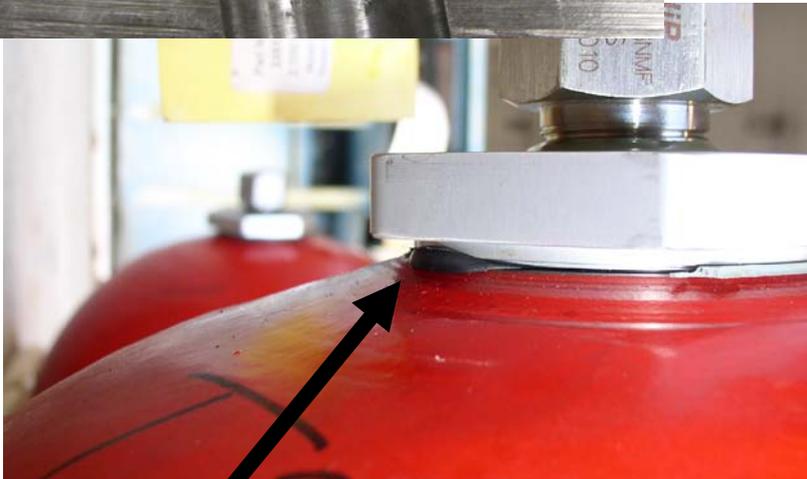
Technical Accomplishments and Progress

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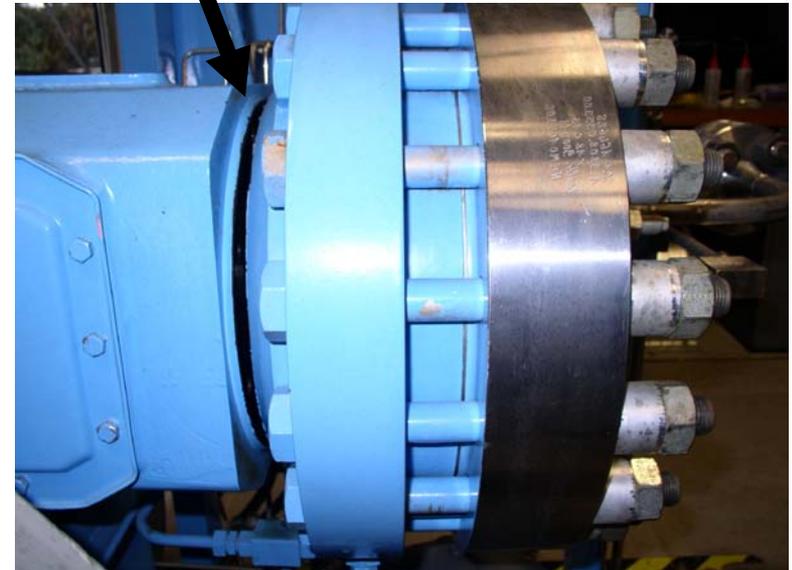


Hydrogen embrittlement emanating from sharp corner in compressor head (materials selection)

Structural failure of compressor due to heavy duty cycle (fatigue failure)



O-ring extrusion between fitting and tank (gap management for o-ring closures)



Collaborations

CSA working group: Compressed Hydrogen Powered Industrial Truck On-board Fuel Storage and Handling Components (HPIT1)

- Peer-review of testing plan and guidance on relevance
- Coordinated with UL activities

Fuel Cell and Hydrogen Energy Association: Fork Lift Task Force

- Peer-review of testing plan and guidance on relevance

Tank manufacturers

- Production of tanks
- Coordination of production/machining of engineered defects

Two system integrators for lift trucks: Nuvera & Plug Power

- Peer-review of testing plan and guidance on relevance to lift truck application as well as standards development



Proposed Future Work

- Primary aim of the remainder of program is to cycle tanks until they fail or reach 50,000 cycles
- Results will be shared with CSA HPIT1 TAG to formalize two design methods:
 - Engineering analysis: design using materials properties
 - Performance testing: qualification using full-scale component testing
- Additional work will depend on tank failures and remaining funding:
 - Evaluate leak-before-break criterion based on observed failures
 - Quantify distribution and activation of defects in vessels using failure analysis tools
 - Quantify crack initiation to the extent possible



Summary

- Commercial pressure vessels being used for hydrogen storage on lift trucks have been subjected to more than 25,000 pressure cycles with gaseous hydrogen and a peak pressure of 43.5 MPa.
- Fatigue crack growth assessment of existing flaws in these pressure vessels using industry standards (engineering analysis) appears to be conservative
 - Cycles to failure due to engineering defect >3 times predicted value
- Code language based on the test methods developed in this study are being drafted as part of CSA HPIT1 and SAE J2579 for performance based tests
- Evaluation of crack initiation and leak-before-break is underway for failed vessel
- Significant experience associated with heavy duty cycles imposed on infrastructure for gaseous hydrogen has been acquired (compressor performance, robustness of o-ring closures, selection of materials of construction)

