Lift-Truck Tank Testing and Analysis

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Sandia is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000

Project ID # SCS012

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Overview

Timeline

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

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

Budget

Total project funding (to date)
DOE share: $1.6M
FY10 Funding: $1.3M
FY11 Planned Funding: $0.3M

Partners

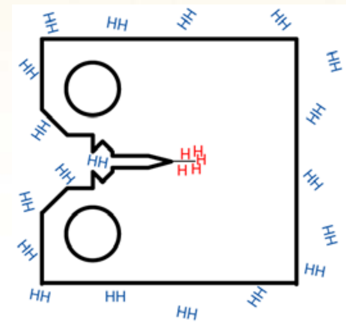
- Collaborators
  - CSA (HPIT1 working group)
  - Nuvera
  - Plug Power
  - Norris Cylinder

Objectives/Relevance

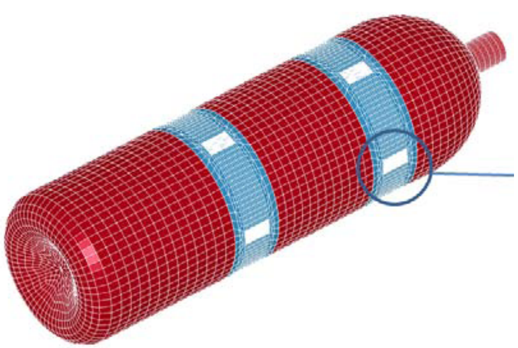
- Provide technical basis for the development of standards defining the use of steel (type 1) storage tanks
  - **Engineering Analysis Method**: validate fracture mechanics-based design approach in ASME BPVC Sec VIII, Div 3, Article KD-10
  - **Performance Evaluation Method**: provide data to help determine 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

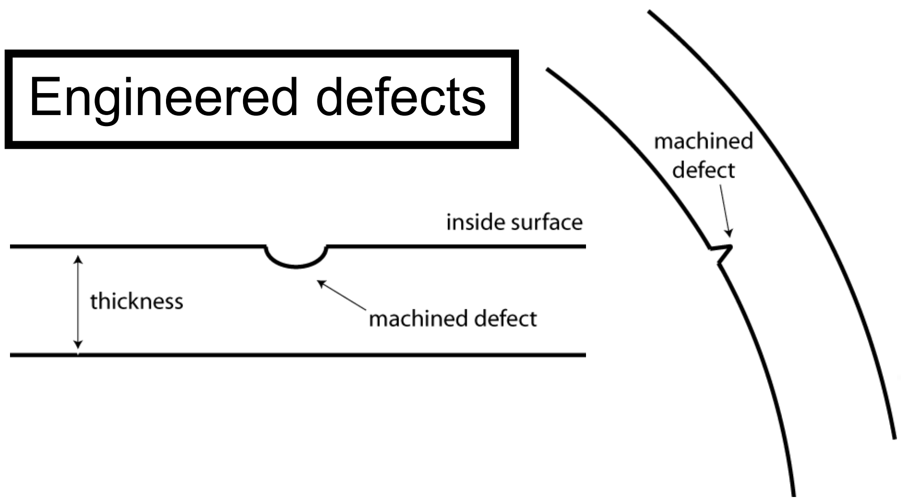
Approach: Full-scale tank testing including tanks with engineered defects to inform failure criteria

- 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





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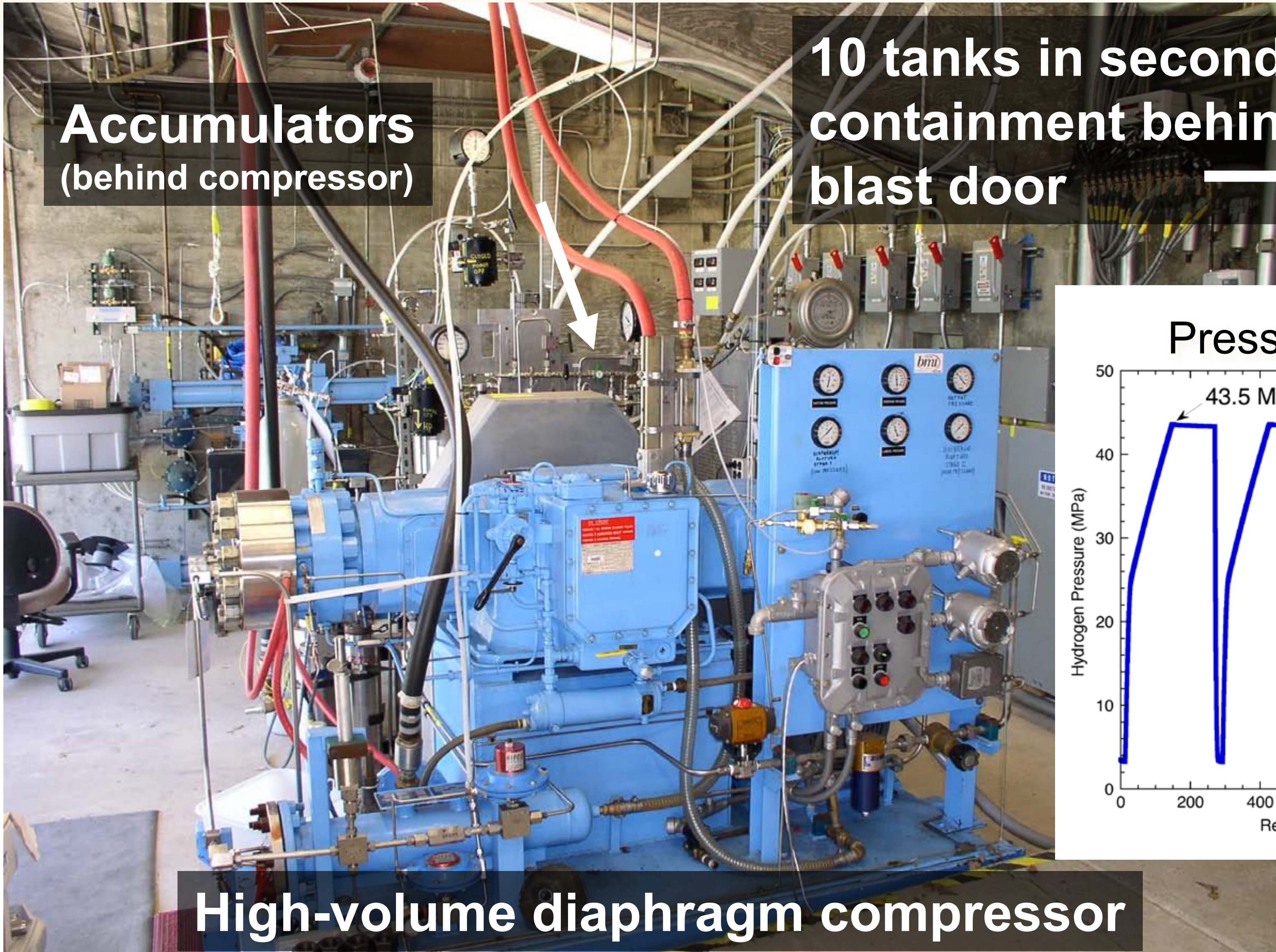
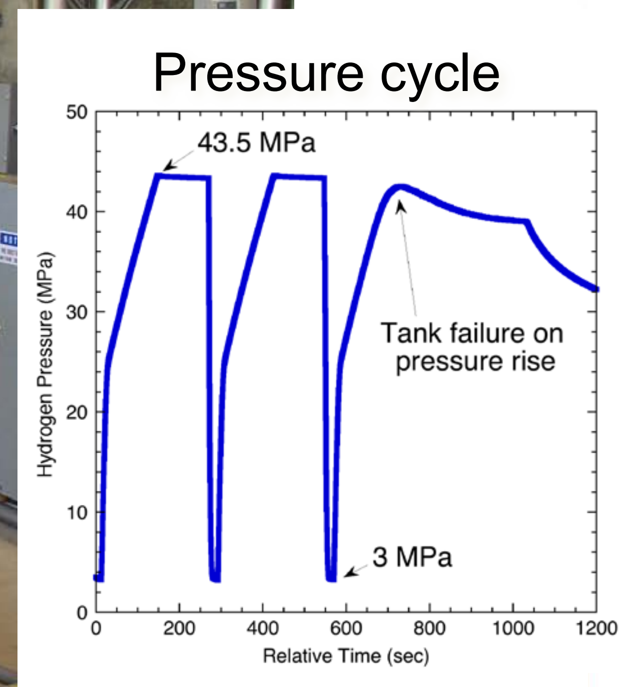
Approach: Full-scale testing requires significant infrastructure and maintenance





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

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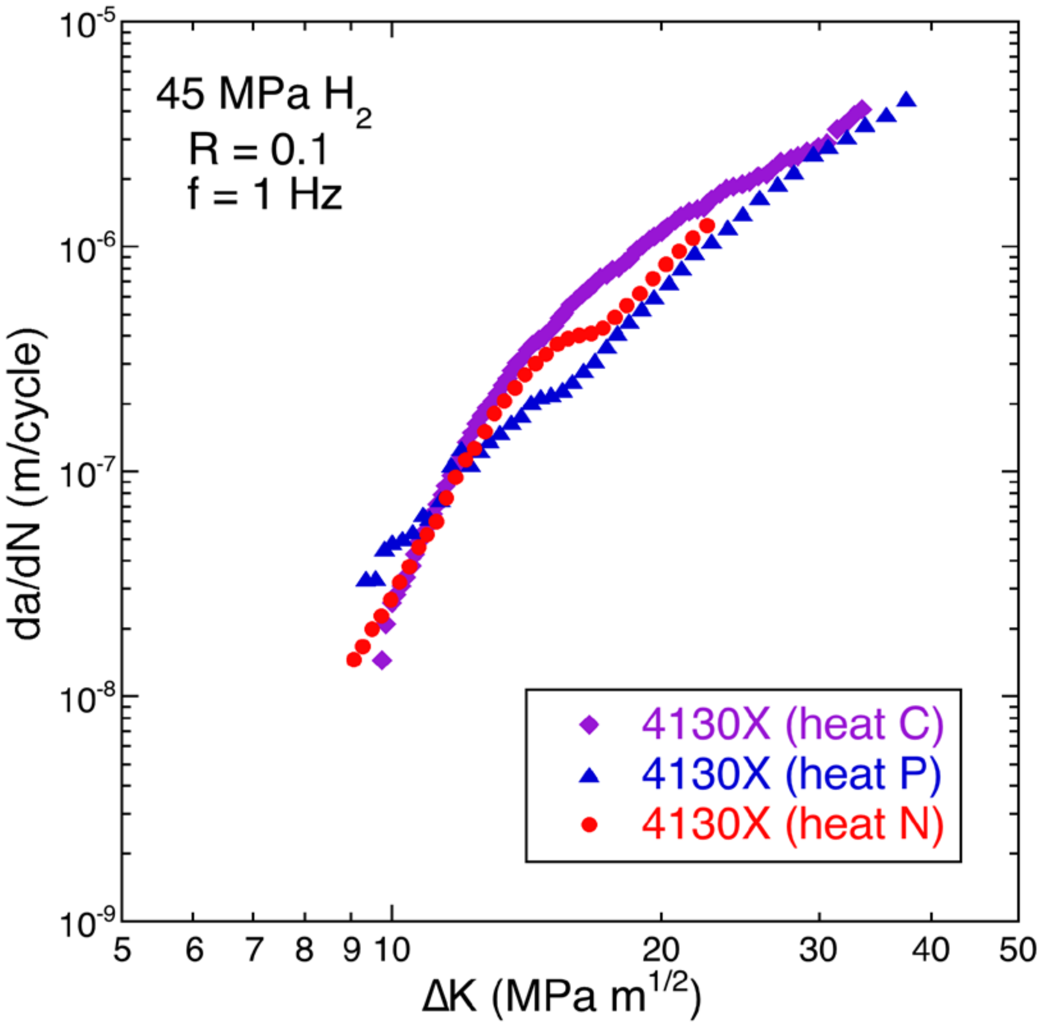
Technical Accomplishments and Progress

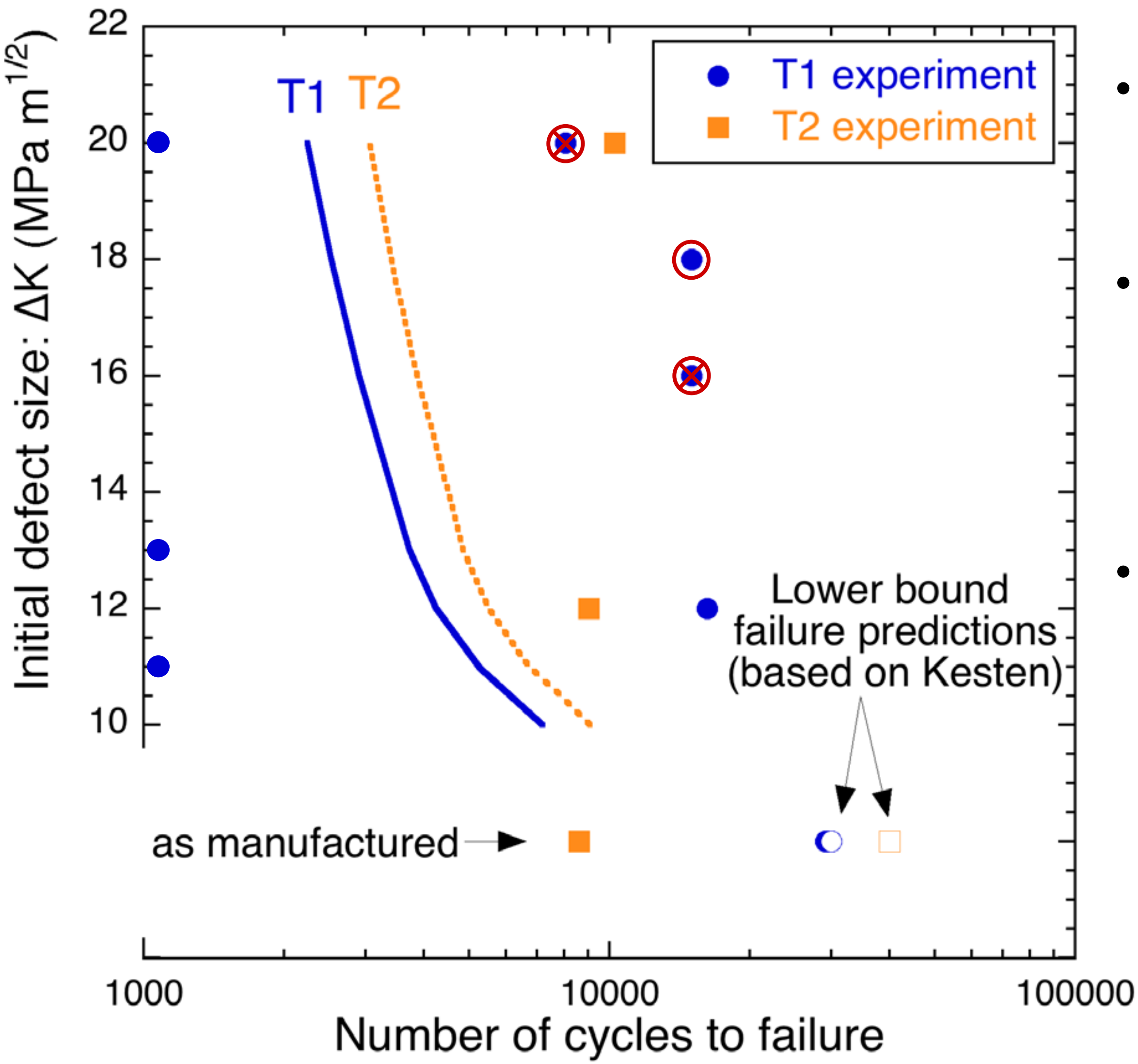
Fatigue crack growth rates measured in gaseous hydrogen are used for *engineering analysis*



- 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

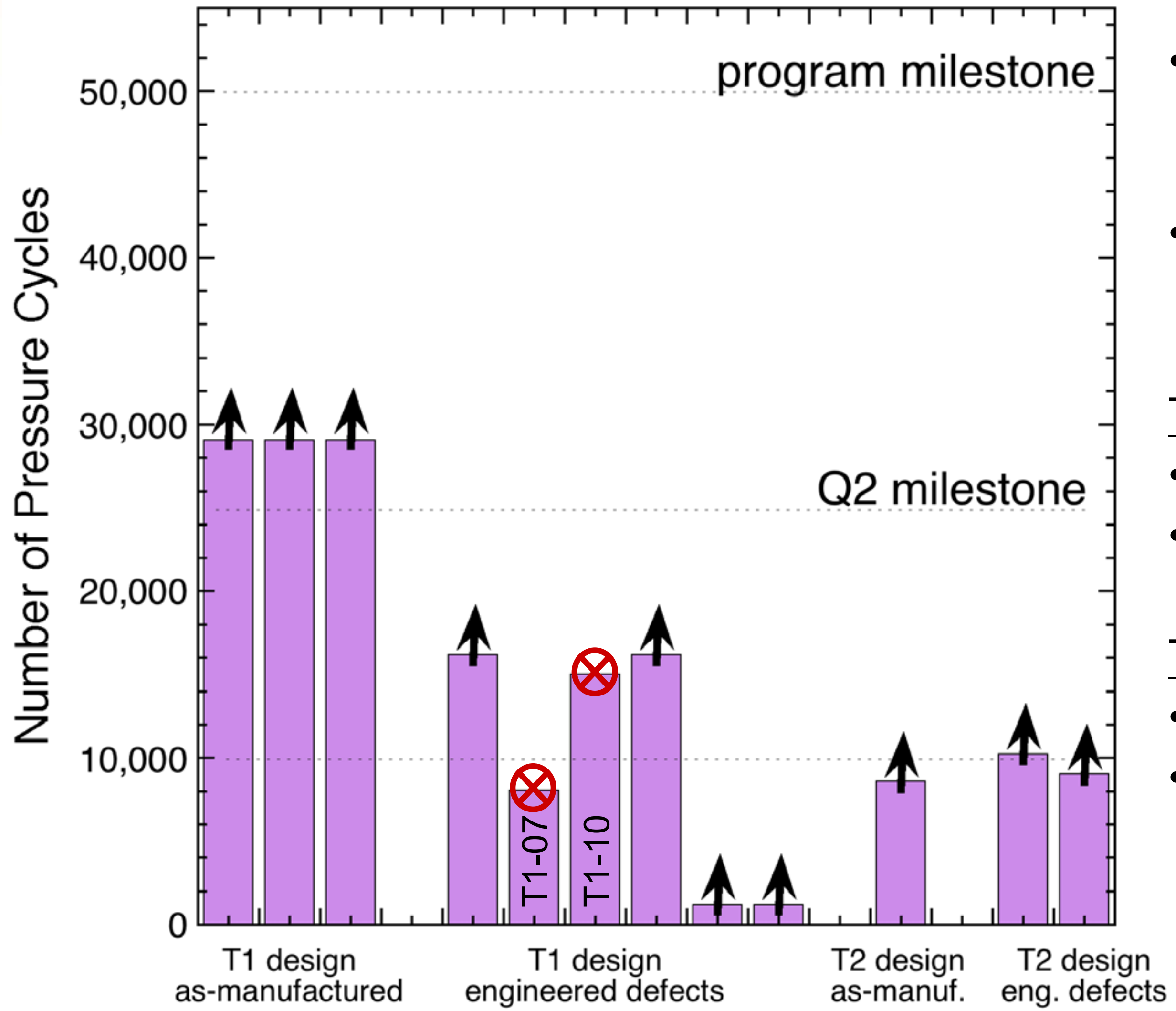


- failure = *initiation* + *crack growth*
- curves are predictions based on *crack growth* only (engineering analysis)
- lower bound failure prediction for as-manufactured vessels based on literature results (performance evaluation)

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

<u>T1-07</u>

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

<u>T1-10</u>

- 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

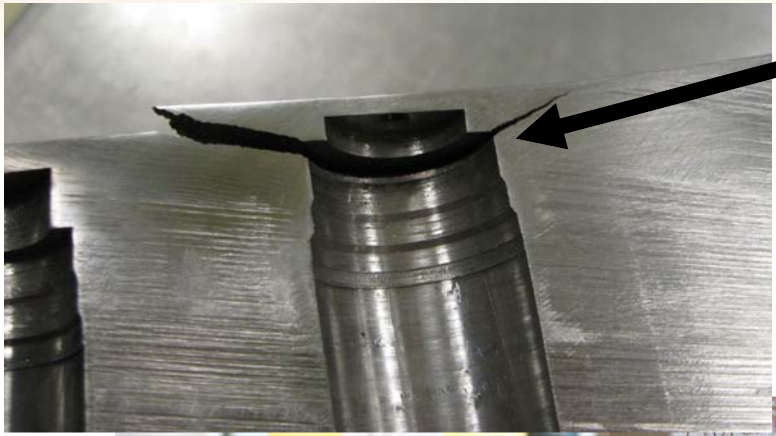
  resolution: compressor rebuilt
- Internal components in ball valves continue to fail, causing unacceptable leakage of hydrogen

  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)

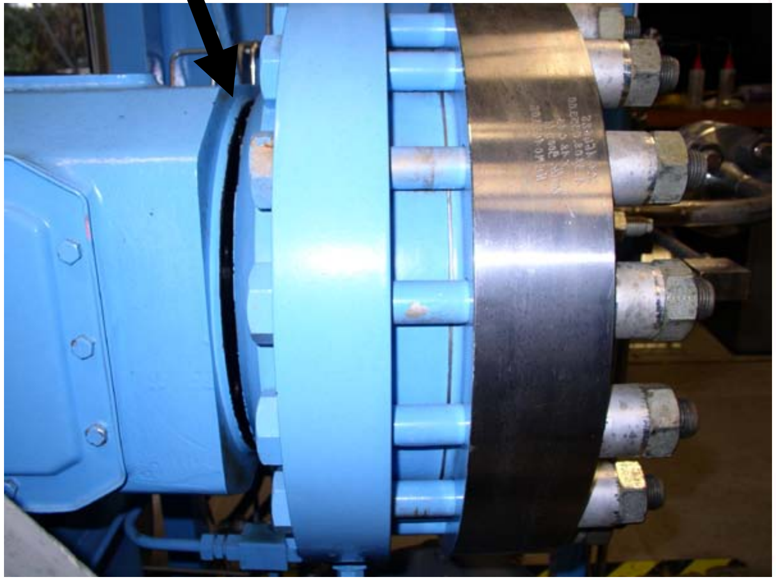
Technical Accomplishments and Progress

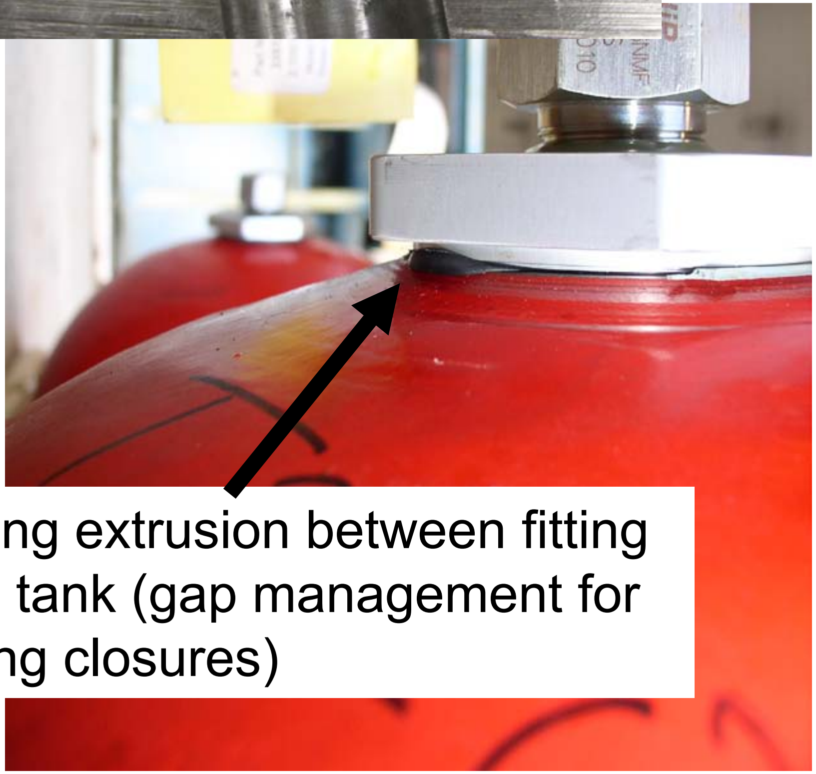
Maintaining infrastructure for tank cycling has been challenging



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)