VIII.5 Component Testing for Industrial Trucks and Early Market Applications

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Project End Date: May 2011 (carryover from Fiscal Year [FY] 2011 extended objectives into FY 2012)

Fiscal Year (FY) 2012 Objectives

(1) Provide technical basis for the development of standards defining the use of steel (Type 1) storage pressure vessels for gaseous hydrogen:
   - Compare fracture mechanics based design approach for fatigue assessment of pressure vessels for gaseous hydrogen to full-scale performance tests.
   - Generate performance test methods and data for fatigue assessment of full-scale pressure vessels with gaseous hydrogen.

(2) Codes and Standards Advocacy:
   - Participate in the standards development activities for gaseous hydrogen storage in pressure vessels, in particular Canadian Standards Association (CSA) and SAE International activities.

This project addresses the following technical barriers from the Safety Codes & Standards section (3.8) of the 2011 Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Safety Data and Information: Limited Access and Availability

(F) Enabling National and International Markets Requires Consistent Regulations, Codes & Standards

(G) Insufficient Technical Data to Revise Standards

Contribution to Achievement of DOE Safety, Codes & Standards Milestones

This project will contribute to achievement of the following DOE milestones from the Safety Codes & Standards section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

- Milestone 2.5: Develop holistic design strategies. (4Q, 2017)
- Milestone 2.6: Validate inherently safe design for hydrogen fueling infrastructure. (4Q, 2019)
- Milestone 2.16: Publish technical bases for optimized design methodologies of hydrogen containment vessels to account appropriately for hydrogen attack. (Q4, 2014)
- Milestone 2.17: Implement validated mechanism-based models for hydrogen attack in material. (Q4, 2018)
- Milestone 2.18: Demonstrate the use of new high performance materials for hydrogen applications that are cost-competitive with aluminum alloys. (4Q, 2017)
- Milestone 4.1: Identify and evaluate failure modes. (3Q, 2013)

FY 2012 Accomplishments

- Hydrogen Powered Industrial Truck (HPIT) component standard, CSA HPIT1 completed September 2011. Publication is delayed by CSA pending harmonization with other hydrogen component standards (e.g., CSA HPRD1, CSA HGV 3.1, etc.). This will be the first standard to allow use of design criteria for qualifying hydrogen storage system. Milestone 2.16 is directly impacted by this work and further understanding is gained toward achieving milestones 2.5, 2.6, 2.18 and 4.1.
- Presentation to American Society of Mechanical Engineers (ASME) project team for revision of ASME Boiler and Pressure Vessel Code (BPVC) Article KD-10. Based on results of testing Type-1 pressure vessels the design approach considered in KD-10 may be revised. This is in direct support of Milestone 2.16 and 2.17. This work also contributes toward achieving milestones 2.5, 2.6, 2.18 and 4.1.

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Introduction

Fatigue cracks can nucleate and grow in metals subjected to cyclic stress. The increment of crack growth per load cycle (*da/dN*) is a function of the driving force for fatigue cracking, which is called the applied stress intensity factor range (ΔK).

Under conditions of stable fatigue crack growth, a simple empirical relationship can be used to describe fatigue crack growth in terms of the driving force: $da/dN = C(\Delta K)^m$, where C and m are experimentally determined constants.

Fatigue crack growth of a pressure vessel subjected to pressure cycling is enabled by the presence of manufacturing defects in the steel and accelerated by exposure to gaseous hydrogen. The latter characteristic is often referred to as "hydrogen embrittlement" and depends on the partial pressure of the gaseous hydrogen and the kinetics of hydrogen uptake into the steel. Consequently, the fatigue crack growth relationship is affected by variables such as hydrogen pressure, pressure-cycle frequency, pressure-time relationship (wave form), and temperature.

Although steel pressure vessels may be vulnerable to fatigue crack growth aided by hydrogen embrittlement, the industrial gas companies have used such pressure vessels for hydrogen transport and storage for decades. Typically, these pressure vessels are subjected to less than one pressure cycle per day (and in many cases less than one cycle per month), thus fatigue crack growth is generally not a concern. Pressure vessels for hydrogen storage in new applications such as those for lift trucks are anticipated to experience up to six pressure cycles per day, approaching an order of magnitude greater than the duty cycle of typical transportable industry gas pressure vessels.

Since the duty cycle for lift truck pressure vessels is outside the window of current experience, a methodology for determining the cycle life must be established. A deterministic engineering analysis for quantifying the progression of fatigue cracks is provided in the ASME BPVC (Section VIII, Division 3, Article KD-4) and extended to the specific case of high-pressure gaseous hydrogen in Article KD-10. This framework provides a method for conservatively estimating the fatigue cycle life of pressure vessels based on assessment of existing flaws in the pressure vessel. An alternate method has been proposed based on the measured performance of manufactured pressure vessels subjected to pressure cycling coupled with statistical assessment of the quality of the pressure vessels and desired cycle life. These two methods have been referred to as engineering analysis method and performance evaluation method respectively.

Approach

During this project, pressure vessels were pressure cycled with gaseous hydrogen; the pressure vessels were identical to those in service for fuel cell forklift applications with gaseous hydrogen, with the exception that defects were engineered in some pressure vessels. The engineered defects were designed to simulate manufacturing flaws in the pressure vessels. Engineering analysis methods were used employed to compare the engineering analysis predictions with experimental results from the performance evaluation of full-scale pressure vessels. These efforts have required collaborations with fuel cell system integrators and pressure vessel manufacturers to obtain as-manufactured pressure vessels and produce pressure vessels with engineered defects for cycle testing, as well as development of a testing plan that reflects relevant engineering conditions, including pressure vessel designs, manufacturing flaws, and pressurization schedules. Additionally, direct participation in standards development activities has been a cornerstone of this effort, in particular with the technical advisory group for CSA's Hydrogen-Powered Industrial Trucks (HPIT1) and the subgroup drafting the language for the pressure vessel appendix in SAE J2579.

Results

Materials Testing

Sandia National Labs measured the rate of fatigue crack growth for three heats of 4130 steels in high-pressure gaseous hydrogen; testing coupons were extracted from pressure vessels supplied by the industrial partners (each heat of material came from a different vendor). ASME BPVC (VIII-3) Article KD-10 requires the testing of three heats of a given steel to demonstrate that the effects of hydrogen are not sensitive to variations in the material's microstructure or processing history. These measured fatigue crack growth rates are used to predict cycle life using engineering analysis methodologies that quantify crack growth through the vessel wall from manufacturing flaws in the pressure vessel.

Full-Scale Tank Testing

A system was designed and constructed to pressure cycle up to 10 full-scale tanks in parallel at a rate of approximately 250 discrete pressure cycles per day (approximately 5-minute pressure cycle time). The pressure vessels are cycled between 3.4 and 43.8 MPa, with an approximately 2-minute pressure ramp rate, 2-minute hold time at maximum pressure, 30-second depressurization rate, and 30-second hold at minimum pressure. Pressure vessels cycled for 47,000 cycles without failure, although not all pressure vessels experienced this number of cycles. Pressure vessels with engineered defects were subjected to fewer cycles and four vessels failed after as few as 8,000 cycles. Generally, there are two components to fatigue life, crack initiation and crack propagation. The engineering predictions are based on crack propagation only, since there is no broadly accepted method to account for crack initiation.

Leak-before-burst was observed for each of the four pressure vessel failures. This is an important observation because larger safety factors are generally applied when burst is a probable failure mode. Additionally, post-mortem analysis suggests that the engineered defects form cracks that propagate with a semi-circular profile, although as the crack depth reaches the full thickness of the vessel the shape again changes. This is also an important observation if shown to be generally true. Cracks with larger aspect ratios (such as the aspect ratio of the engineered defects) propagate at higher rates because the driving force is greater for a "long" crack compared to a "short" crack of the same depth.

These results were incorporated into the standard CSA HPIT1. The testing procedures are also under development in SAE J2579.

The conclusion of the testing revealed that ASME BPVC calculations were conservative by a factor of 4 or more, with the safety factor for small initial defects approaching 10. Figure 1 shows the number of cycles experienced by the cylinder as a function of the depth of the initial crack. Symbols with arrows indicate cylinders that had not yet failed and were still capable of achieving more cycles. The solid lines represent the predictions based on the ASME BPVC Article KD-10 approach.

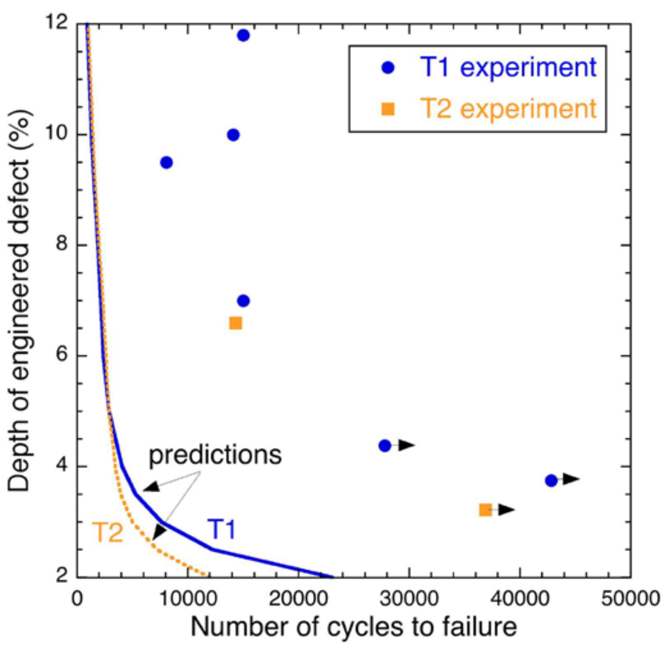

FIGURE 1. Number of cycles vs. depth of engineered defect for various cylinders in the 'full tank' testing. Symbols with arrows represent tanks which had not yet failed and were capable of further cycles. Solid lines represent the predicted failure from ASME BPVC Article KD-10.

Conclusions and Future Directions

Previous Conclusions:

- Commercial pressure vessels being used for hydrogen storage on forklifts have been subjected to more than 47,000 pressure cycles with gaseous hydrogen (between pressure of 3.4 and 43.8 MPa):
  - Primary aim of the remainder of project is to cycle tanks until they fail or reach 50,000 cycles.
- Fatigue crack growth assessment of engineered defects in these pressure vessels using engineering analysis appears to be conservative:
  - Post-mortem analysis is being used to refine predictions and interpret failure process.
- 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:
  - Results are being shared with committees as they are generated.
- Leak-before-burst was observed in all failures.

Additional conclusions gained in FY 2012:

- Revision of ASME BPVC Article KD-10 is necessary based on the results of the full tank cycling.

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FY 2012 Publications/Presentations

1. B. Somerday and C. Sloane, "Addressing Hydrogen Embrittlement in the SAE J2579 Fuel Cell Vehicle Tank Standard", International Conference on Hydrogen Safety ICHS 2011, San Francisco CA, September 2011, Paper No. 130.

2. C. San Marchi, D. Dedrick, P. Van Blarigan, B. Somerday, K. Nibur, "Pressure Cycling of Type 1 Pressure Vessels with Gaseous Hydrogen", International Conference on Hydrogen Safety ICHS 2011, San Francisco CA, September 2011, Paper No. 215.

3. C. San Marchi and B. Somerday, "Fatigue Crack Growth of Structural Metals for Hydrogen Service", ASME Pressure Vessels & Piping Division Conference (PVP 2011), Baltimore MD, July 2011, Paper No. PVP2011-57701.