DOE Hydrogen and Fuel Cells Program Record	
Record #: 15005	**Date:** September 30, 2015
Title: Testing of Hydrogen Effects on Full-Scale Type 1 Pressure Vessels in High Cyclic Fatigue (>30,000 cycles)	
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Item:

Full-scale pressure cycling of Type I pressure vessels[1] with gaseous hydrogen over more than 30,000 cycles (in some cases) demonstrates a service life for hydrogen storage vessels for industrial trucks (e.g., forklifts) that is significantly greater than the predicted design life from fatigue crack growth in gaseous hydrogen.

Supporting Information:

This activity at Sandia National Laboratories in Livermore, California, involved the cycling of full-scale Type I pressure vessels with artificially-created defects between pressures of approximately 3.5 and 43.8 MPa (35 and 438 bar) with gaseous hydrogen. The testing also confirmed the leak-before-burst failure mode of the tested pressure vessels: a fatigue crack propagates through the wall of the vessel without causing the vessel to rupture. This is an important outcome because the leak-before-burst failure mode confines the hazard associated with failure of the pressure vessel to a gaseous leak, thus mitigating the hazard associated with fatigue-induced rupture of the pressure vessel. The testing methodology as developed in this study for full-scale pneumatic testing (i.e., pressure cycling with gaseous hydrogen) has been influential in the development of several standards. Important outcomes of this work include:

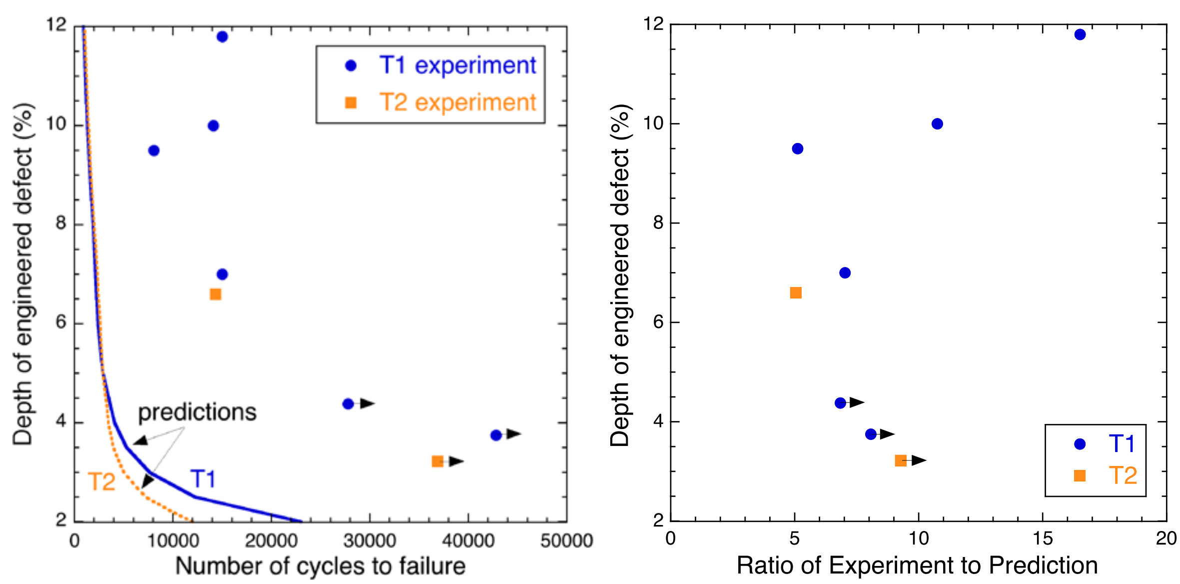
i. The measured cycle life of the tested pressure vessels is significantly greater than engineering predictions based on fatigue crack growth in gaseous hydrogen;
ii. All observed failures were leak-before-burst;
iii. The results are being used to justify design criteria based on stress-life calculations for hydrogen storage pressure vessels onboard industrial trucks, such as forklifts; and
iv. The test method has been adopted for inclusion in standards such as CSA HPIT1 [1] and SAE J2579 [2].

[1] Type I pressure vessels are all-metal construction, generally steel or aluminum.

Two pressure vessel designs were cycled in the as-received condition (i.e., without artificial defects); one design sustained 35,000 cycles before failure, while triplicates of the second design sustained 55,000 cycles without failure. The cycle-life (number of cycles to failure) was compared with design calculations based on the requirements of the ASME Boiler and Pressure Vessel Code, Section VIII, Division 3 (BPVC VIII.3). The significance of this work is described in brief below. Details of the testing and initial engineering analysis can be found in Refs. [3,4].

The demonstration of leak-before-burst is an important safety consideration that mediates some of the risk associated with the failure of a pressure-containing component. For example, ASME BPVC VIII.3, Paragraph KD-140 allows for stress-life design criteria to be applied when a pressure vessel is demonstrated to be leak-before-burst except for hydrogen service. If a stress-life approach is allowed by the BPVC VIII.3 code for hydrogen service, a significantly greater design life is predicted for the tested vessels, suggesting the potential for cost reductions over the life cycle of the pressure vessels. The testing of the forklift pressure vessels suggests that the existing stress-life design criteria (based on fatigue test data performed in laboratory air) from the ASME BPVC VIII.3 code are sufficient for the needs of the forklift application.

ASME BPVC VIII.3 currently has language that addresses special requirements for pressure vessels in service with high-pressure gaseous hydrogen (i.e., non-welded vessels with hydrogen partial pressure exceeding 41 MPa or 410 bar). The ASME design requirements for hydrogen (article KD-10) apply a standardized fracture mechanics-based approach to assess the design life of a pressure vessel. Figure 1 (below) shows the predictions based on fracture mechanics relative to the life measured in gaseous hydrogen: the fracture-mechanics approach underestimates the design life of the vessel.



(a) (b)

Figure 1. (a) Design predictions (curves) using fracture-mechanics approach compared to full-scale experiments with gaseous hydrogen (points). Two pressure vessel designs were tested (T1 and T2, respectively) and the arrows represent pressure vessels where cycling was interrupted prior to failure. (b) The ratio of experiment to design life prediction shows the conservative nature of the fracture-mechanics approach.

Note that each data point in the in Figure 1 (above) represents a unique pressure vessel with 10 engineered (i.e., machined) defects on the inside wall of the vessel. Data points without arrows indicate a pressure vessel that failed by propagation of a crack (which initiated from an engineered defect) through the entire wall of the vessel such that hydrogen leaked from the vessel without causing the vessel to burst. Data points with arrows represent a pressure vessel where a crack did not propagate through the wall during pressure cycling to the number of indicated cycles (i.e., the pressure cycling was interrupted prior to leak or burst failure). The curves in Figure 1a represent design life predictions based on fatigue crack growth rates measured in gaseous hydrogen at pressure of 45 MPa (450 bar) using standardized test specimens [3,4]. Two Type 1 pressure vessel designs were evaluated, denoted T1 and T2 respectively. In all cases, the data points indicate a service life that is substantially longer than the design life predicted from fracture mechanics (i.e., fatigue crack growth). The ratio of experimentally measured cycles to failure to design life prediction is presented in Figure 1b, demonstrating the conservative nature of the fracture mechanics approach by a factor of at least 5 for these specific vessel designs.

This work has demonstrated the reliability of commercial Type I pressure vessels subjected to pressure cycling with gaseous hydrogen. These results provide experimental evidence for the integrity of Type I pressure vessels for hydrogen storage applications on industrial trucks and improve confidence that hydrogen embrittlement can be managed in highly demanding applications. The results of the pressure vessel testing have been communicated to the ASME Project Team on Hydrogen Tanks and are being used to motivate additional code development work to adopt the stress-life approach for high-pressure hydrogen.

References:

1. CSA Group, "Compressed Hydrogen Powered Industrial Truck On-board Fuel Storage and Handling Components (HPIT1)", Technical Information Report (TIR) currently under development.
2. Society of Automotive Engineers (SAE), "J2579 Standard for Fuel Systems in Fuel Cell and Other Hydrogen Vehicles", revised 2013.
3. C. San Marchi, D.E. Dedrick, P. Van Blarigan, B.P. Somerday, K.A. Nibur: "Pressure Cycling of Type 1 Pressure Vessels with Gaseous Hydrogen". 4th International Conference on Hydrogen Safety (ICHS4), 12-14 September 2011, San Francisco, CA.
4. C. San Marchi, A. Harris, M. Yip, B.P. Somerday, K.A. Nibur: "Pressure Cycling of Steel Pressure Vessel with Gaseous Hydrogen" (PVP2012-78709), ASME Pressure Vessels and Piping Division Conference, 15-19 July 2012, Toronto, Canada.