VII.C.4 Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High Pressure Liquid Hydrogen Pump

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Subcontractors:

- Spencer Composites Corporation, Sacramento, CA
- Linde LLC, Hayward, CA

Project Start Date: January 2014
Project End Date: January 2017

Overall Objectives

- Demonstrate small (63.5-L internal volume), high aspect ratio (34 cm outer diameter and 100 cm length) cryogenic pressure vessels with high volumetric and gravimetric hydrogen storage performance (50 gH_2/L and 9% H_2 weight fraction).
- Demonstrate durability (1,500 thermomechanical cycles) of thin-lined high fiber fraction pressure vessels.
- Measure liquid hydrogen pump performance after 6,000 refuelings (24 tonnes of liquid hydrogen).

Fiscal Year (FY) 2016 Objectives

- Complete construction and commission LLNL's hydrogen test facility.
- Analyze, design, and fabricate full-scale (65 L) 700 bar pressure vessel prototypes with thin metal liner (<2 mm).
- Demonstrate long life of thin-lined vessels by conducting 1,500 thermomechanical cycles with cryogenic hydrogen at LLNL's test facility.

Technical Barriers

This project addresses the following technical barriers from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

(C) Hydrogen Storage

(D) Lack of Hydrogen Refueling Infrastructure Performance and Availability Data

Contribution to Achievement of DOE Technology Validation Milestones

This project will contribute to achievement of the following DOE milestones from the Technology Validation section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

- Milestone 3.4: Validate station compression technology provided by delivery team. (4Q, 2018)

FY 2016 Accomplishments

- Built and commissioned LLNL's hydrogen test facility.
- Built and cycle tested—with water—six thin-lined pressure vessels rated for 700 bar.
- Built a seventh thin lined vessel and cycle tested it with hydrogen.

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INTRODUCTION

Cryogenic pressure vessels have demonstrated high performance for automotive hydrogen storage, with density (43 gH_2/L), weight fraction (7.3%), cost ($12/kWh), and safety advantages (~8X lower expansion energy than compressed gas and secondary protection from vacuum jacket) [1-3]. This project explores the potential for reaching high volumetric (50 g H_2/L target) and gravimetric (9% H_2 weight fraction target) storage performance within a small (63.5-L internal volume), high aspect ratio (34 cm outer diameter and 100 cm length) cryogenic pressure vessel with long durability (1,500 thermomechanical cycles) refueled by a liquid hydrogen pump to be tested for degradation after delivery of 24 tonnes of liquid hydrogen.

APPROACH

Reaching the very challenging weight and volume targets set for this project demands innovative cryogenic pressure vessel design. Spencer Composites Corporation, in collaboration with LLNL, is developing thin-lined, high fiber fraction cryogenic pressure vessels. At a target liner thickness of 1.5 mm and 80% fiber fraction, these thin-walled vessels may be able to reach the weight and volume targets when installed within a thin vacuum gap and refueled at high density (up to 80 gH_2/L) with the liquid hydrogen pump.

RESULTS

Work in the reporting period focused on building and commissioning the hydrogen test facility, and on building and cycle testing thin-lined pressure vessels.

Hydrogen Test Facility

LLNL's hydrogen test facility, completed during the reporting period (Figure 1), offers a unique platform for testing hydrogen systems over a wide range of pressures, temperatures, volumes and flow rates.

The main component of LLNL's hydrogen test facility is a liquid hydrogen pump. Manufactured by Linde, a leading supplier of cryogenic equipment, the pump takes liquid hydrogen from the station dewar at low pressure (2–3 bar) and very low temperature (23–25 K) and pressurizes it up to an 875 bar cryogenic fluid. Flow rate is very high (up to 120 kg of hydrogen per hour), enabling (future) 5 minute refuels. The station dewar has an 11,000-L capacity, sufficient to refuel ~150 vehicles. When empty, it is refilled by a liquid hydrogen truck.

Another key component of the hydrogen test facility is a containment vessel (Figure 2) that enables testing thin-lined pressure vessels manufactured for this project. These one-of-a-kind experimental vessels are not certified by current standards (American Society of Mechanical Engineers, International Organization for Standardization, Federal Motor Vehicle Safety Standards) and are therefore unsafe to pressurize in manned areas. Made of 3.2 cm thick stainless steel 304 and weighing almost 5,000 kg, the containment vessel is rated for 65 bar maximum pressure and can contain the equivalent energy of 1.8 kg of trinitrotoluene, therefore enabling testing of full-scale vessels and hydrogen systems. The containment vessel can also hold high vacuum down to 0.1 Pa.

The Hydrogen Test Facility can be operated from a control room strategically located for maximum visibility and far enough from the dewar (23 m) to meet National Fire Protection Association (NFPA) standards. Full instrumentation is also available with sensors for temperature, pressure, flow, liquid hydrogen level, electricity, and vent rates. All sensors and system components are explosion-proof (Class 1 Division 1 Group B), as demanded by NFPA for systems that may be exposed to hydrogen.

A 9-m high vent stack completes the facility, enabling rapid venting of hydrogen subsequent to pressure testing. High altitude venting of hydrogen is demanded by NFPA for rapid dispersion away from personnel at ground level. Hydrogen, being so light and therefore buoyant, rapidly diffuses upward once it is released and warms up to ambient temperature.

In the next quarter, a 40-kW electric heater and heat exchanger will be added in order to provide varying hydrogen outlet temperature, from cryogenic to room temperature, enabling cost effective, rapid thermomechanical testing at high pressure and low (60 K) to elevated (360 K) temperature.

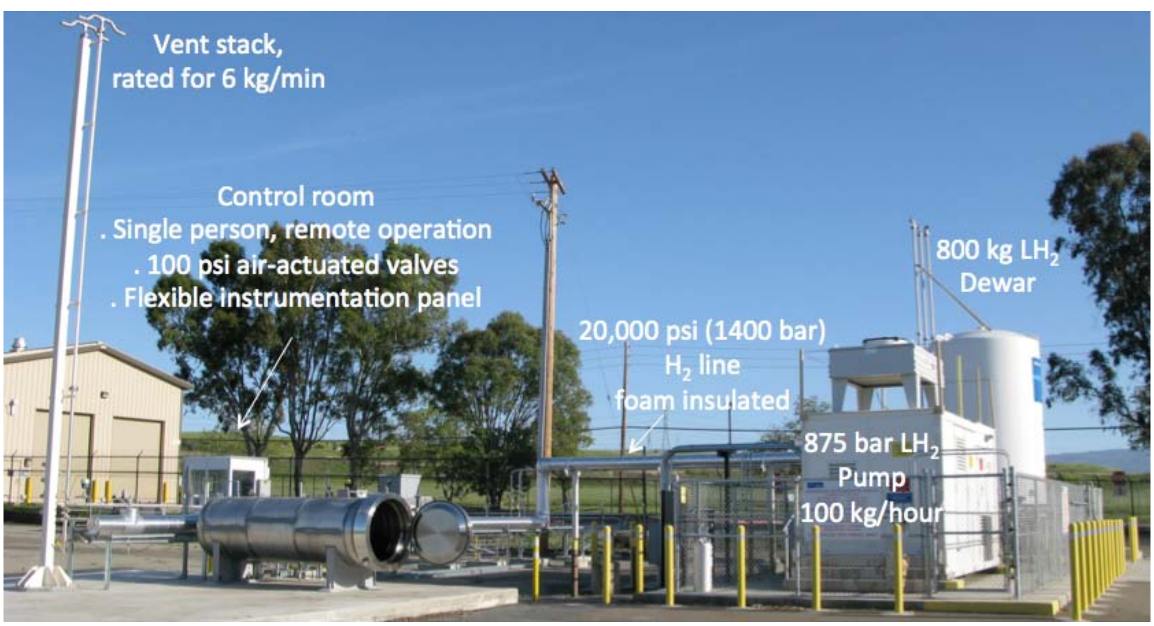
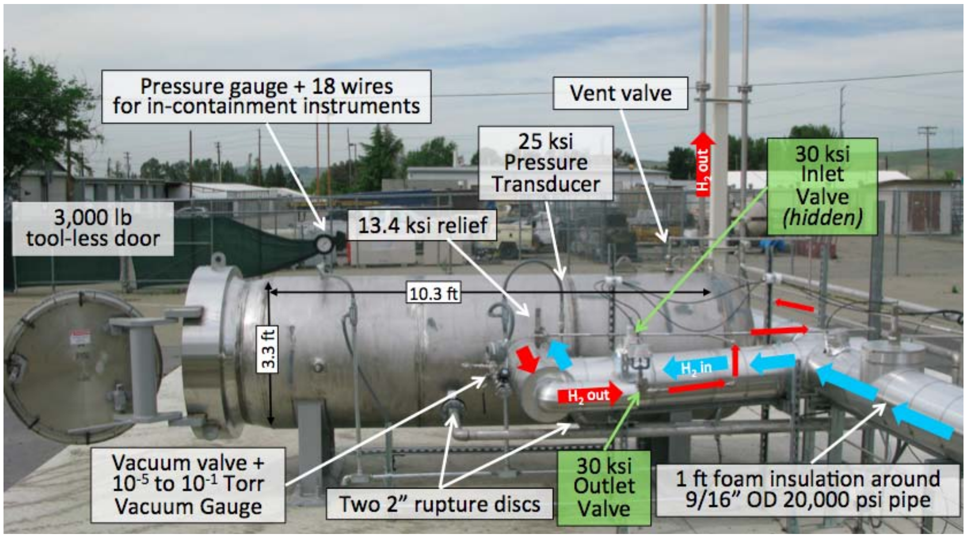


FIGURE 1. LLNL's hydrogen test facility showing the main components and their performance metrics: liquid hydrogen pump, liquid hydrogen dewar, containment vessel, control room, insulated hydrogen tubes, and vent stack



OD – Outside diameter

FIGURE 2. Containment vessel for testing pressure vessels and systems with cryogenic and ambient temperature hydrogen

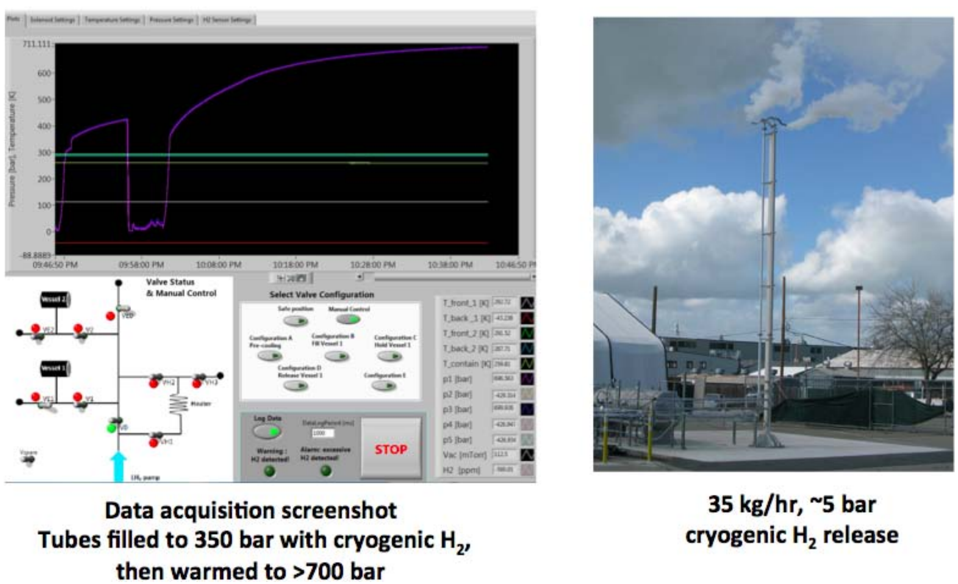


FIGURE 3. Commissioning of hydrogen test facility showing a data acquisition system screen shot (left) and 35 kg/h hydrogen vent (right)

The hydrogen test facility was commissioned in February of 2016 (Figure 3), on time for cycle testing the new generation of thin-lined pressure vessels.

Thin-lined Pressure Vessels

Following last year's strength testing of a pressure vessel to 1,560 bar (2.23 safety factor for 700 bar operation), we dedicated this year to designing and producing a vessel that could be cryogenically cycled over 1,500 times. This demanded detailed finite element and fatigue analysis to determine composite layer strength to meet cyclability requirements. In collaboration with BMW, we conducted linked thermo-fluid and stress analysis of the fill process to determine improved boss designs for surviving thermal gradients that may result while filling an initially warm vessel with cryogenic hydrogen.

In total, we manufactured and tested seven vessels during the year (Table 1). The first two vessels failed during autofrettage. Research into this failure mode indicated that lack of roundness weakened the structure and resulted in

TABLE 1. Experimental Results from the Testing of Seven Pressure Vessels

Date	#	Liner	Resin	Test result
Aug 15	1	1.3 mm Steel	High Fiber Fraction	Buckling then burst @ 8 ksi (during autofrettage)
Sep 15	2	1.5 mm Alternate	Epoxy	Buckling then burst @ 12 ksi (during autofrettage)
Oct 15	3	1.7 mm Alternate	Epoxy	Leak after **133** water cycles, T-weld failure
Nov 15	4	1.5 mm Alternate	Epoxy	Leak after **247** water cycles, root cause not found, NOT at T-weld
Jan 16	5	1.7 mm Steel	Epoxy	Leak after **468** water cycles, longitudinal weld failure
Mar 16	6	1.7 mm Steel, annealed	High Fiber Fraction	Burst @ 10 ksi (during autofrettage)
May 16	7	1.7 mm Steel	Epoxy	Leak after **456** hydrogen cycles

premature failure at low pressure. Process modifications led to vessels that survived autofrettage and an increased number of water pressure cycles to 700 bar (except for Vessel 6 that failed during autofrettage while researching alternate resins). After partial success with water cycling, a final vessel was tested with cryogenic hydrogen, reaching 456 cycles, well short of the 1,500 cycle target.

CONCLUSIONS AND FUTURE DIRECTIONS

Research into the cause of failure points to liner welds as the likely culprit. Tungsten inert gas welds done by hand are irregular by nature and introduce flaws that may initiate crack propagation during vessel cycling. Future work in this topic will demand alternative liner manufacture techniques such as e-beam welding, pulsed laser welding, or spin forming. The potential still remains to manufacture thin-lined vessels with long cycle life to demonstrate the ultimate performance limits of cryogenic pressure vessels. In addition to this, future experiments remain to be done to determine pump performance parameters (fill density, flow rate, energy consumption, venting losses) when filling vessels to 700 bar.

After careful review of the experimental results, DOE decided to reduce the scope of the project, eliminating vessel development activities and instead testing pressure vessels supplied by BMW. This may be initiated in Fall 2016 after vessels are received, a test protocol is identified, and the 40 kW electric heater (possibly necessary for vessel testing) is installed at LLNL's test facility.

REFERENCES

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