IV.F.4 Thermomechanical Cycling of Thin-Liner High-Fiber-Fraction Cryogenic Pressure Vessels Rapidly Refueled by a LH_2 Pump to 700 Bar

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Subcontractors
- Linde LLC, Hayward, CA
- Spencer Composites Corporation, Sacramento, CA
- BMW, Munich, Germany

Start Date: January 1, 2014
End Date: December 31, 2016

Overall Objectives

- Demonstrate small (60 liters internal volume), high aspect ratio (35 cm outer diameter and 110 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 (LH_2) pump performance after 5,000 refuelings (24 tonnes of LH_2)

Fiscal Year (FY) 2014 Objectives

- Write a safety plan and receive DOE operational approval
- Complete fabrication drawings for pressure vessel test facility
- Manufacture a vacuum jacket cryogenic pressure vessel with 163 liter capacity
- Conduct cryo-pump testing at 700 bar with 163 liter vessel
- Fabricate the first thin-lined high-fiber-fraction vessel
- Pressure test the thin-lined high-fiber-fraction vessel (Go/No-Go)

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

(A) System Weight and Volume

(D) Durability/Operability

(E) Charging/Discharging Rates

(N) Hydrogen Venting

TABLE 1. Progress toward Meeting DOE Hydrogen Storage Technical Targets

Cryogenic Pressurized Storage			
Characteristic	Units	2017/ultimate targets	LLNL 2014 status
System gravimetric capacity	kWh/kg	1.8/2.5	2.45
System volumetric capacity	kWh/L	1.3/2.3	1.51
Storage system cost	$/kWh	12/8	12

FY 2014 Accomplishments

- Demonstrated weldability of candidate liner material by performing tension tests of welded dog bones
- Completed site design and construction-ready drawings for a pressure vessel test facility
- Wrote the preliminary version of a safety plan

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INTRODUCTION

Cryogenic pressure vessels have demonstrated the highest 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) [1,2]. This project will explore the potential for reaching high volumetric (50 gH_2/L target) and gravimetric (9% hydrogen weight fraction target) storage performance within a small (60 liters internal volume), high aspect ratio (35 cm outer diameter and 110 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 LH_2.

APPROACH

Reaching the very challenging weight and volume targets set for this project demands an innovative cryogenic pressure vessel design. Spencer Composites Corporation, in collaboration with LLNL, will develop 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 targets when installed within a thin vacuum gap and refueled at high density (up to 80 gH_2/liter) with the LH_2 pump.

RESULTS

The first seven months (January-July 2014) of this project have focused on the three initial tasks described next.

1. Development of Thin-Lined, High-Fiber-Fraction Vessels. In collaboration with Spencer Composites Corporation, LLNL selected appropriate liner materials for high-pressure cryogenic operation that can withstand compression from the composite overwrap without buckling. At 1.5 mm target thickness, the focus is on hydrogen-compatible stainless steels (316). Recent experiments have helped establish weldability. Dog bones were made from the baseline material, and then cut in half and TIG welded with and without welding rods. The results have been very satisfactory. Little loss in strength (10%, (Figures 1 and 2), resulted from welding, and all dog bones failed at the heat-affected zone indicating a high quality weld.
2. Construction Planning. Experimental vessels to be built by Spencer Composites Corporation are not certified and therefore cannot be tested in a manned area according to LLNL pressure safety standards. Extensive cycling and pressurization of these experimental vessels therefore demands a pressure vessel test facility where the vessels can be tested within the confines of an appropriately sized containment vessel that guarantees safe operation. The Facilities group at LLNL has produced a package of construction-ready drawings for the test facility (Figure 3), and construction is projected to start in FY 2015.
3. Safety Plan. Aside from extensive safety reviews internal to LLNL, DOE demands a comprehensive safety plan to be reviewed by DOE´s Safety Panel. These reviews are especially important for this project due to extensive pressure and cycle testing with hydrogen. A preliminary safety plan including all construction and system component details has been produced and is being reviewed by the Safety Panel.

CONCLUSIONS AND FUTURE DIRECTIONS

- This project attempts to identify volumetric and gravimetric performance limits for cryogenic pressurized storage at small size (60 liters) and high aspect ratio (35 cm outer diameter and 110 cm length)
- Performance targets demand thin walled vessels, and these are being developed in collaboration with Spencer Composites Corporation
- Vessel durability over 1,500 thermomechanical cycles will be demonstrated before pressure testing to minimum burst pressure
- Pump durability will also be demonstrated by measuring performance after pumping 24 tonnes of LH_2

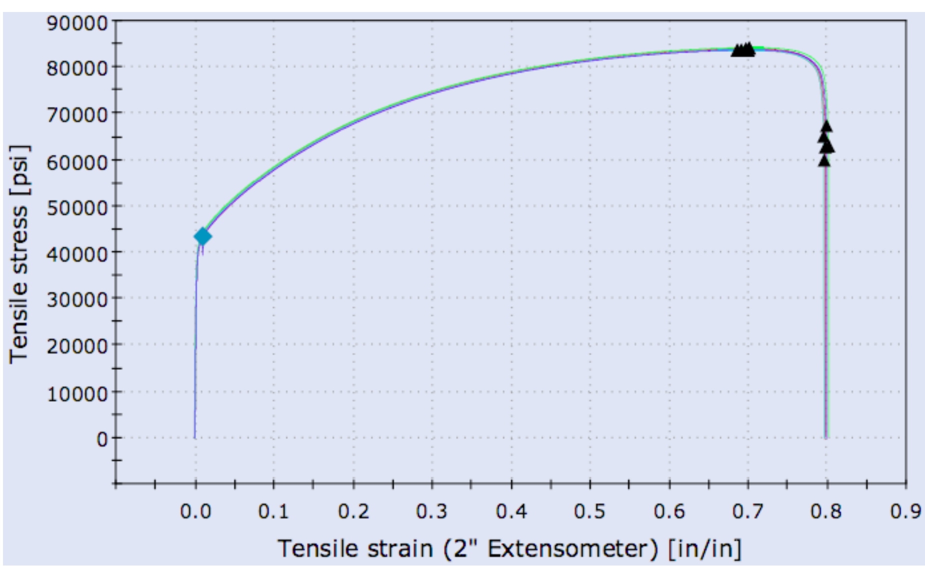

FIGURE 1. Stress-Strain for Stainless Steel 316 for a Dog Bone made of the Parent Material and No Welds

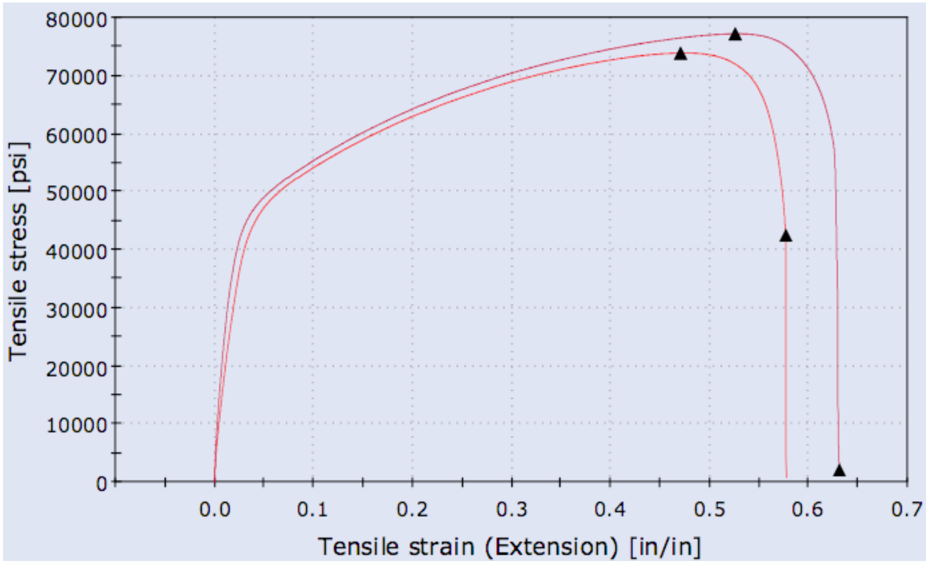

FIGURE 2. Stress-Strain for Stainless Steel 316 for a Dog Bone Welded with No Welding Rod

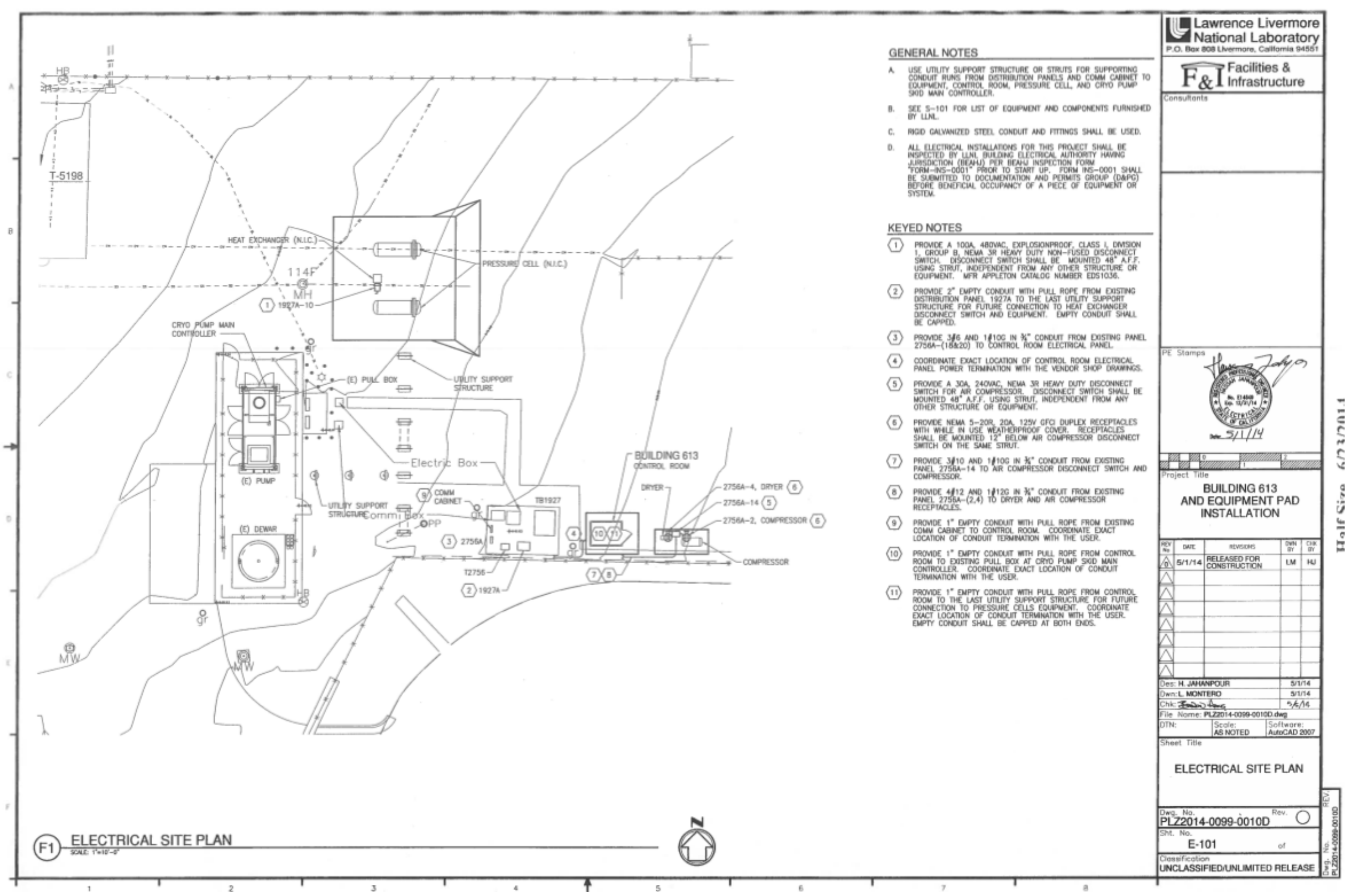

FIGURE 3. Electrical Site Plan for the Future LLNL Pressure Vessel Test Facility

SPECIAL RECOGNITIONS AND AWARDS/ PATENTS ISSUED

1. **Methods for tape fabrication of continuous filament composite parts and articles of manufacture thereof**. Weisberg AH. United States Patent US 8545657 B2, November 2013.

FY 2014 PUBLICATIONS/PRESENTATIONS

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2. **Hydrogen Storage in Pressure Vessels: Liquid, Cryogenic, and Compressed Gas**, Guillaume Petitpas and Salvador Aceves, in Hydrogen Storage Technology: Materials and Applications, Edited by Leonard E. Klebanoff, CRC Press, Taylor & Francis, Chapter 4, pp. 91-107, 2013.

3. **Cold Hydrogen Delivery in Glass Fiber Composite Pressure Vessels: Analysis, Manufacture, and Testing,** Andrew H. Weisberg, Salvador M. Aceves, Francisco Espinosa-Loza, Elias Ledesma-Orozco, Blake Myers, Brian Spencer, International Journal of Hydrogen Energy, Vol. 38, pp. 9271-9284, 2013.

4. **Modeling of sudden hydrogen expansion from cryogenic pressure vessel failure,** Petitpas, G. and Aceves, S.M., International Journal of Hydrogen Energy, Vol. 38, pp. 8190-8198, 2013**.**

5. **Web-Based Resources Enhance Hydrogen Safety Knowledge,** Weiner, S.C., Fassbender, L.L., Blake, C., Aceves, S.M., Somerday, B.P., and Ruiz, A., International Journal of Hydrogen Energy, Vol. 38, pp. 7583-7593, 2013.

6. **Safe, long range, inexpensive and rapidly refuelable hydrogen vehicles with cryogenic pressure vessels**, SM Aceves, G Petitpas, F Espinosa-Loza, MJ Matthews, E Ledesma-Orozco, International Journal of Hydrogen Energy, Vol. 38, pp. 2480-2489, 2013.

7. **A Comparative Analysis of the Cryo-Compression and Cryo-Adsorption Hydrogen Storage Methods,** G. Petitpas, P. Benard, L.E. Klebanoff, J. Xiao, S. Aceves, International Journal of Hydrogen Energy, 2014.

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1. Aceves, S.M., Espinosa-Loza, F., Ledesma-Orozco, E., Ross, T.O., Weisberg, A.H., Brunner, T.C., Kircher, O., "High-density automotive hydrogen storage with cryogenic capable pressure vessels," International Journal of Hydrogen Energy, Vol. 35, pp. 1219-1226, 2010.

2. Ahluwalia, R.K. Hua, T.Q. Peng, J.-K. Lasher. S, McKenney. K. Sinha, J., Gardiner. M. "Technical assessment of cryo-compressed hydrogen storage tank systems for automotive applications," International journal of hydrogen energy, Vol. 35, pp. 4171–4184, 2010.