III.8 Rapid High-Pressure Liquid Hydrogen Refueling for Maximum Range and Dormancy

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Subcontractors:
- Linde LLC, Hayward, CA
- Engineering, Procurement & Construction (EPC), Lakewood, CO

Start Date: October 1, 2009
Projected End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- Demonstrate rapid refueling of cryogenic vessels
- Refuel cryogenic vessels even when warm and/or pressurized
- Refuel at high density (>80 kg H_2/m^3)

Fiscal Year (FY) 2013 Objectives

- Install liquid hydrogen pump
- Measure refuel performance

Technical Barriers

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

(C) Reliability and Costs of Liquid Hydrogen Pumping

Technical Targets

The technical targets for this project are listed in Table 1.

FY 2013 Accomplishments

- Built and certified high-pressure fill hose
- Completed liquid hydrogen pump site construction and installation
- Operated pump and conducted 350 bar refuel experiments

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INTRODUCTION

Cryogenic pressure vessels have demonstrated the highest performance for automotive hydrogen storage, with density (43 g H_2/L), weight fraction (7.3%), cost ($11.3/kWh), and safety advantages (~8X lower expansion energy than compressed gas and secondary protection from vacuum jacket) [1,2]. Optimum refuel conditions are, however, still unknown. Today's hydrogen storage technologies (compressed and liquid hydrogen) operate at fixed temperature. Cryogenic pressure vessels, however, drift across the phase diagram depending on the level of use, cooling down and depressurizing when driven and heating up and pressurizing when parked. The challenge is demonstrating rapid, inexpensive refueling that maximizes driving range for typical utilization scenarios.

APPROACH

LLNL is researching a liquid hydrogen pump for cryogenic pressure vessel refueling. Manufactured by Linde, a leading supplier of cryogenic equipment, this pump takes liquid hydrogen at low pressure (near atmospheric) and delivers it at high pressure (up to 875 bar), high flow rate (100 kg/hour), low temperature (30-60 K), high density (>80 g/L), and low evaporative losses (less than 3% of

TABLE 1. Progress toward Meeting DOE Hydrogen Delivery Technical Targets for Liquid Hydrogen Pumps

Liquid hydrogen pumps				
DOE targets	**FY 2011 status**	**FY 2015 target**	**FY 2020 target**	**LLNL Pressurized LH_2 pump**
Uninstalled capital cost, $ (870 bar, 100 kg/hr)	-	150,000	150,000	1,300,000

LH_2 – liquid hydrogen

dispensed H_2). Pumped hydrogen can be directly dispensed into a cryogenic pressure vessel, even when warm and/or pressurized. In this project, LLNL has installed a liquid hydrogen pump and is planning to demonstrate its virtues for rapid and efficient cryogenic vessel refueling.

RESULTS

This year's LLNL effort was dedicated to installing and operating a high-pressure liquid hydrogen pump. The main activities necessary for pump construction and installation were as follows:

- Institutional permits—The initial phase of the work demanded obtaining institutional LLNL approvals. These approvals included environmental, facilities, and utilities.
- Utility planning—LLNL conducted a detailed study of different options to bring electric power to the site. It was finally decided that the most cost-effective option was an overhead power line into the site from a nearby (200 m) electric pole and a 500-kVA, 480-V transformer near the pump site. LLNL also analyzed options for bringing water and communication lines to the site and documented the best alternative in construction-ready drawings.
- Foundation calculations—In collaboration with Linde and EPC, LLNL calculated the necessary foundations for supporting both the pump and the Dewar. The resulting foundation design was documented into construction-ready drawings.
- Professional Engineer-stamped design package—In collaboration with EPC and Linde, LLNL produced a construction-ready design package consisting of about 30 drawings, including all the details for site construction (Figure 1).
- Foundation construction—Once the design package was complete, LLNL proceeded to build the foundation necessary for installing the pump and Dewar and for bringing the utilities. This was a major part of the construction effort, taking about two months.

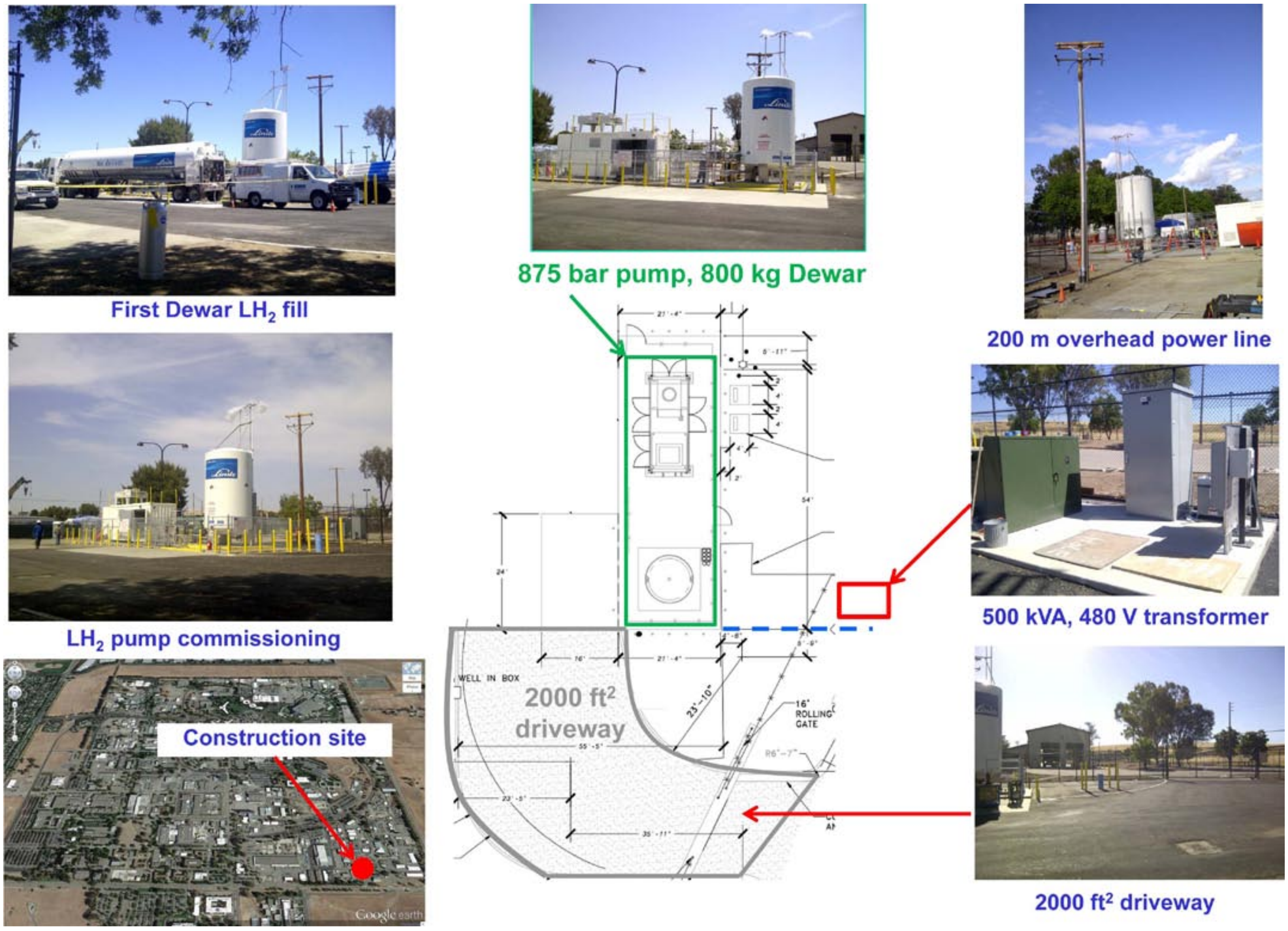

FIGURE 1. Construction-ready liquid hydrogen pump site drawing including pictures of the main features and events leading to pump commissioning.

- Pump and Dewar installation—Once the foundation was built, the pump and Dewar were installed in place.
- Fencing and paving—The final stages of construction after pump installation included fencing around the pump and around the construction site as well as paving a 2,000 ft^2 access driveway enabling liquid hydrogen trucks to make site deliveries.
- High-pressure fill line design and construction—The LLNL contract with Linde does not include a dispenser. Instead, LLNL built a high-pressure flexible fill line rated for 875 bar for dispensing high-pressure hydrogen from the liquid hydrogen pump. This fill line is 3 meters long and was assembled by welding together three commercially available hose segments.
- High-pressure fill line qualification—The high-pressure flexible fill line was cryogenically pressure tested at liquid nitrogen temperature, demonstrating a safety factor greater than 4 (Figure 2) without bursting. Based on this experimental result and detailed documentation of strength calculations in a Lawrence Livermore Safety Note [3], the fill line was approved for operation at LLNL at pressures up to 875 bar.
- Installation of liquid hydrogen and cryogenic pressurized hydrogen tubes—Linde, in collaboration with LLNL, installed vacuum-jacketed tubes connecting the Dewar and the liquid hydrogen pump. They also installed the high-pressure pump outlet line up to the refuel point, as well as vent lines connecting all relief devices to the Dewar stack.
- Commissioning—In early July 2013, the pump was operated for the first time by Linde and LLNL. The pump demonstrated operation to 350 bar (the current pressure limit set by the existing LLNL experimental vessel).
- Authorities having jurisdiction authorization—TUV SUD, a nationally recognized test laboratory, reviewed and certified the pump electric system for safe operation. Based on this certification, LLNL electric authorities having jurisdiction authorized pump operation.
- High-pressure line insulation—The high-pressure pump outlet line was insulated with 5 cm of foam. Fittings remained uninsulated because these tend to loosen after several cold cycles. Full insulation will be applied in a few weeks after enough cold cycles are performed to avoid loosening of the fittings.

Once construction and commissioning was finalized, LLNL was able to start vessel refueling operations. LLNL has conducted 11 refuels at initial temperatures between 300 K and 20 K, dispensing around 70 kg of hydrogen into the existing 151-L, 350-bar cryogenic pressure vessel.

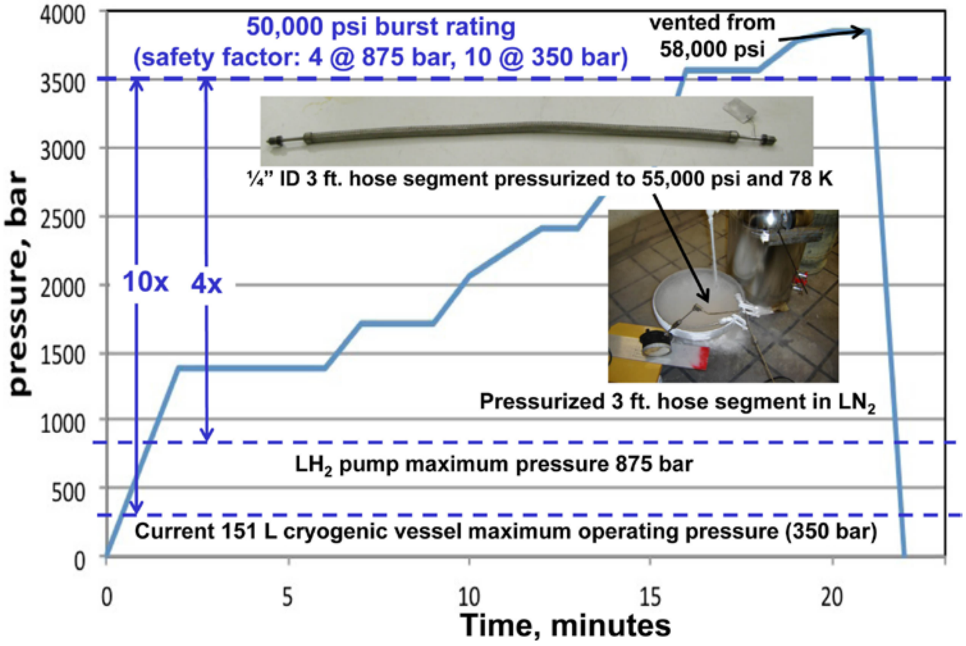

FIGURE 2. Pressure testing of cryogenic high-pressure fill line. A 3-ft long high-pressure line segment was tested while immersed in liquid nitrogen. The blue line shows pressure as a function of time during the 22-minute experiment. The target pressure (50,000 psi) was necessary for fill line certification at a safety factor of 4 over planned maximum working pressure of 875 bar. This safety factor was exceeded because the fill line was pressurized to 58,000 psi without failure.

The first step for conducting refueling experiments is precooling the high-pressure cryogenic pump outlet and flexible refuel line. Precooling was accomplished by running cryogenic hydrogen at a low flow rate for 12 minutes to reduce thermal shock and increase refuel density. This step would not be necessary in a fueling station where the line would remain cold due to frequent vehicle refuel operations.

Vessel refueling starts after precooling is concluded. Although the refueling time was quite short (~5 min), a waiting period was always held after each fill to make sure that vessel and hydrogen temperature equilibrated, thereby enabling accurate calculation of hydrogen refuel density. Including precooling, refueling, and equilibration time, each fill experiment takes about 90 minutes.

Analysis of pump refueling performance continues and demands calculation of the exact initial and final hydrogen density in the experimental 151-L cryogenic pressure vessel. Preliminary results (subject to change) indicate average total flow rate of at least 1.3 kg/min and electricity consumption between 1.3 and 1.5 kWh/kg. We anticipate that pump performance will improve when the high-pressure cryogenic pump outlet line is fully insulated.

CONCLUSIONS AND FUTURE DIRECTIONS

- Rapid, low-loss refueling of cryogenic vessels is possible through pressurized liquid hydrogen dispensing.
- LLNL installed a cryogenic high-pressure liquid hydrogen pump and Dewar and conducted preliminary refuel experiments to 350 bar.
- Further experiments are necessary to fully characterize pump performance to 350 bar with existing experimental vessel.
- Pump characterization to full pressure range (875 bar) will demand construction of a stronger experimental pressure vessel. This is planned for FY 2014-2015.

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. **Cryogenic Capable High Pressure Containers for Compact Storage of Hydrogen Onboard Vehicles,** Gene D. Berry, Salvador M. Aceves, Andrew H. Weisberg, Francisco J. Espinosa-Loza, Timothy O. Ross, European Patent EP 2,276,966, October 17, 2012.

FY 2013 PUBLICATIONS/PRESENTATIONS

1. Compact Hydrogen Storage in Cryogenic Pressure Vessels, Salvador M. Aceves, Francisco Espinosa-Loza, Elias Ledesma-Orozco, Guillaume Petitpas, in Handbook of Hydrogen Energy, Edited by S.A. Sherif, E.K. Stefanakos, and D.Y. Goswami, CRC Press, Taylor & Francis, ISBN-13: 978-1420054477, 2013.

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**, S.M. Aceves, G. Petitpas, F. Espinosa-Loza, M.J. Matthews, E. Ledesma-Orozco, International Journal of Hydrogen Energy, Vol. 38, pp. 2480-2489, 2013.

7. **Hydrogen Safety Training for Researchers and Technical Personnel,** Aceves, S.M., Espinosa-Loza, F., Petitpas, G., Ross, T.O., and Switzer, V.A., International Journal of Hydrogen Energy, Vol. 37, pp. 17497-17501, 2012.

8. **Vehicle refueling with liquid hydrogen thermal compression**, Guillaume Petitpas, Salvador M. Aceves, Nikunj Gupta, International Journal of Hydrogen Energy, Vol. 37, pp. 11448-11457, 2012.

REFERENCES

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.

3. Switzer, V., Aceves, S.M., “Cryogenic high pressure hydrogen refuel line,” Mechanical Engineering Safety Note MESN 13-500008-AA, Lawrence Livermore National Laboratory, Livermore, CA, 2013.