# III.8 Preliminary Testing of LLNL/Linde 875-bar Liquid Hydrogen Pump


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## Overall Objectives

- Demonstrate rapid (100 kg $H_2$/hr) refueling of cryogenic vessels
- Refuel cryogenic vessels even when warm and/or pressurized
- Refuel at high density (up to 80 kg $H_2/m^3$)

## Fiscal Year 2013 Objectives

Measure refuel performance of liquid hydrogen pump at 350 bar

## 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 Cost of Liquid Hydrogen Pumping

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

| Liquid hydrogen pumps | | | |
|---|---|---|---|
| **Characteristic** | **Units** | **2015/2020 targets** | **LLNL 2014 status** |
| Uninstalled capital cost (870 bar, 100 kg/hr) | $ | 150,000/150,000 | 1,300,000 |

## FY 2014 Accomplishments

Operated pump and conducted 350-bar refuel experiments:

- Verified 100 kg/hr hydrogen flow rate
- Measured <1.5 kWh/kg electricity consumption
- Refueling density of 70 g/L achieved at 340 bar, 62 K

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## INTRODUCTION

Unlike existing technologies (liquid and compressed hydrogen) that remain at nearly constant temperature during operation, cryogenic pressurized storage drifts in temperature and pressure depending on use patterns. Practical cryogenic pressurized storage demands rapid refueling under any initial operating condition, even as the vessel warms up and pressurizes due to long parking periods. Liquid hydrogen pumping promises to meet the challenge of practical cryogenic pressurized storage refueling.

## APPROACH

LLNL is researching a liquid hydrogen ($LH_2$) 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 (up to 80 g/L), and low evaporation at the pump (less than 3% of dispensed hydrogen). Evaporation at the pump does not result in hydrogen venting because evaporated hydrogen is recycled into the Dewar to maintain its pressurization. Pumped hydrogen can be directly dispensed into a cryogenic pressure vessel, even when warm and/or pressurized. As a part of this project, LLNL has installed a $LH_2$ pump and is planning to demonstrate its virtues for rapid and efficient cryogenic vessel refueling [1,2].

## RESULTS

In FY 2013, LLNL and Linde installed an $LH_2$ pump at the Lawrence Livermore campus (Figure 1). FY 2013′s annual progress report [3] covers all phases of construction, installation, and commissioning. We now report preliminary results of pump operation conducted on an existing cryogenic pressure vessel with 151 liters of capacity and 350-bar rating.

Table 2 shows technical data for the first 11 refuel experiments conducted with the pump. These experiments


**FIGURE 1.** Liquid Hydrogen Pump Installed at the LLNL Campus

are preliminary because thermal insulation on the high-pressure delivery line was lacking, the pump was not fully instrumented, and the cryogenic vessel is only rated for 350 bar vs. the 875 bar pump rating.

From Table 2, we can observe the following results.

1. Refuel density is lower than expected. In a previous year [4], LLNL developed a thermodynamic fill model that was validated by comparison with experimental data collected by BMW on a similar liquid hydrogen pump manufactured by Linde and rated at 300 bar. Preliminary results with the LLNL pump show lower refuel density than predicted by the thermodynamic fill model (Figure 2). There may be several reasons for this: (1) the LLNL delivery line was uninsulated, resulting in considerable heating of the delivered hydrogen (estimated at 3 kW); (2) due to differences between U.S. and European standards, the LLNL pump is located relatively far from the Dewar (6 meters), potentially introducing losses in the liquid hydrogen transfer line between the Dewar and the pump; (3) higher pressure lines in LLNL's 875-bar pump demand foam insulated delivery lines vs. vacuum insulated lines in BMW's 300-bar pump. Further research in oncoming years should help in developing a better understanding of how pump conditions affect refuel density.
2. The pump succeeded in delivering the target flow rate of 100 kg per hour for most experiments, and is within the experimental margin of error for the others. This is a key result that minimizes refueling cost; rapid vehicle refueling enables amortization of liquid hydrogen pump cost over many refueled vehicles.
3. Electricity consumption is higher than expected (1.5 kWh/kg $H_2$ measured vs. 1 kWh/kg $H_2$ anticipated). New instrumentation and thermal insulation in the delivery line may bring experimental results closer to anticipated values.

## CONCLUSIONS AND FUTURE DIRECTIONS

- Rapid refueling of cryogenic vessels is possible through pressurized $LH_2$ dispensing.
- LLNL installed a cryogenic high-pressure liquid hydrogen pump and Dewar and conducted preliminary refuel experiments to 350 bar.
- Experiments confirm the pump target refueling rate (100 kg $H_2$/hr). However, pump delivery density is lower than expected, and electricity consumption is higher than expected. Further experiments are necessary to fully understand these deviations.

**TABLE 2.** Summary of the first 11 experiments conducted with the liquid hydrogen pump with an uninsulated delivery line on a 350-bar, 151-liter cryogenic pressure vessel. Experiments marked in blue indicate starting conditions within the two-phase region.

| Experi-ment | Initial T K | Initial Pressure bar | Initial density g/L | Final T K | Final pressure bar | Final density g/L | $H_2$ mass pumped kg | Refuel time minutes | Average flow rate kg/hr | Steady flow rate Kg/hr | Refuel energy kWh | Refuel energy kWh/kg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 288 | 18.93 | 1.58 | 219 | 166.5 | 16.4 | 2.24 | 5 | 26.8 | | 6 | 2.62 |
| 2 | 204 | 85.1 | 9.52 | 153 | 330 | 38.6 | 4.39 | 6.5 | 40.5 | 103 | 7 | 1.58 |
| 3 | 95 | 1.25 | 0.32 | 87 | 333 | 58.5 | 8.78 | 6.5 | 81.1 | 108 | 11 | 1.22 |
| 4 | 21 | 1.25 | 5 | 74 | 340 | 64.7 | 9.0 | 7 | 77.3 | 94.2 | 13 | 1.45 |
| 5 | 21 | 1.25 | 12.5 | 67 | 338 | 67.9 | 8.4 | 6.25 | 80.3 | 94.8 | 12 | 1.48 |
| 6 | 63.2 | 51.3 | 22.4 | 84.6 | 338 | 59.9 | 5.67 | 4.38 | 77.6 | 97.2 | 8 | 1.43 |
| 7 | 21 | 1.25 | 4.13 | 71.4 | 338 | 65.8 | 9.31 | 6.46 | 86.5 | 110 | 13 | 1.39 |
| 8 | 21 | 1.25 | 11.4 | 67.1 | 338 | 67.8 | 8.52 | 5.8 | 88.1 | 111 | 11 | 1.29 |
| 9 | 21 | 1.25 | 18 | 64 | 338 | 69.3 | 7.75 | 5.6 | 83 | 106 | 10 | 1.28 |
| 10 | 21 | 1.25 | 22 | 61.9 | 339 | 70.4 | 7.31 | 5.26 | 83.4 | 106 | 10 | 1.37 |
| 11 | 21 | 1.25 | 22 | 61.9 | 339 | 70.4 | 7.31 | 5.13 | 85.5 | 108 | 10 | 1.37 |

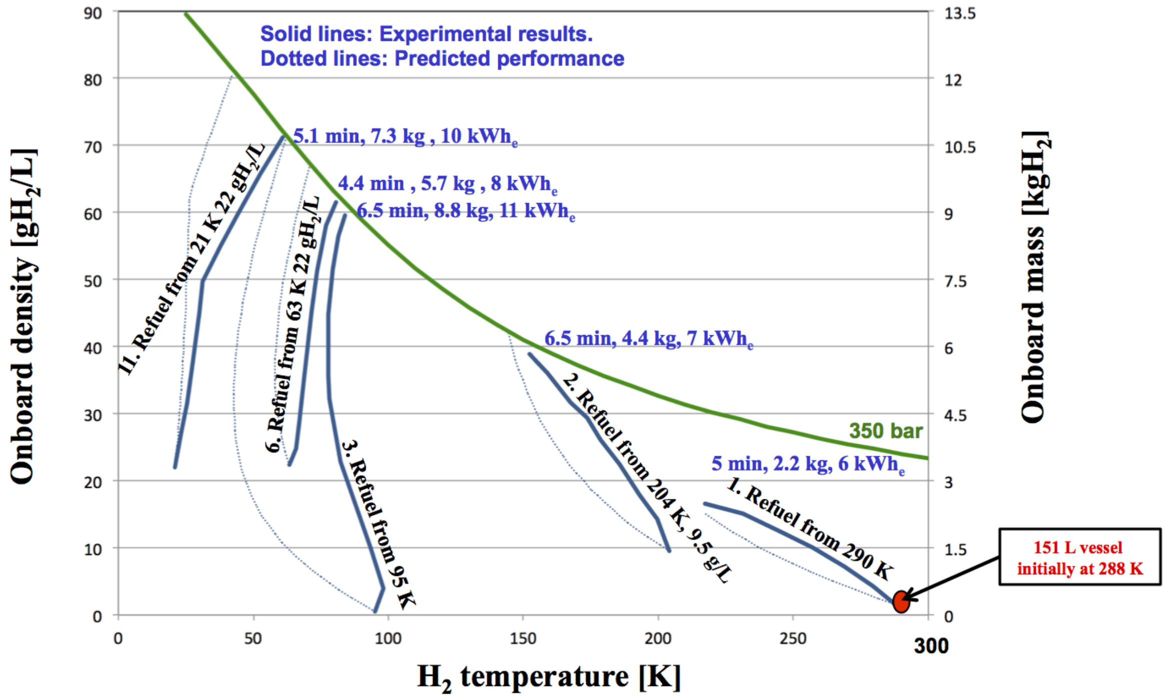


**FIGURE 2.** Onboard density vs. temperature during five refuel experiments (1, 2, 3, 6 and 11) listed in Table 2. The figure shows experimental (blue solid lines) as well as numerical (dotted lines) results for the five refuel experiments. Numerical results were obtained with a thermodynamic fill model validated by comparison with experimental data provided by BMW for a similar pump rated at 300 bar. The figure also shows a green line with density vs. temperature for 350-bar storage.

- Pump characterization to full pressure range (875 bar) will demand construction of a stronger experimental pressure vessel. This is planned for FY 2014.

## FY 2014 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**, 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.

**8. Para-H2 to ortho-H2 conversion in a full-scale automotive cryogenic pressurized hydrogen storage up to 345 bar**, Guillaume Petitpas, Salvador M. Aceves, Manyalibo J. Matthews, James R. Smith, International Journal of Hydrogen Energy, Vol. 39, pp. 6533-6547, 2014.

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**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.** Aceves, S.M., Berry, G., Espinosa-Loza, F., Petitpas, G., Switzer, V. "Rapid High Pressure Liquid Hydrogen Refueling for Maximum Range and Dormancy," FY 2013 Annual Progress Report, DOE Hydrogen Program, Washington, DC, 2013.

**4.** Aceves, S.M., Berry, G., Espinosa-Loza, F., Petitpas, G., Switzer, V. Tuholski, S., "LLNL/Linde 875 bar Liquid Hydrogen Pump for High Density Cryogenic Vessel Refueling," FY 2012 Annual Progress Report, DOE Hydrogen Program, Washington, DC, 2012.