Rapid Low Loss Cryogenic H$_2$ Refueling

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Overview

Timeline
• Start date: October 2009
• End date: September 2011
• Percent complete: 10%

Budget
• Total project funding
  – DOE: $300k
• Funding for FY09:
  – $0
• Funding for FY10:
  – $300k

Barriers
• J. Refueling site operations

Targets
• 2015 refueling efficiency

Partners
• Collaborating with Linde
  and BMW to demonstrate
  practical refueling of
  cryogenic pressure vessels
High density cryogenic hydrogen enables compact, lightweight, and cost effective storage

- **Cost effective**: Cryogenic vessels use 2-4x less carbon fiber. Substantial cost reduction with high capacity.

- **Compact**: 235 L system holds 151 L fuel (10.3-10.7 kg H₂)
Relevance: reducing or eliminating onboard evaporative losses results in vessel warming requiring pressurized refueling.
Approach: pressurize LH$_2$ for rapid refueling of cryogenic vessels with low evaporative losses and pumping power

- High LH$_2$ density minimizes pump power & compression heating

\[ \text{Pumping power} = \int \frac{dP}{\rho} \]

- Compression heating = \[ \frac{P}{\rho} \]

- Pressurized LH$_2$ pump quickly fills even warm and/or pressurized vessels

- Recycled H$_2$ vapor from pump maintains stationary vessel pressure

BMW high pressure cryogenic pump
Pressurized LH$_2$ pump delivers high density hydrogen (>70 kgH$_2$/m$^3$) at rapid flow rates

Room for improvement to even higher density via after-cooling of pressurized LH$_2$
Pressurized LH₂ refueling does not require compressor, cascade, or refrigerator; reducing station capital cost.

700 bar dispensing

35-350 bar LH₂ dispensing

Source: Argonne National Laboratory
Ambient vessels store $\text{H}_2$ always at high temperatures, safety factor only improves as vessel empties.

- **Compressed gas vessels reach maximum pressure every refueling**

Hydrogen annual merit review, LLNL, June 9, 2010, p. 8
Even when filled to 80 kg/m$^3$, cryogenic pressure vessels depressurize quickly due to isentropic cooling.
Refueling and on-road safety factors of cryogenic vessels can be very high with typical driving.

- Refueling safety factor of 10+ cold fill may not need maximum pressurization.
- Potentially fewer maximum pressure cycles reduces liner fatigue.
- On-road safety factor of 10+ due to cooling from regularly driven vehicles.
Steel vacuum jacket offers an inert vessel environment, strong secondary protection, and expansion volume

6 kg H₂, 12,500 psi, 350 K, \( \rho = 40.5 \text{ kg/m}^3 \)

6 kg H₂, 2200 psi, 80 K, \( \rho = 40.5 \text{ kg/m}^3 \)
Cryogenic operation substantially reduces expansion energy

Isentropic expansion energy to 1 atm [kWh/kg]

Comparative to absorbent refueling (15% void space, 30 bar, 360 K)

H₂ temperature, not pressure, controls theoretical maximum burst energy
Future work: we will acquire a cryogenic pump and demonstrate pressurized cryogenic refueling

- Purchase and install a pressurized cryogenic pump
- Demonstrate rapid refueling of (even warm) cryogenic pressure vessels with low evaporative losses
- Explore effect of higher pressure on evaporative losses, refueling speed and maximum vessel capacity
Collaborations: We are working with two major companies in the field of cryogenic hydrogen storage and dispensing

- **Linde**: Extensive expertise on cryogenics and liquid hydrogen automotive systems. Supplier of high pressure cryogenic pump. Delivered first ever system to BMW last year. Planning a custom design for the experimental needs of LLNL.

- **BMW**: Long standing collaboration with LLNL through cryogenic pressure vessel technology CRADA. Demonstrating first prototype cryogenic pump technology. Contributing technical information and expertise.
Summary: We look forward to demonstrating practical cryogenic pressure refueling with low evaporative losses

- **Rapid, low loss refueling** of cryogenic vessels is possible through pressurized LH\(_2\) dispensing
- **Reduce station cost** by avoiding compressor, cascade, and refrigerator
- **Improved safety** of cryogenic pressure vessels is expected from fundamental thermodynamics: cryogenic operation minimizes expansion energy and maximizes safety factor (>10 under typical operating conditions)