V.D Storage

V.D.1 Inexpensive Delivery of Compressed Hydrogen with Advanced Vessel Technology

Salvador M. Aceves (Primary Contact), Gene Berry, Andrew Weisberg
Lawrence Livermore National Laboratory
7000 East Avenue, L-644
Livermore, CA 94551
Phone: (925) 422-0864; Fax: (925) 423-7914; E-mail: saceves@llnl.gov

DOE Technology Development Manager: Mark Paster
Phone: (202) 586-2821; Fax: (202) 586-9811; E-mail: Mark.Paster@ee.doe.gov

Start Date: October 1, 2004
Projected End Date: September 30, 2007

Objectives

- Evaluate high performance containers for delivery truck applications
- Evaluate high performance containers for fueling station applications
- Examine potential synergies between H_2 delivery vessel conditions and refueling station requirements

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- A. Lack of Options Analysis
- F. Transport Storage Costs

Technical Targets

Table 1. LLNL Progress Toward Meeting DOE Hydrogen Delivery Targets

Delivery Parameter	Units	2010 Target	LLNL advanced vessel (projected)
Total cost contribution of delivering hydrogen from the production site through dispensing at the refueling site.	$/kg ($/gge)	1.70	<0.5*

*Currently projected interim costs only include truck delivery. Further analysis will consider refueling station cost estimates.

Approach

- Design conformable and cryogenic compatible pressure vessels for delivery trucks and fueling stations
- Analyze possible energy and economic savings from hydrogen delivery in advanced vessels

Accomplishments

- Identified delivery truck operational regimes in a temperature vs. density (T-ρ) diagram.

- Estimated possible savings by delivering high density hydrogen (high pressure and possibly cooled) where potential additional capital costs of trailers are balanced by reduced operating or energy costs.
- Identified preliminary design parameters for glass fiber macrolattice conformable pressure vessels for inexpensive hydrogen delivery truck trailers (~$0.50/gge).

Future Directions

- Determine favorable hydrogen storage parameters and refueling operations to minimize delivery cost from a large scale production site through dispensing at the refueling station.
- Conduct a detailed design of a truck size macrolattice pressure vessel.
- Manufacture and test small scale container components to verify performance

---

Introduction

Conventional forms of truck delivery (ambient temperature compressed H_2 gas at ~2600 psi or liquid hydrogen (LH_2) cooled to 20 K) represent extreme regions of temperature and density within the hydrogen phase diagram (Figure 1) [1]. Hydrogen delivery in today's low density compressed H_2 tube trailers is expensive (H2A based analyses suggest $1.45/kg H_2 for conventional steel tube trailers). Substantial cost reductions appear possible with development of advanced pressure vessels and/or a broadened range of thermodynamic conditions under which H_2 is trucked and delivered.

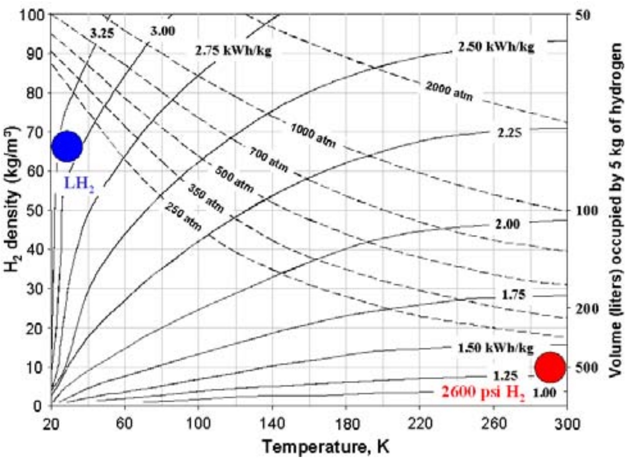

Figure 1. Hydrogen Storage Thermodynamics [Contours of pressure and minimum storage energy as a function of temperature (horizontal axis), density (left axis) and volume (right axis). The circles indicate regions of interest for conventional hydrogen delivery approaches: cryogenic LH_2 and ambient compressed H_2 at 2,600 psi.]

Herein we report interim analysis results of both approaches to reduce the cost of hydrogen truck delivery to as low as $0.50/kg H_2 using H2A based analyses provided by DOE. These savings are based on the compounding of four factors (volumetric efficiency, lower burst pressure ratio, increased storage pressure, and reduced temperature) relative to conventional tube trailers. Based on these results, on a preliminary basis, we can recommend pressures as high as 7,000 psi and cooling hydrogen to temperatures as low as 200 K for compressed hydrogen delivery by truck. Thermodynamic and infrastructure analyses will refine these conditions based on refueling station operation parameters and ranges of H2A economic assumptions.

Approach

Our approach has been to first analyze what has been developed by H2A to estimate the costs of current hydrogen delivery by truck. We then analyzed the thermodynamic properties of hydrogen, materials and design for pressure vessels, and onboard storage implications to find favorable synergies aimed at achieving substantial rather than incremental *overall* cost reductions. We developed a range of hydrogen storage and vessel design parameters which formed the technical basis for our preliminary cost estimates using delivery cost models provided by DOE. Our general tactic has been to choose delivery parameters to reduce all cost components simultaneously rather than analyze potential tradeoffs between cost components, since the first is more likely to produce a robust result for a variety of delivery logistics scenarios.

Results

Cost breakdown of conventional tube trailers

Using H2A cost models provided by DOE, delivery of 2,640 psi hydrogen by conventional steel tube trailer is estimated to cost \$1.44/kg H_2 for a 30 mile delivery distance. A cost structure examination reveals that labor, overhead, fuel, maintenance, and hazardous cargo insurance account for \$0.51/kg H_2. These costs vary in direct proportion to the quantity of H_2 delivered per trailer trip (340 kg H_2 for a tube trailer with 9 tube vessels pressurized to 2,640 psi). In addition, a \$165,000 truck tractor driven 4 trips daily and replaced every 5 years (i.e. 440,000 miles) accounts for another \$0.12/kg H_2. The remaining \$0.81/kg H_2 delivery cost is accounted for by the cost of the trailers themselves (\$165,000 for a 9 tube trailer with a total internal volume of 23.4 m^3) including an annual property tax of 1.5% (\$0.09/kg H_2 delivered).

This cost breakdown implies that deep reductions in hydrogen delivery cost will require not just trailers with lower costs, but also trailers with much greater storage capacity. The deviation of hydrogen room temperature pressure-volume-temperature (PVT) properties from the ideal gas law means that doubling the hydrogen capacity of a conventional tube trailer would require more than doubling the pressure (130% increase) to 6,200 psi. This in turn would more than double the weight of the vessels with a cost penalty of greater than 20% per kg of H_2 capacity. This cost penalty would rise substantially if higher strength steels were required to meet gross vehicle weight maximums or maintain volumetric efficiency.

Improving volumetric efficiency

A more cost-effective approach to higher trailer capacities is to improve volumetric efficiency. A tube trailer contains less than 400 kg H_2 within an internal volume of 23 m^3. This volumetric efficiency is relatively low. Large liquid hydrogen delivery trucks, for example, have internal volumes as high as 57 m^3, permitting storage of up to 4000 kg LH_2. Drawing on existing LLNL work for onboard hydrogen storage we have modeled and costed a conformable macrolattice pressure vessel design suitable for a 14 meter (45ft.) long trailer, conservatively assuming a maximum *external* vessel volume of 56 m^3, for a trailer in future widespread use.

Our design employs 1,400 identical ~40 liter unit cells built of lightweight high strength glass fiber composites (~300,000 psi tensile strength priced @ 3\$/lb). The design includes an isothermal burst pressure ratio of 1.7, comparable to a safety factor of 2.25 with allowed transient overpressures of 30% from fast-fill thermal rises.

Projected volumetric efficiencies range from 85% to 50% for hydrogen pressures of 240-720 atm (3,600-11,000 psi). At 300 K these trailer designs store between 800-1200 kg H_2, a capacity 2-3 times greater than conventional tube trailers.

Vessel costs for these designs are estimated to be between \$65,000-\$216,000 (\$80-\$180 per kg H_2 capacity). A midrange vessel pressure of 7,000 psi is projected to cost \$133,000. A 12% tax (as per H2A estimates for tube trailers) and \$15,000 for a trailer bed yields total projected trailer cost of \$165,000 – equivalent to a conventional tube trailer, but with a much larger storage capacity (1150 kg H_2). Lower pressures would reduce trailer cost, but also capacity, and increase the need for compression at the refueling station. A detailed optimization would likely result in a storage pressure below 7,000 psi, so delivery costs benchmarked to an 1150 kg H_2 capacity 7,000 psi trailer are likely conservative.

Delivery cost estimates (Table 1) based on this 7,000 psi spreadsheet design using H2A truck delivery models are \$0.92/kg H_2 for a 100 kg H_2/day station and \$0.43/kg H_2 for a 340 kg H_2/day station (scaling station demand to account for the increased capacity of the macrolattice vessel trailer relative to conventional steel tube trailer capacities). Even if our trailer cost estimates prove optimistic by a factor of 2 (i.e. up to \$330,000 for an 1150 kg H_2 trailer) macrolattice hydrogen truck delivery costs would only increase from \$0.43/kg H_2 to \$0.66/kg H_2 at a refueling station with 340 kg H_2/day demand.

Potential advantages of delivering hydrogen at reduced temperatures

Delivering hydrogen in a cooled state has multiple advantages:

- hydrogen density increases for a given pressure (35% for 7,000 psi H_2 cooled to 200 K)
- colder hydrogen can reduce fast-fill onboard hydrogen vessel temperatures, improving range and/or easing vessel requirements and associated capital costs.
- colder hydrogen rises to higher pressure when warmed, potentially reducing refueling station mechanical compression requirements.
- cooling hydrogen gas reduces its mechanical stored energy substantially, improving safety. This could potentially justify lower burst pressure ratios, with further reductions in vessel material costs and improved volumetric efficiency.
- lower temperatures substantially improve the fatigue strength of glass fibers by reducing or eliminating stress corrosion from water vapor.

These advantages merit analyzing the potential of delivering cooled compressed hydrogen by truck. It is often considered that hydrogen cooling is too expensive and energy intensive for practical applications. However, Figure 1 indicates that this is not necessarily the case. Figure 1 shows that the *theoretical* energy requirements to achieve a given hydrogen density does not increase considerably as the hydrogen is cooled from 300 K to 200 K. This is true over a wide range of densities. Consequently we have calculated the effect of storing hydrogen at 200 K on the macrolattice trailer designs outlined earlier and found substantial potential advantages.

At 200 K the strength of S-glass fibers increases approximately 50% from room temperature. This advantage, compounded with the approximate 35% increase in hydrogen density for cooling to 200 K at 7,000 psi yields very lightweight vessels using substantially less material, yet storing substantially more hydrogen. Modifying our spreadsheet model incorporating these improved parameters results in macrolattice vessel designs for trailers storing between 1200-2000 kg H_2 with estimated vessel costs of $45,000-145,000 for pressures of 3,600-11,000 psi and a temperature of 200 K. A 7,000 psi 200 K trailer would have an 1,800 kg H_2 capacity and an estimated vessel cost of $90,000. Allowing $15,000 for a trailer bed, and $45,000 for a thin wall vacuum jacket to maintain temperature would yield a $165,000 cooled macrolattice trailer (including a 12% tax noted in H2A models), corresponding to a capital cost below $100/kg H_2 capacity.

Using H2A cost models, 30 mile hydrogen delivery costs with such a trailer are estimated to be $0.83/kg H_2 for a 100 kg H_2/day station, falling substantially to $0.27/kg H_2 for a 530 kg H_2/day station (again scaled to account for the larger capacity of the macrolattice trailer relative to a conventional hydrogen tube trailer). A doubling of trailer cost to $330,000 (roughly half the cost of an LH_2 trailer) would only raise estimated delivery costs to $0.42/kg H_2 (Table 2).

Table 2. Preliminary Projected 30 Mile (50 km) H_2 Trailer Delivery Costs

Trailer Technology Capacity and Cost	\$/kg H_2 delivered @100 kg H_2/day	\$/kg H_2 delivered @ 340 kg H_2/day	\$/kg H_2 delivered @ 530 kg H_2/day
2,640 psi steel trailer 340 kg H_2, $165k	$1.44	$0.99	$0.89
7,000 psi fiberglass 1150 kg H_2, $165k	$0.92	$0.43	$0.35
7,000 psi, 200 K 1800 kg H_2, $165k	$0.83	$0.34	$0.27
7,000 psi fiberglass 1150 kg H_2, $330k	$1.65	$0.66	$0.52
7,000 psi 200 K 1800 kg H_2, $330k	$1.54	$0.58	$0.42

Cooling and compression costs for hydrogen

All of the costs mentioned above do *not* include the energy and other costs of compressing and cooling hydrogen. We will examine these costs in further detail later in the year, but at present note that the theoretical minimum energy requirements to densify hydrogen at 300 K and 200 K (from atmospheric pressure at room temperature as shown in Figure 1) are small. Electricity costs of $0.05-$0.08/kWh could imply approximately $0.10-0.20/kg H_2 in cooling and compression costs above room temperature cost of compression to 2,600 psi. On the other hand, the energy spent in cooling may be recoverable down stream in reduced costs or improved operations at the refueling station. In general, it is likely to be more cost effective to cool and compress hydrogen at a large scale central plant than a smaller scale refueling station.

Conclusions

To date we can conclude that delivery of hydrogen by more volumetrically efficient and higher storage capacity trucks can reduce the cost of hydrogen substantially, especially at station scales larger than 100 kg H_2/day (up to 500 kg H_2/day). A macrolattice based glass fiber composite vessel for a delivery trailer operating between 3,600 -7,000 psi will likely represent a broad optimum across the spectrum of hydrogen delivery parameters. Trailers storing 2-3 times more hydrogen (800-1200 kg H_2) than conventional tube trailers appear very attractive, even with somewhat conservative material cost estimates.

H2A based cost models suggest delivery costs below \$0.50/kg H_2 appear feasible if such high capacity trailers can be developed. In addition these costs are determined chiefly by increased performance (storage capacity) than by low materials costs, lending great robustness to their relative advantages. For example a *zero* cost tube trailer still has a hydrogen delivery cost of \$0.63/kg H_2 using H2A models, this cost is comparable to the delivery cost estimate for an 1150 kg H_2 capacity 7,000 psi macrolattice trailer costing up to \$330,000 (more than twice our actual cost estimate).

Cooling hydrogen to 200 K offers even greater delivery cost savings potential, and reduced dependence on glass fiber material costs, by increasing hydrogen storage capacities to between 1100-2000 kg H_2 due to compounding advantages from increased hydrogen density and strength increases of glass fibers under reduced temperatures. The additional costs of cooling and counterbalancing advantages of cold hydrogen at the refueling station need to be evaluated.

Reference

1. Gene Berry, Joel Martinez-Frias, Francisco Espinoza-Loza, Salvador Aceves, “Hydrogen Storage and Transportation,” Encyclopedia of Energy, Volume 3, pp. 267-281, Elsevier Academic Press, New York, 2004.