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

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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 Delivery section (3.2.4.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) Lack of Hydrogen/Carrier and Infrastructure Options Analysis

(F) Hydrogen Delivery Infrastructure Storage Costs

Technical Targets

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.

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 replicant conformable pressure vessels for inexpensive hydrogen delivery truck trailers (~$0.30/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 glass fiber replicant 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 ~2,600 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]. Delivering hydrogen in today's low capacity compressed H_2 tube trailers is expensive. 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.

Herein we report interim analysis results of both approaches to reduce the cost of hydrogen truck delivery to $0.50/kg H_2 or less using H2A-based analyses provided by DOE. These savings are based on the compounding of four factors (volumetric efficiency, increased storage pressure, reduced temperature, and higher strength of glass fiber at low temperature) relative to conventional tube trailers. Based on these results, on a preliminary basis, we can recommend hydrogen truck delivery carrying hydrogen gas at pressures as high as 10,000 psi, cooled to approximately 200 Kelvin (-73 degrees Celsius) in glass fiber vessels. Later thermodynamic and infrastructure analyses will refine

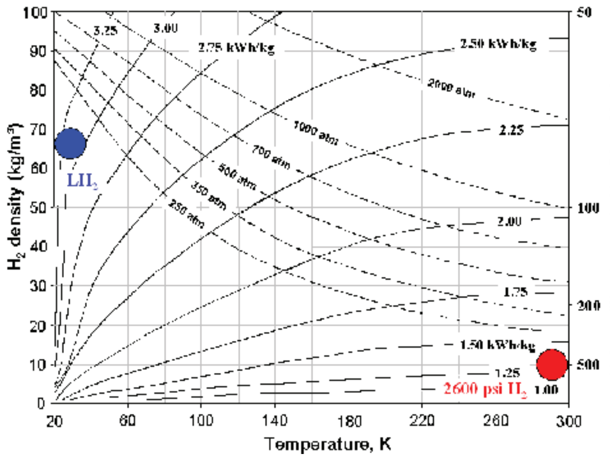

FIGURE 1. Hydrogen storage thermodynamics. Contours of pressure and minimum storage energy as a function of temperature (horizontal axis), density (left axis) and volume (right axis). The circles indicate regions of interest for conventional hydrogen delivery approaches: cryogenic LH_2 and ambient compressed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

these conditions based on refueling station operation parameters and ranges of H2A economic assumptions.

Approach

Our approach has been to use 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 was to choose delivery and trailer storage parameters which simultaneously reduce cost components rather than optimize detailed tradeoffs between cost components, since the first is more likely to produce a robust result for a variety of delivery logistics scenarios.

Results

Our analysis is based on the following preliminary operational and economic assumptions:

- 100 km delivery distance.
- Trailer drop-off time determined by capacity and station scale.
- All trailers sized to 1,300 kg H_2 capacity (1,150 kg deliverable), except for metallic compressed hydrogen trailers (up to 300 kg deliverable).
- We use real hydrogen thermodynamic and pressure-volume-temperature (PVT) properties.
- All trailers store hydrogen at 10,000 psi, except for metallic compressed hydrogen trailers (2,640 psi).
- Trailers designed for burst pressure of 22,500 psi (safety factor of 2.25).
- 300 Kelvin ambient assumed.
- Analysis is consistent with H2A methodology - H2A financial parameters are used for everything except trailer cost.
- $0.08/kWh electricity for hydrogen cooling and/or compression.
- Costs analyzed as a function of station demand from 70 kg H_2/day to 1,000 kg H_2/day.

Using these economic assumptions, we obtain the results of Figure 2. The minimum cost for hydrogen delivery in a metallic tube trailer cannot be reduced below ~$1/kg H_2, due to low capacity of the trailer magnifying the impact of labor cost. Increasing the delivery pressure (to 10,000 psi) reduces labor cost per kg H_2 for higher capital cost. The overall balance in terms of delivery cost is positive. Carbon composite tanks delivering hydrogen into a large (1,000 kg H_2/day) fueling station reduces delivery cost to ~$0.50/kg H_2, if today's composite costs are used ($430,000 per trailer). Assuming that the capital expense of the trailer (per kg H_2 capacity) tank consistent with the *automotive onboard* DOE 2010 storage cost goal ($4/kWh, or $175,000 for the trailer), a delivery cost as low as ~$0.30/kg H_2 can be projected. This, however, requires manufacture of composite tank trailers at ~40% of today's cost.

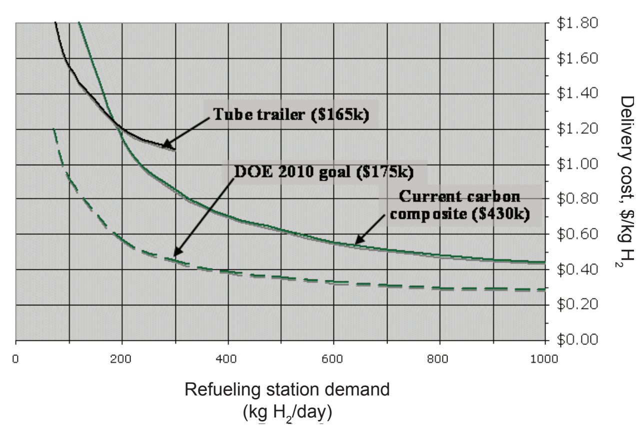

FIGURE 2. Hydrogen delivery cost as a function of fueling station size for metallic tube trailers, current carbon composite tanks, and carbon composite tanks achieving costs comparable to the DOE 2010 hydrogen storage capital expense goal for automotive onboard storage on a kg H_2 capacity basis.

We can look for reduction in delivery cost below ~\$0.50/kg H_2 by considering the whole hydrogen phase diagram. A 200 Kelvin delivery temperature can increase the density of hydrogen delivery by ~35% for a small increase in theoretical storage energy requirement. Low temperatures have the additional advantage of being synergistic with glass fiber composites. Inexpensive glass fiber strengthens 50% at 200 Kelvin (vs. 300 Kelvin), expanding weight limited trailer capacity and reducing capital expense.

We also find an advantage of making glass fiber vessels with replicant technology. Replicant vessels use an internal structure to hold the pressure, along with a thin outer skin that contains the hydrogen. The internal structure is made of "replicants," which are small structural members that fill the interior of the vessel (Figure 3). It is believed that replicant vessels will have a mass production advantage for large sizes, such as delivery trucks, where conventional filament winding technologies become difficult due to the large scale of winding machines and curing ovens. Mass production of the replicants and robotic assembly could result in trailer vessels with reduced manufacturing costs.

Figure 4 shows the cost of hydrogen delivery in light of these new delivery concepts. The figure includes the lines of Figure 2 but now adds two lines of estimated 100 km delivery cost for a replicant glass fiber vessel operating at 10,000 psi and 200 K. The dotted line shows the delivery cost of the hydrogen at 200 K. The solid line shows an estimate including the additional cooling cost of hydrogen to 200 K in a central plant.

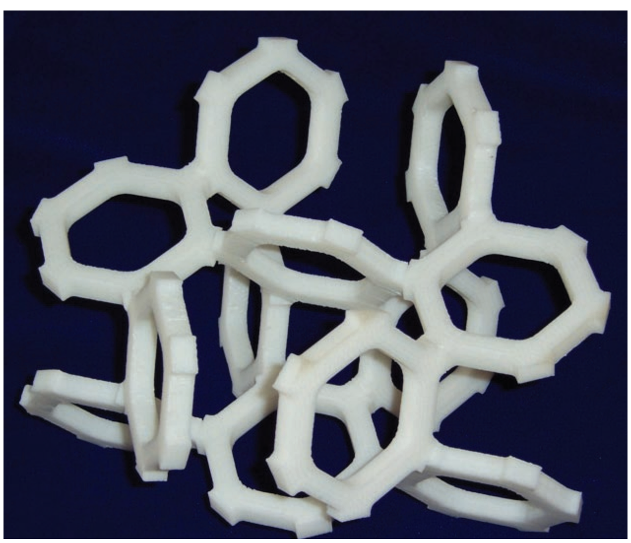

FIGURE 3. Internal Structure Made of Replicants for Conformable Pressure Vessel

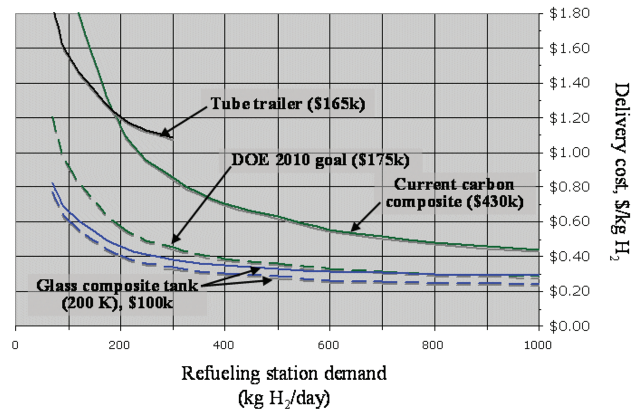

FIGURE 4. Hydrogen delivery cost as a function of fueling station size. In addition to the costs for metallic and carbon composite tanks shown in Figure 2, the figure shows costs for hydrogen delivery in glass fiber replicant vessels at 200 K and 10,000 psi without including (dotted line) and including (solid line) estimated costs of cooling the hydrogen to 200 K.

The figure shows that replicant cryogenic glass fiber can reduce the cost of hydrogen delivery to ~\$0.30/kg at today's glass fiber costs.

Conclusions

We have identified glass fiber replicant vessels as capable of delivering hydrogen at ~\$0.30/kg H_2 in large-scale (1,000 kg/day) fueling stations. This cost is much lower than possible with metallic tube trailers (~\$1/kg H_2), and it is approximately equal to the cost of delivering hydrogen in an ambient temperature composite vessel that meets the DOE 2010 storage cost goal (which has ~40% of the cost of today's carbon storage vessels). This low cost is obtained by taking advantage of the high density of hydrogen at 200 K, the relatively low cost of cooling down the hydrogen, and the high strength of glass fiber at low temperature.

An extra synergy exists which has not been captured in the above figures: delivering 200 Kelvin compressed hydrogen avoids overheating and overpressurizing of automobile storage tanks, increasing the fill speed and potentially reducing cost of automotive storage. This advantage may be as important as the reduction in delivery cost.

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.