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# Cold hydrogen delivery in glass fiber composite pressure vessels: Analysis, manufacture and testing

*Andrew H. Weisberg* [a], *Salvador M. Aceves* [a,*], *Francisco Espinosa-Loza* [a], *Elias Ledesma-Orozco* [a], *Blake Myers* [a], *Brian Spencer* [b]

[a] *Lawrence Livermore National Laboratory, CA 94550, USA*
[b] *Spencer Composites Corporation, USA*

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ABSTRACT

This paper describes Lawrence Livermore National Laboratory (LLNL) and Spencer Composites Corporation (SCC) efforts in demonstrating an innovative approach to hydrogen delivery. This approach minimizes hydrogen delivery cost through utilization of glass fiber pressure vessels at 200 K and 70 MPa to produce a synergistic combination of container characteristics and properties of hydrogen gas: (1) hydrogen cooled to 200 K is ~35% more compact for a small increase in theoretical storage energy (exergy); and (2) these cold temperatures (200 K) strengthen glass fibers by as much as 50%, expanding trailer capacity without the use of much more costly carbon fiber composite vessels.

Analyses based on US Department of Energy H2A cost and efficiency parameters and economic methodology indicate the potential for hydrogen delivery costs below $1/kg $H_2$ (not including storage at the terminal, and cascade, compression, and chilling at the forecourt, but including compression and refrigeration at the terminal). Further savings are possible by integrating the delivery trailer into the station cascade to avoid chilling typically required for 700 bar hydrogen dispensing.

The report also describes experimental work leading to demonstration of the potential for low cost delivery, starting with measurement of cold glass fiber strengthening, and continuing with subscale and full-scale pressure vessel development and testing, and concluding with successful development of an ASME X certifiable full-scale (60 cm diameter) glass fiber pressure vessel made of innovative materials with potential to meet the cost targets when integrated into an insulated tube trailer.


## 1. Introduction

Today's hydrogen delivery technologies [1–3] occupy the extremes of the phase diagram (Fig. 1). Hydrogen is often delivered as a compressed gas at ambient temperature, high pressure, and relatively low density. Hydrogen is also delivered at much higher density as a cryogenic liquid with higher energetic cost.

Substantial reduction in delivery cost and energy appears possible with development of advanced pressure vessels and a broadened range of thermodynamic conditions under which hydrogen is trucked and delivered (Fig. 1). This paper

* Corresponding author.
E-mail addresses: acevesss@gmail.com, saceves@llnl.gov (S.M. Aceves).
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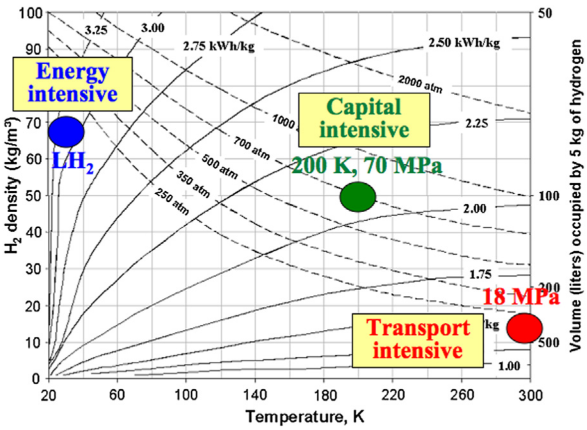


**Fig. 1 – Commercial hydrogen delivery technologies occupy the extremes of this phase diagram. Hydrogen is often delivered as a compressed gas (red dot) at ambient temperature (horizontal axis), high pressure (dotted lines), and relatively low density (vertical axis). Hydrogen is delivered at much higher density as a cryogenic liquid (blue dot) with higher energetic cost (solid lines indicate the theoretical minimum work, also known as thermomechanical exergy necessary to densify hydrogen). Analyzing the entire phase diagram offers the possibility of finding operating conditions (such as 200 K and 70 MPa) that may offer a favorable trade-off between the high transport cost of compressed hydrogen and the high-energy cost of hydrogen liquefaction. The challenge is to operate in this region while keeping capital costs under control. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)**

describes the results of analyzing these approaches using the Department of Energy's (DOE) H2A infrastructure analysis tool [4] applied to the cost of hydrogen truck delivery. These cost savings are based on the compounding of three factors relative to conventional tube trailers: increased storage pressure, reduced temperature, and higher strength of glass fiber at low temperature. Integrating the tube trailer with the station cascade will further reduce delivery cost by eliminating hydrogen chilling typically necessary for rapid refueling at 700 bar.

H2A [4] is used to estimate the costs of hydrogen delivery by truck from candidate pressure vessel designs. These designs embody the thermodynamic properties of hydrogen, choice of structural materials, optimization of operating pressure and temperature, and onboard storage implications. These candidates allowed finding favorable synergies aimed at achieving substantial rather than incremental *overall* cost reductions. A range of hydrogen storage and vessel design parameters was developed, which form the technical basis for cost estimates using H2A delivery cost models. The general strategy has been to choose delivery and trailer storage parameters that *simultaneously* reduce cost components rather than optimize detailed tradeoffs between cost components, since the first approach is more likely to produce a robust result for a variety of delivery logistics scenarios.

Following the cost analysis results, the paper describes the experimental approach undertaken to demonstrate the potential to meet $1/kg $H_2$ delivery cost (including compression and refrigeration at the terminal but not including storage at the terminal, and cascade, compression, and chilling at the forecourt). The experimental effort includes testing of cryogenic glass fiber strengthening, small-scale glass fiber development using innovative ROMP (Ring Opening Metathesis Polymerization) resins and liners, and full-scale vessel development concluding with demonstration of an ASME X certifiable pressure vessel.

## 2. Delivery cost analysis

We present a short summary of the cost analysis. For more detail, please see a previous publication [5].

Cost analysis is based on the following operational and economic assumptions:

- 50 km one-way (100 km round trip) delivery distance from production site to fueling station.
- Trailer drop-off time determined by trailer capacity and station scale (throughput in kg-$H_2$/day).
- Trailers sized to 1300 kg $H_2$ capacity (1000 kg deliverable; trailer returns to the production site with 300 kg $H_2$), except for metallic compressed hydrogen trailers (300 kg $H_2$ deliverable).
- Hydrogen thermodynamic and Pressure–Volume–Temperature (PVT) properties from the NIST computerized database [6].
- All trailers store hydrogen at 70 MPa, except for metallic compressed $H_2$ trailers (18 MPa).
- Trailers are designed for a safety factor of 2.25 (burst pressure 157.5 MPa in 70 MPa vessels).
- Hydrogen is delivered to stations at either 200 K (glass fiber vessels) or 300 K (metallic and carbon fiber vessels).
- Analysis is consistent with H2A methodology [4]. H2A financial parameters are used for everything except trailer and refrigerator cost (not available in H2A database).
- Electricity cost at $0.08/kWh for hydrogen compression and/or cooling.
- Analysis assumes a refrigerator 30% as efficient as an ideal (Carnot) refrigerator. This efficiency is comparable to existing hydrogen liquefaction plants [7].
- Refrigerator capital costs are difficult to calculate due to the complex and proprietary nature of large-scale low temperature refrigerators. While natural gas liquefiers are in widespread use and may guide cost analysis of low temperature refrigerators, detailed modeling of these proprietary systems remains a challenge [8,9]. We therefore assume that refrigerator capital cost (in dollars per kg $H_2$) is equal to the cost of electricity driving the refrigerator. We look forward to more detailed refrigerator cost analysis that may improve on this assumption and therefore assist in further optimizing the hydrogen delivery process.
- We analyze costs as a function of station demand from 70 kg $H_2$/day to 1000 kg $H_2$/day.

The analysis includes driver cost in addition to the capital and energy costs of hydrogen compression, hydrogen