IV.F.2 Cost Analysis of Hydrogen Storage Systems

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Objectives

The overall objective for this project is to provide independent analysis to help guide the DOE and developers toward promising research and development (R&D) and commercialization pathways by evaluating the various on-board hydrogen storage technologies on a consistent basis. Specific objectives include:

- Compare different on-board hydrogen storage approaches in terms of lifecycle costs, energy efficiency and environmental impact;
- Identify and compare other performance aspects that could result in barriers to successful commercialization (e.g., on-board system weight and volume);
- Examine the effects of system-level cost and performance trade-offs for different storage approaches; and
- Project performance and cost relative to DOE targets.

Technical Barriers

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

(A) System Weight and Volume
(B) System Cost
(K) System Life-Cycle Assessments

Technical Targets

This project evaluates the various on-board hydrogen storage technologies being developed by the DOE Hydrogen Storage Centers of Excellence and independent projects. Insights gained from these evaluations will help guide DOE and developers toward promising hydrogen storage materials and system-level designs and approaches that could meet the DOE targets for storage system cost, specific energy, energy density, fuel cost and efficiency.

Accomplishments

We have performed preliminary evaluations on cryo-compressed, liquid, and activated carbon hydrogen storage systems based on recent literature and developer input, in particular from Argonne National Laboratory (ANL) and Lawrence Livermore National Laboratory (LLNL). Accomplishments include:

- Independently evaluated and confirmed system-level conceptual designs for on-board storage systems;
- Projected on-board system performance and high-volume manufactured cost;
- Determined the most important cost drivers and conducted single- and multi-variable sensitivity analyses to bound cost results;
- Reviewed key assumptions and results with developers, DOE, and stakeholders (e.g., material suppliers, national labs, FreedomCAR and Fuel Partnership Tech Teams) and incorporated their feedback into the final results; and
- Compared performance and cost results to baseline technologies (5,000 and 10,000 psi storage systems) and DOE targets for the on-board storage system.

In addition, preliminary results have been generated for the off-board (i.e., fuel cycle) cost, energy efficiency, and greenhouse gas emissions from sodium borohydride (SBH) and magnesium hydride hydrogen storage pathways. These preliminary results are being reviewed by developers, DOE, and stakeholders.

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Introduction

DOE is funding the development of a number of hydrogen storage technologies as part of its “Grand

Challenge" applied R&D program. This independent analysis project helps guide the DOE and Grand Challenge participants toward promising R&D and commercialization pathways by evaluating the various hydrogen storage technologies on a consistent basis. Using this consistent and complete comparison of various technology options, R&D can be focused and accelerated. Without such an approach, erroneous investment and commercialization decisions could be made, resulting in wasted effort and risk to the development of hydrogen vehicles and a hydrogen infrastructure.

TIAX is conducting system-level evaluations of the on-board storage systems' cost and performance, as well as the well-to-wheel (or lifecycle) cost, primary energy use, and environmental impact for three broad categories of on-board hydrogen storage. The three categories of storage are reversible on-board (e.g., metal hydrides and alanates), regenerable off-board (e.g., chemical hydrides), and high-surface-area sorbents (e.g., carbon-based materials). Evaluations are based on developers' on-going research, input from DOE and key stakeholders, in-house experience, and input from material experts.

Approach

This project utilizes an approach that is designed to minimize the risks associated with achieving the project objectives. In coordination with ANL and other analysis activities, system-level conceptual designs are developed for each on-board storage system and required fueling infrastructure. Next, system models and cost models are used to develop preliminary performance and cost results. We utilize in-house activities- and product-based cost models to determine high-volume manufactured cost projections for the on-board storage system, and H2A-based discounted cash flow models to estimate hydrogen selling prices based on the required off-board hydrogen infrastructure. Subsequently, these results are vetted with developers and key stakeholders and refined based on their feedback. Coordination with DOE's Hydrogen Storage System Analysis Working Group avoids duplication and ensures consistency. This is an on-going and iterative process so that DOE and its contractors can increasingly focus their efforts on the most promising technology options.

Prior on-board cost and performance assessments (e.g., compressed hydrogen, sodium alanate, and SBH reported last year) were based on detailed technology evaluation and bottom-up cost modeling for both materials and processing. Under direction of the DOE, and to accelerate preliminary results, the focus in the past fiscal year has been on conducting less detailed cost estimates for on-board storage systems utilizing cryo-compressed, liquid hydrogen, and activated carbon hydrogen storage techniques. We worked with developers to obtain a bill of materials (BOM) and a set of operating conditions on which to base the cost estimates. Using these inputs, we developed preliminary high-volume (~500,000 units/year) cost estimates which included an assumed tank processing cost factor. The preliminary results were compared with previously analyzed on-board storage technologies and presented to developers and stakeholders. Currently, feedback is being solicited from cryogenic and compressed gas tank manufacturers to improve the accuracy of the material and processing cost estimates.

Results

We used the LLNL second generation cryo-compressed tank [4] as the design basis for our cryo-compressed system cost estimate. The LLNL tank is a hybrid cryogenic and compressed hydrogen storage system that aims to lower the carbon fiber costs per hydrogen capacity, extend dormancy, and allow for flexible (i.e., both liquid and gaseous hydrogen) refueling. The 151-liter tank allows for a maximum of 10.7 kg of liquid hydrogen storage, and 10.1 kg of "usable" hydrogen based on a 94% drive cycle utilization calculated by ANL [2]. A detailed BOM and operating conditions were obtained from both LLNL and ANL [2,4]. We used netting analyses to validate the tank's carbon fiber requirement, which proves to be the most critical cost variable. Using the compiled inputs, we estimated the material and balance of plant (BOP) costs to be \$6.80/kWh H_2, based on 10.1 kg of "usable" hydrogen. However, we did not evaluate a detailed manufacturing process (and corresponding processing cost) specifically for the cryo-compressed storage system. Based on initial developer feedback, we applied a fixed tank processing cost factor of 50% on top of the total tank material costs to arrive at a total high-volume system cost of \$8.40/kWh H_2 as a preliminary estimate. We are working with cryogenic tank and compressed gas tank manufacturers to develop a more detailed high-volume cost estimate.

TIAX also developed a preliminary cost model for an activated carbon (AC) storage system. Our cost estimate is based on a system using the activated carbon AX-21 as an in-tank absorbent, modeled by ANL [1]. The AX-21 system operates at 100 K and up to approximately 3,000 psi, and therefore resembles the design of the cryo-compressed tank. The AC system also has similarities to the previously analyzed sodium alanate tank insofar as its in-tank heat exchanger and aluminum foam media support requirements. Based on the ANL-estimated 42 kg/m^3 of recoverable hydrogen for the given operating conditions (and a 50 K temperature swing), we calculated an overall tank volume of 175 L for 5.6 kg of usable hydrogen storage. This volume includes an in-tank heat exchanger and 2-wt% aluminum foam. The AX-21 media, which proves to be an important cost variable, is currently manufactured in volumes several orders of magnitude less than would be required for 500,000 hydrogen tanks per year. We used a relatively low-volume cost estimate from the Kansai Coke and Chemical Company [3] and projected the cost at high-volume to be $7 per pound in today's dollars. The AC system with a usable hydrogen capacity of 5.6 kg is estimated to cost $15.6/kWh H_2, based on our preliminary set of input assumptions.

Finally, a preliminary liquid hydrogen (LH_2) storage system cost was estimated based on the BOM of the cryo-compressed system. The main difference between the two tanks is that the lower pressure LH_2 tank does not require a carbon fiber composite layer. LH_2 systems are also more likely to require a boil-off management sub-system to extend dormancy. Finally, the LH_2 BOP components may be de-rated for lower pressure operation. Very early results show the LH_2 system costs to be as low as $4.9/kWh H_2 for a 10.1 kg (usable) LH_2 tank. Again, the assumed tank processing cost factor contains a high level of uncertainty, and we are working with manufacturers to develop a more accurate, high-volume cost estimate. Initial developer feedback suggests the LH_2 tank cost estimate will likely increase.

The preliminary results for all three cost estimates are plotted in Figure 1 along with other previously evaluated storage technologies. Note that cost per kWh is expected to be less for the larger tank capacities (i.e., cryo-compressed and LH_2) mainly because BOP costs are not significantly affected by tank size. For each storage system, we conducted single- and multi-variable sensitivity analyses to evaluate the effects of the uncertainties of critical cost variables. These variables are the focus of on-going discussions with developers and stakeholders. As an example, Figure 2 shows the underlying critical cost variables for the cryo-compressed system along with their uncertainties. Figure 3 illustrates the single-variable sensitivity analysis results based on those cost variables.

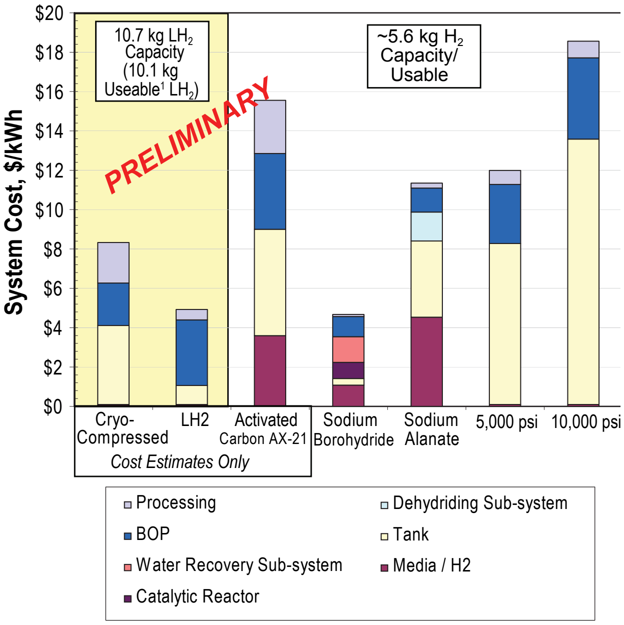

FIGURE 1. Preliminary On-Board Storage System Cost Results

In addition to on-board storage analysis activities, we conducted an off-board storage assessment of the earlier SBH system based on published information (see Lasher et al 2007 for details) and reviewed our preliminary results with Millennium Cell, Rohm & Haas and other stakeholders. The off-board storage analysis includes an estimate of the cost and energy inputs for SBH reprocessing, trucking, and vehicle fueling. We developed base-case assumptions and cost estimates for the reprocessing system, which include the purchase of one mole of sodium (Na) per mole of SBH, as well as recycling the NaOH with hydrogen-assisted electrolysis. We also analyzed the capacity limitations for hauling SBH and spent material and developed modified H2A Delivery Component models to analyze trucking, reprocessing and forecourt costs. Figure 4 illustrates a preliminary comparison of the equivalent hydrogen price for SBH, compressed gaseous hydrogen (cH_2), and LH_2.

Conclusions and Future Directions

Although this year's cost estimates were conducted in less detail than prior assessments, important knowledge was gained in a short period of time about critical cost components for each system, which enables focused discussion with tank developers and manufacturers.

- Cryo-compressed on-board storage costs are governed by carbon fiber related variables including fiber and matrix costs, translation strength, and safety factor, as well as system processing costs. Preliminary results show system costs falling between those of LH_2 and 5,000 psi cH_2 storage systems.
- Activated carbon storage costs are governed by carbon fiber costs, processing costs, and the cost of the AX-21 storage media. The preliminary cost estimate places the AC system between the 5,000 and 10,000 psi cH_2 systems.
- LH_2 on-board storage costs may be driven by boil-off management sub-systems as well as processing costs. We need a better understanding of each. Preliminary results show the 10.1 kg LH_2 system costs approaching the 2010 DOE on-board storage cost target, but these results are being updated.
- Raw material costs, in particular make-up Na costs, are a key cost driver for SBH refueling. The equivalent hydrogen selling price for SBH refueling is significantly more expensive than compressed

FIGURE 2. Critical Cost Variables and Estimated Value Ranges for the Cryo-Compressed System

Key Sensitivity Parameters	Cryo-Compressed Key Variable Assumptions			
	Baseline	Min	Max	Comments/Source
Carbon Fiber Composite Cost ($/lb)	14.6	12.8	25.5	◆ Includes Epoxy (1.27x CF) ◆ Baseline from TIAX (2003) inflated to 2005$ ◆ Min and max based on developer input
Processing Cost Markup (%)[1]	50%	10%	100%	◆ Min equivalent to compressed-only tanks; max based on cryo-tank developer comments
Safety Factor	2.25	1.80	3.00	◆ Baseline assumes a typical industry factor ◆ Min and max based on Quantum and Dynatek, respectively
Carbon Fiber Translation Strength (%)	81.5%	78%	85%	◆ Estimates reported by Quantum for 5,000 psi tanks
Fill Port Cost ($)	90	90	170	◆ Industry interviews (2003), inflated to 2005$ ◆ Need to develop bottom up cost for min
Stainless Steel (SS304) Cost ($/kg)	2.7	2.1	3.1	◆ Baseline from TIAX (2003) inflated to 2005$
Regulator Cost ($)	170	140	200	◆ Industry interviews (2003), inflated to 2005$

[1] The processing cost markup is applied to the tank cost.

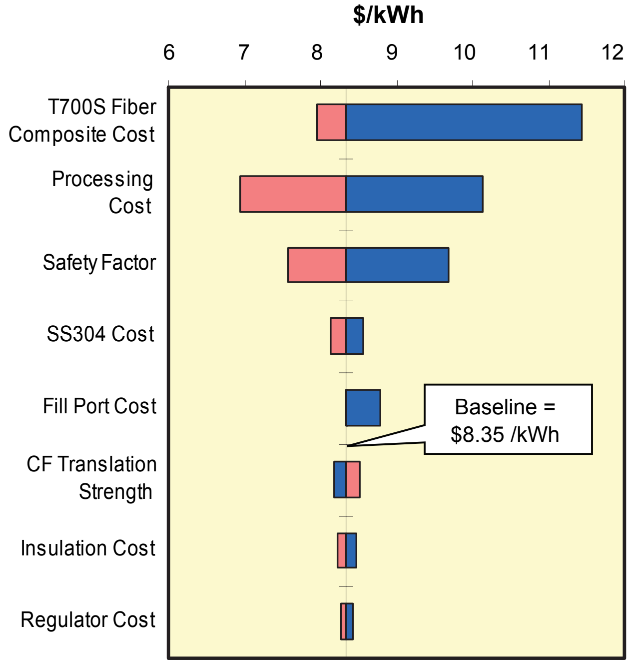

FIGURE 3. Single-Variable Sensitivity Analysis Results for Cryo-Compressed System

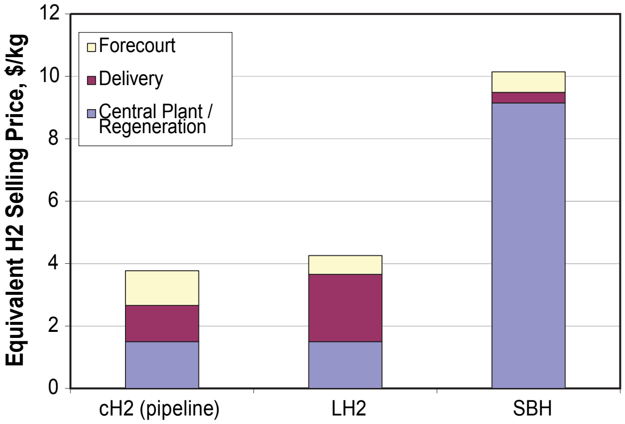

FIGURE 4. Preliminary Hydrogen Selling Price Comparison

or liquid hydrogen pathways based on the SBH regeneration process evaluated to date.

The rest of this fiscal year, we plan to continue to work with developers and stakeholders to improve the accuracy of the on-board and off-board system models analyzed to date.

- Incorporate developer and manufacturer feedback and generate final results for cryo-compressed, liquid hydrogen, and activated carbon storage systems;
- Complete SBH on-board and off-board assessments incorporating the latest R&D results from MCell, Rohm & Haas, and Penn State University and provide input to the SBH go/no-go decision; and
- Update all hydrogen storage systems as necessary to ensure an accurate comparison of storage technologies.

In the next fiscal year, we will evaluate other storage technology options as directed by the DOE. The first option will likely be an additional regenerable off-board technology, such as the Air Products chemical hydrogen storage system.

FY 2007 Publications/Presentations

1. Hooks, M., Unnasch, S., Lasher, S.; “H_2 Novel Carriers: Major Issues & Next Steps”; Hydrogen Delivery Analysis Meeting; Washington, DC; February 20, 2007.

2. Unnasch, S., Hooks, M., Lasher, S. (TIAX), and Ringer, M. (NREL); “H2A Hydrogen Carrier Analysis”; presented by Lasher at the Annual NHA Meeting; San Antonio, TX; March 21, 2007.

Presentations made by S. Lasher et al under the title “Analyses of Hydrogen Storage Materials and On-Board Systems” since last year:

3. FreedomCAR and Fuel Partnership Hydrogen Delivery Tech Team Meeting; June 2006, Columbia, MD.

4. DOE Storage System Analysis Working Group Meeting; December 2006, Washington, D.C.

5. FreedomCAR and Fuel Partnership Hydrogen Storage Tech Team Meeting; April 2007, Detroit, MI.

6. DOE Annual Hydrogen Merit Review; May 2007, Crystal City, VA.

References

1. Ahluwalia, R. K., 2005, “Systems Analysis of Hydrogen Storage at Low Temperatures,” Argonne National Laboratory, December 16, 2005.

2. Ahluwalia, R. K. et al., 2006, “Independent Review of Cryo-compressed Storage of Hydrogen: Interim Report,” Argonne National Laboratory, Hydrogen Storage Tech Team Meeting, August 2006.

3. Directed Technologies, Inc (DTI), 1996, “Comparison of Onboard Hydrogen Storage for Fuel Cell Vehicles,” Task 4.2 Final Report under Subcontract 47-2-R31148, May 1996.

4. Lawrence Livermore National Laboratory, 2006, “Why Insulate Pressure Vessels,” Component List Aug 17 06.pdf.

5. Lasher, S. et al; “Analyses of Hydrogen Storage Materials and On-Board Systems,” DOE Annual Hydrogen Merit Review, May 17, 2007.