IV.E.4 Hydrogen Storage Cost Analysis, Preliminary Results

Brian D. James (Primary Contact),
Andrew B. Spisak, Whitney G. Colella
Strategic Analysis, Inc.
4075 Wilson Blvd. Suite 200
Arlington, VA 22203
Phone: (703) 778-7114
E-mail: bjames@sainc.com

DOE Managers
HQ: Grace Ordaz
Phone: (202) 586-8350
Email: Grace.Ordaz@ee.doe.gov
GO: Katie Randolph
Phone: (720) 356-1759
Email: Katie.Randolph@go.doe.gov

Contract Number: DE-EE0005253

Project Start Date: September 30, 2012
Project End Date: September 29, 2016

Fiscal Year (FY) 2012 Objectives

- Develop cost models of carbon fiber hydrogen storage pressure vessels.
- Explore the sensitivity of pressure vessel cost to design parameters including hydrogen storage quantity, storage pressure, and the number of vessels.
- Validate pressure vessel cost model results and sensitivities against measured data for industry partner costs.
- Develop cost models for the off-board recycle cost of spent chemical hydrogen storage media (hydrogen depleted materials from the alane and ammonia borane onboard storage systems).

Technical Barriers

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

(B) System Cost
(H) Balance of Plant (BOP) Components
(K) System Life-Cycle Assessments

Technical Targets

This project conducts cost modeling to attain realistic, process-based system costs for a variety of hydrogen storage systems. These values can help inform future technical targets for System Storage Cost.

- System Storage Cost: to be determined

FY 2012 Accomplishments

- Prepared a cost model and completed a preliminary cost analysis of onboard compressed hydrogen storage pressure vessels. Preliminary analysis identifying a total cost of $13.11 kilowatt-hour (kWh) of hydrogen energy for a 70 megapascal (MPa, 10,000 pounds per square inch, psi), 5.6 kilograms (kg) hydrogen (H_2) pressure vessel system produced at a rate of 500,000 systems per year.
- Conducted a pressure vessel sensitivity study to explore the cost effect of tank storage capacities of 4 to 8 kg of H_2 per tank and manufacturing rates of 10,000, 30,000, 80,000, 130,000, and 500,000 vessels per year.
- Initiated cost analysis of the off-recycle process of spent ammonium borane (BNH_2) back into an ammonia borane (AB or BH_3NH_3) slurry suitable for use in a vehicular onboard H_2 storage system.
- Initiated cost analysis of the off-recycle process of aluminum (spent alane) back into an alane slurry suitable for use in a vehicular onboard alane (AlH_3) H_2 storage system.

✧ ✧ ✧ ✧ ✧

Introduction

To better assess differing technologies for fuel cell vehicle (FCV) hydrogen storage, it is important to have an understanding of the potential cost of each technology, and the primary drivers underlying those costs. The aim of this project is to obtain realistic, process-based system costs for a variety of hydrogen storage systems and to use those cost models to determine sensitivity to design parameters, manufacturing methods, system components, and materials costs. Through this process, it is possible to demonstrate the impact of DOE technical targets and barriers on the overall system cost. These results can be used to gauge and guide future DOE Research and Development efforts by identifying the most fruitful research paths to cost reduction.

During the first year of the project, onboard hydrogen storage in pressurized carbon composite pressure vessels was selected for analysis. While this system has been previously analyzed by DOE, the objective is to update and expand the cost analysis while also validating the cost analysis methodology and results against industry estimates, thereby increasing confidence for future cost analysis projects. Additionally, two off-board chemical hydride recycle systems were selected for cost analysis: regeneration of ammonia borane and alane from their respective spent fuel. The vehicular onboard components of these systems have been previously analyzed. However, an assessment of the off-board recycle costs is needed to allow DOE to assess the full cost of the storage method.

Approach

To generate cost estimates for the compressed hydrogen pressure vessel system, a Design for Manufacturing and Assembly (DFMA®)-style analysis was conducted. Key system design parameters and an engineering system diagram describing process flows were obtained from a combination of industry partners, Argonne National Laboratory (ANL), and members of the DOE's Hydrogen Storage Engineering Center of Excellence (HSECoE) [1]. From this system design, the physical embodiment of the system was developed, including materials, scaling, dimensions, and design. Based on this physical embodiment, the manufacturing process train was modeled to attain the cost to manufacture each part. Industry partners were consulted to assess current and future manufacturing procedures and parameters. Cost was based on the capital cost of the manufacturing equipment, machine rate of the equipment, equipment tooling amortization, part material costs, and other financial assumptions. Once the cost model was complete for the system design, sensitivity data for the modeled technology are obtained by varying the key parameters. These results are shared with ANL, the National Renewable Energy Laboratory, and industry partners to obtain feedback and further refine the model.

The analysis explicitly includes fixed factory expenses such as equipment depreciation, tooling amortization, utilities, and maintenance as well as variable direct costs such as materials and labor. However, because this analysis is intended to model manufacturing costs, a number of components that usually contribute to the original equipment manufacturer price are explicitly not included in the modeling. The following costs are excluded in this analysis: profit and markup, one-time costs such as non-recurring research/design/engineering, and general expenses such as general and administrative costs, warranties, advertising, and sales taxes.

The off-board recycle cost analysis for the alane and AB systems is based on a less-detailed cost analysis methodology. For each of the systems, a process flow diagram is developed based on input from ANL. The AB recycle system is based on the Los Alamos National Laboratory one-pot process using hydrazine to recycle spent AB (BN_2) back into AB (BH_3NH_3) [2-4]. Since hydrazine is a major cost contributor in the recycle process, hydrazine cost is independently analyzed based on the benzophenone process, which converts ammonia, oxygen, and water into hydrazine [5]. The alane recycle system is based on the dimethylethylamine (DMEA) process [6]. Both recycle systems are nominally sized for a central plant with an equivalent capacity of 100 metric tons per day of hydrogen. A modified form of the H2A hydrogen production cost analysis spreadsheet [7] is used to assess recycle cost. While we do not seek to compute hydrogen production costs, the H2A model is based on a discounted cash flow tool that applies to this recycle analysis. Furthermore, the H2A model is a transparent and familiar tool to the hydrogen community. Recycle cost are computed per kg of H_2 eventually releasable onboard the vehicle. Capital cost of the systems are estimated by a summation of major subsystem identified on the process flow diagram, and are based on hand-book [8] capital cost correlations for the type of subsystem and pertinent scaling factors (such as flow rate, pressure, temperature, etc.).

Results

The pressure vessel baseline system was defined with the following parameters and characteristics:

H_2 Stored (usable and dispensable as fuel)	5.6 kg
H_2 Stored (total)	5.77 kg
Rated Pressure	700 bar (10 kpsi, 70 MPa)
Number of Tanks	1
Pressure Vessel Type	Type 4
Liner Thickness	5 millimeters (mm)
End Caps	Foam, energy-absorbing
Boss Material	316 stainless steel
Water Volume (interior)	145 L
Vessel External Diameter	563 mm
Vessel External Length	900 mm
Carbon Fiber Type	T-700S carbon fiber
Carbon Fiber Tensile Strength	4.9 gigapascals (GPa) (711 kpsi)
Carbon Fiber Modulus	230 GPa (33.4 Mpsi)
Safety Factor	2.25
Translation Efficiency	80%
Fiber Strength Rating	100%

For the modeled baseline system, costs are broken down into three broad categories:

(1) manufacturing and tooling
(2) BOP and assembly
(3) materials

Figure 1 shows preliminary results for the baseline compressed gas system. Note that research is ongoing, with assumptions continuing to be vetted and improved after discussion with industry and the HSECoE. The results show that materials cost declines only very slightly with manufacturing rate (~13% over a production increase from 10,000 systems/year to 500,000 systems/year) while manufacturing and tooling cost declines dramatically (~60% over the same range).

The results from sensitivity studies demonstrated the effects of varying tank design parameters. Figure 2 shows the variation of system cost with usable H_2 storage capacity at different annual production rates. The H_2 storage cost per unit of energy ($/kWh) decreases steadily and approximately linearly as usable H_2 storage capacity increases. At the same storage capacity, the H_2 storage cost per unit energy also decreases with increase annual production rate.

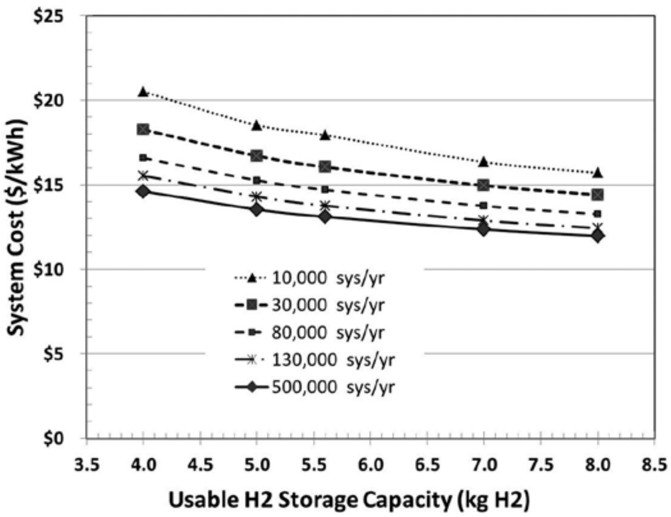

FIGURE 1. System Cost Breakdown for Multiple Manufacture Rates

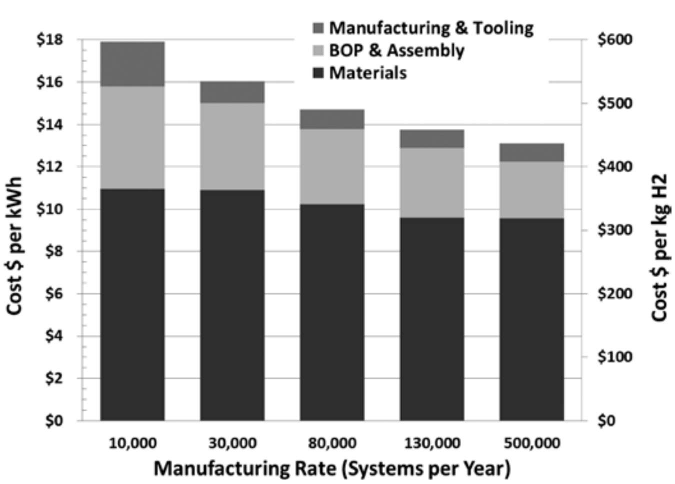

FIGURE 2. Pressure Vessel System Useable H_2 Storage Capacity Sensitivity

Process flow diagrams for the alane and AB off-board recycle systems have been identified and are being used to generate capital costs estimates for each plant. The DOW report [9] pertaining to AB recycle has been an invaluable aid in the analysis. Based on the parameters in that report, the AB recycle cost is preliminarily estimated at $47.23 per kg of hydrogen releasable on the vehicle assuming a hydrazine price of $5.51/kg (all in 2007 dollars). While this is a prohibitively high cost, sensitivity analysis indicates that the recycle cost is highly sensitive to hydrazine price. Thus, AB recycle cost might be acceptable if hydrazine was reduced to <$1/kg. Cost analysis of the potentially low cost benzophenone process for hydrazine production is not yet complete. Preliminary results from the alane recycle process are also not yet available.

Conclusions and Future Directions

Based upon the work conducted this year, the following conclusions and future directions are revealed:

- Carbon fiber pressure vessels are highly sensitive to carbon fiber cost. Thus accurate estimation of the carbon fiber price and the mass of fiber required in each vessel is very important.
- 700 bar pressure vessel system costs (for a single vessel holding 5.6 kg of usable H_2 fuel) are expected to range from ~$18/kWh (at 10,000 systems per year) to ~$13 Wh (at 500,000 systems per year).
- Industry validation of the required pressure vessel carbon fiber mass is needed for confidence in the cost projections.
- A sensitivity analysis regarding tank size (4-8 kg H_2), lower pressure (300 bar), and number of pressure vessels within the system (1, 2, or 3) is helpful to better understand cost tradeoffs.
- The AB recycle system is particularly sensitive to the price of hydrazine. If hydrazine is only available at current market price (~$5.51/kg), the AB recycle cost is prohibitively expensive (~$47 per kg of H_2 eventually releasable onboard the vehicle).
- The AB and alane recycle analyses will be concluded.

FY 2012 Publications/Presentations

1. "Preliminary Pressure Vessel Cost Analysis," presentation to the DOE Hydrogen Storage Tech Team, 15 March 2012.

2. "Hydrogen Storage Cost Analysis, Preliminary Results," presentation at the 2012 DOE Hydrogen and Fuel Cells Program Review, Washington, D.C., 15 May 2012.

References

1. "Technical assessment of compressed hydrogen storage tank systems for automotive applications," T.Q. Hua, R.K. Ahluwalia, J.-K. Peng, M. Kromer, S. Lasher, K. McKenney, K. Law, J. Sinha, International Journal of Hydrogen Energy 36 (2011) 3037-3049. (doi:10.1016/j.ijhydene.2010.11.090)

2. Sutton, A.D., "Efficient Regeneration of Ammonia Borane", ACS Meeting, Aug 20 2009.

3. Sutton et al., "Regeneration of Ammonia Borane Polyborazylene", US Patent Application 2010/0272622 A1, October 28, 2010.

4. "Off-board Regeneration of Ammonia Borane for Use as a Hydrogen Carrier for Automotive Fuel Cells," Thanh Hua, Rajesh Ahluwalia, submission for publication in the International Journal of Hydrogen Energy, 2 April, 2012.

5. "Hydrazine Production from Ammonia via Azine." Hiromu Hayashi et. al., Industrial and Engineering Chemistry Product Research and Development, Vol. 15 No. 4 (1976) 299-303.

6. "Alane hydrogen storage for automotive fuel cells - Off-board regeneration processes and efficiencies," Thanh Q. Hua, Rajesh K. Ahluwalia, International Journal of Hydrogen Energy, Volume 36, Issue 23, November 2011, Pages 15259–15265. (doi:10.1016/j.ijhydene.2011.08.081)

7. "H2A Hydrogen Production Analysis Model Version 3," Darlene Steward, National Renewable Energy Laboratory, presented at 2012 DOE Hydrogen and Fuel Cells Program Review, Washington, DC, May 15, 2012.

8. Peters, Max S., Timmerhaus, Klaus D., West, Ronald E., Equipment Costs Plant Design and Economics for Chemical Engineers – 5th Edition, (New York, NY: McGraw-Hill, 2002). http://www.mhhe.com/engcs/chemical/peters/data/ce.html

9. "Low-Cost Precursors to Novel Hydrogen Storage Materials", Final Report, Suzanne W. Linehan, Arthur A. Chin, Nathan T. Allen, Robert Butterick, Nathan T. Kendall, I. Leo Klawiter, Francis J. Lipiecki, Dean M. Millar, David C. Molzahn, Samuel J. November, Puja Jain, Sara Nadeau, Scott Mancroni, The Dow Chemical Company, December 31, 2010, Prepared for U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy Hydrogen Program, Hydrogen Storage, Under Contract DE-FC36-05GO15053.