IV.A.2 Hydrogen Storage Cost Analysis

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Project End Date: September 29, 2016

Overall Objectives

- Identify and/or update the configuration and performance of a variety of hydrogen storage systems for both vehicular and stationary applications.
- Conduct rigorous cost estimates of multiple hydrogen storage systems to reflect optimized components for the specific application and manufacturing processes at various rates of production.
- Explore cost parameter sensitivity to gain understanding of system cost drivers and future pathways to lower system cost.

Fiscal Year (FY) 2014 Objectives

- Update and expand the cost analysis of onboard hydrogen storage in pressurized carbon composite (fiber and resin) pressure vessels.
- Validate the cost analysis methodology and results as a function of manufacturing rate against a Type IV compressed natural gas (CNG) storage tank. Compare CNG storage tank Design for Manufacturing and Assembly (DFMA®) cost modeling results with industry estimates for higher volume tanks currently produced, thereby increasing confidence in the hydrogen pressure vessel storage cost estimates.
- Exploration of high cost balance-of-plant (BOP) components using DFMA® analysis.
- Assess cost and performance impact of Pacific Northwest National Laboratory enhanced materials and design concepts for pressurized hydrogen storage.
- Identify cost drivers and future pathways to lower cost.
- Document all analysis results and assumptions.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Office 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 inform future technical targets for system storage cost.

- System Storage Cost: <$12/kWh net (2017 target)

FY 2014 Accomplishments

- Validated the Strategic Analysis Inc. hydrogen pressure vessel DFMA® cost model by using it to model a CNG pressure vessel and then comparing the CNG vessel predicted cost with industry quotations. These CNG model results showed agreement with industry quotations (between 2 and 20%) for the same size tank at an annual production rate of 1,000 vessels per year.
- Completed a DFMA® analysis of high-pressure (HP, >12 kpsi) and low-pressure (LP, <400 psi) hydrogen fittings.
- The accuracy of DFMA® cost analysis methodology to assess solenoid valve cost was tested by modeling a CNG integrated valve and comparing the results to vendor quotations. Excellent agreement between the DFMA® analysis predictions and vendor quotations was achieved (within ~6% of vendor quotation)
- The CNG integrated valve DFMA® analysis was modified to represent a hydrogen integrated valve (adjusted for higher pressure, materials, and construction). The projected results were generally lower than previous hydrogen integrated valve price projections and the limited set of vendor quotes available.

- Initiated a cost and performance validation of the Pacific Northwest National Laboratory cold gas storage concept system.
- Refined assumptions, models, and analysis based on expert feedback.

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INTRODUCTION

The Fuel Cell Technologies Office (FCTO) states that hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell power technologies in transportation, stationary, and portable applications. Consequently, the FCTO has established a goal of developing and demonstrating viable hydrogen storage technologies for transportation and stationary applications. This cost assessment project supports the FCTO goals by identifying the current technology system components, performance levels, and manufacturing/assembly techniques most likely to lead to the lowest system storage cost. Furthermore, the project forecasts the cost of these systems at a variety of annual manufacturing rates to allow comparison to the overall 2017 and "Ultimate" DOE cost targets. The cost breakdown of the system components and manufacturing steps can then be used to guide future R&D decisions.

During the second year of the project, onboard hydrogen storage in pressurized carbon composite pressure vessels was selected for continued 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. Key BOP components were selected for an in-depth analysis as they constitute a significant portion of the storage system cost.

APPROACH

To generate cost estimates for the compressed hydrogen pressure vessel system, a 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 Hydrogen Storage Engineering Center of Excellence [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 was obtained by varying the key parameters. These results were 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. These 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.

In the case of compressed hydrogen pressure vessel BOP components, there are a limited number (if any) of industry vendors that manufacture hydrogen components in high volumes. For example, the integrated in-tank valve incorporates many individual components currently made in industry, but there are very few companies that commercially produce the complete integrated in-tank valves for hydrogen fuel cell systems in high volumes. However, there are multiple manufacturers that have developed similar valves for CNG light-duty vehicles. Consequently, whenever appropriate, DFMA® models of CNG components were generated and the cost projections compared to quotations as a method of validating and improving cost projection accuracy. Then the models were altered to reflect their hydrogen system analog. From this approach, a more accurate projection of hydrogen storage system BOP component costs is achieved.

RESULTS

A validation study of the hydrogen pressure vessel cost model was completed this year by adapting the cost model to represent a CNG pressure vessel and then comparing the projected results to actual vendor high-production CNG quotes. CNG pressure vessels are manufactured in a very similar way to compressed hydrogen Type IV tanks: a polymer liner overwrapped by continuous carbon fiber filament. For this comparison, a 270-liter (internal water volume) CNG tank (sizing for light-duty trucks) was selected for modeling based on discussions with CNG industry professionals who suggested that this size tank is currently produced at 500 to 1,000 units per year. While the Honda Civic CNG tank (120-liter water volume) is produced at higher manufacturing rates (5,000 systems/year) by Structural Composite Industries (SCI)/Worthington Cylinders, the vessels are Type III tanks (metal lined, waist wrapped) rather than the Type IV tanks assumed for current hydrogen storage pressure vessels. Consequently, the Honda Civic-based tanks by SCI were rejected for the CNG validation basis.

After a tank size was selected, ANL used ABAQUS™ finite element analysis modeling tool to identify material weights, masses, and dimensions: these served as input values for SA's DFMA® pressure vessel cost model. Results from the cost analysis were then compared to price quotations acquired from CNG tank manufacturers (Quantum Technologies, 3M, and Hexagon Lincoln), so as to validate the cost modeling approach. The final analysis results shown in Table 1 compare price quotations provided by manufacturers with the corresponding assumed markup schemes to allow comparison to DFMA® cost results. SA's results align quite well with Quantum and 3M quotation base tank costs. However the Hexagon Lincoln costs are 15% lower, most likely due to Hexagon Lincoln's higher total tank production volume (i.e. production total of all size vessels not just the DFMA® modeled size). Additionally, Hexagon Lincoln's interior tank volume is lower than the other manufacturers in part due to their addition of fiberglass to both the outer tank wrapping (for abrasion and chemical resistance) and to the inner fiber wrapping (for impact resistance). Quantum and 3M restrict fiberglass to the outside of the tank only, thereby providing a higher internal volume for the same outer tank dimensions. During this analysis, it was noted that the DFMA® cost projection is quite sensitive to production rate. Thus, minor assumption differences in annual production rate can lead to significant changes in projected cost.

BOP components have been identified as costly components worthy of further detailed examination, and DOE has directed SA to make BOP cost analysis a focus of the FY 2014 effort. According to SA's 2013 analysis, the two most significant cost drivers for the BOP are the fittings and the integrated in-tank valve. These two elements account for almost 40% of the total BOP costs for a single tank system, at a production rate of 500,000 tank systems per year.

Price quotations were solicited from high-pressure fitting manufacturers for two main types of fittings: 1) Metal-on metal cone/thread sealing fittings (e.g. Swagelok or EV Metal fittings), and 2) O-ring face seal fittings (e.g. Parker Hannifin Seal-Lok™ fittings). A wide variation in fitting cost quotation exists for both types of fittings. Additionally, cost quotations were not available for quantities greater than 50,000 parts although demand is expected to be approximately 3 million fittings per year (for system production 500,000 systems/yr). It is anticipated that fitting cost would decrease with purchase quantity due to both a reduction in production cost and a reduction in manufacturer markup rate. That some distributors did not indicate a purchasing quantity discount is felt to be a reflection of their inability or unwillingness to project the sales price at such high purchase quantities, and not that fitting cost is truly constant with production rate.

For the 2014 analysis, a DFMA® cost analysis was conducted on two representative hydrogen fittings: Parker Hannifin Seal-Lok™ type fittings (4 F57OLO-SS H2U 990549 for HP at 12 kpsi and 4-6 F57OLO-SS H2U for LP at 400 psi). Figure 1 details the projected cost breakdown of the HP fitting at 500,000 systems/yr (6 HP units per system at 3 million units per year). The total fitting cost for both HP and LP fittings at 500,000 systems/yr is approximately \$12/fitting. The fitting body cost and individual testing costs are observed to be the most expensive (they include materials, manufacturing, testing equipment needed, and labor). Overall, the 2014 DFMA® analysis predicts total

TABLE 1. CNG Storage Tank Cost Parameters for Three Manufacturers and SA's DFMA® Cost Model Results (Text in red denotes vendor price quotes or DFMA cost modeling results.)

CNG Storage Tank Cost Parameter	Quantum	3M	SA DFMA	Hexagon Lincoln
Annual Purchase Quantity (vessels per year)	Not Spec. (But est. at 1,000)	Not Spec. (But est. at 1,000)	1,000 (prod. Rate)	500
Tank Interior Volume (liters)	274	279	275	251
Tank Mass (kg)	60.8	59.4	65.5	92.1
Tank Cost before markup(\$/tank)	\$2,800	\$2,260 - \$2,730	\$2,852	\$2,420
Tank Manufacturer Markup %	15%	15%	15%	15%
Tank Cost after markup (\$/tank)	\$3,220	\$2,600 - \$3,140	\$3,280	\$2,785
Authorized Installer Markup %	10%	8-13%	10%	10%
Tank Cost after markup (\$/tank)	\$3,500	\$2,800 - \$3,550	\$3,607	\$3,030

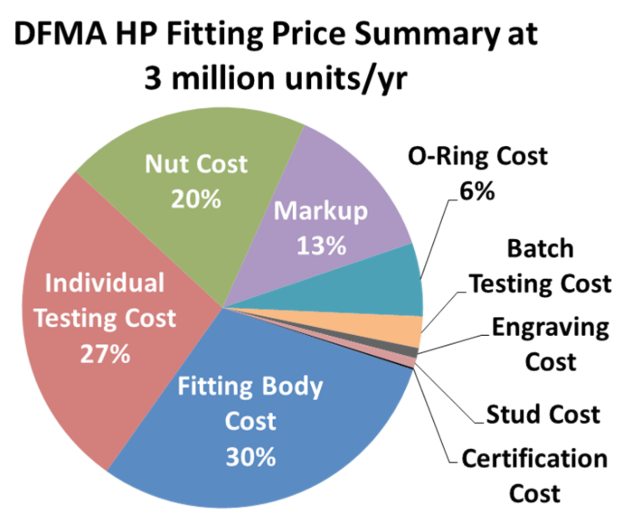

FIGURE 1. DFMA® Results for Breakdown of Fitting Price Based on Six High-Pressure Fittings per System at 500,000 Systems/Yr

fitting and piping system cost to be 11% less (on average over all manufacturing rates) than 2013 levels.

As currently envisioned, the integrated valve body is an in-tank pressure gas solenoid valve that has the additional functionalities of a temperature activated pressure relief device, excess flow valve, particle filter, port provision, a valve for manual override (to allow manual tank depressurization), and a temperature sensor. For the 2013 analysis, the cost of this integrated in-tank valve was assessed by summing the cost contribution of each functional aspect. The sum of these costs was compared to an auto manufacturer's proprietary cost estimates at 10,000 and 100,000 per year and judged reasonable. For the 2014 analysis, a DFMA® analysis was conducted on the integrated valve to more fully understand cost related issues and scaling with manufacturing rate. CNG integrated valves were also considered as they are currently produced in relatively high quantities and therefore provide an opportunity to calibrate the cost estimation procedure.

A full DFMA® analysis was completed for a CNG integrated valve to understand and compare to quotations of existing units at low production rates (10,000 systems/yr). The CNG integrated valve design concept used by SA as the basis for the DFMA® cost analysis is based on an internal flow concept detailed in a GFI patent [2], and uses valve dimensions similar to the OMB Saleri Lyra CV valve (one of the most widely used integrated valves and used on Quantum Technologies, 3M, and Hexagon Lincoln CNG tanks). Price quotations were acquired from CNG BOP component manufacturers (OMB and Tomasetto) and are displayed on the left side of Figure 2 along with the results of the DFMA® analysis. Price quotations were acquired from Tomasetto at an unknown production volume, but are estimated to be between 1,000 and 4,000 units/year. Markup was added to the DFMA® cost results (10-20% depending on production volume) to allow direct comparison to the price quotations. At 17,000 units/year, the DFMA® cost of a CNG integrated valve with markup aligns well with price projections for the currently produced Lyra CV CNG integrated valve ($130/valve).

With confirmation that a DFMA® analysis can successfully be applied to a CNG integrated tank valve product, a similar DFMA® analysis was applied to an hydrogen integrated in-tank valve. While functionality is similar, there are multiple component differences between a CNG and hydrogen integrated valve. The following five differences were identified for this analysis: 1) The operating pressure for CNG valves is typically 3,600 psi while the pressure for hydrogen valves is 10,000 psi (leading to a higher cost due to thicker walls and higher tolerances). 2) The solenoid valve is internal to the hydrogen tank and external to CNG tank. 3) The temperature transducer and filter are included on the hydrogen valve, but are not included on the CNG valve. 4) CNG valves can be composed of

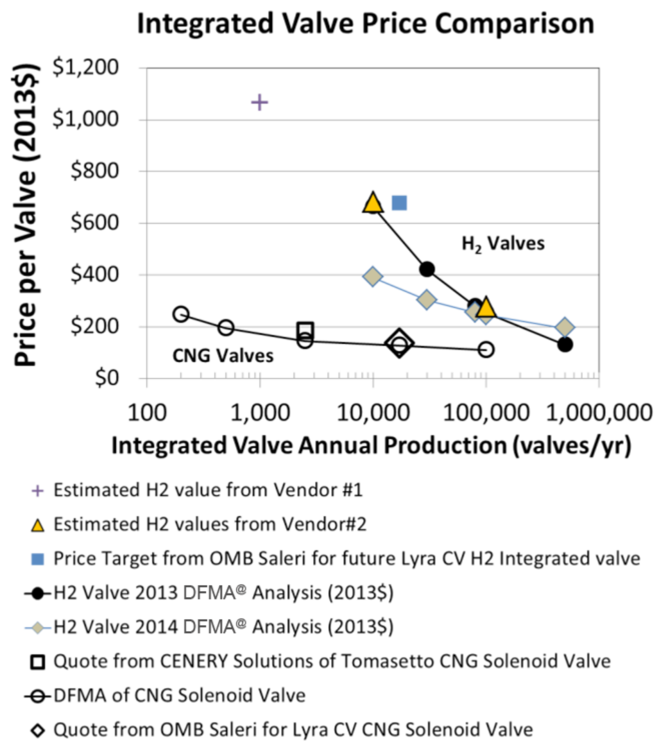

FIGURE 2. Price Quotations Compared to 2014 DFMA® Analysis on CNG (left) and Hydrogen (right) Tank Integrated Valves

aluminum or brass while hydrogen valves are typically made of stainless steel. 5) The typical neck opening is 2 inches in diameter on a CNG tank and 1.5 inches on a (higher pressure) hydrogen tank.

The design and sizing used for the hydrogen integrated valve DFMA® are loosely based on Quantum Technology's in-tank valve. Informal discussions with OMB Saleri suggest the current cost of a hydrogen integrated valve is around $2,000/valve. OMB Saleri is working to reduce the cost of the valve, and has set a future target of $675/valve (at an unknown production volume). The results from the 2014 DFMA® analysis for the hydrogen integrated valve are shown on the right side of Figure 2, and show a shallower slope in valve cost with production volume compared to the 2013 analysis. The OMB Saleri cost target for a hydrogen integrated valve is close to the 10,000 systems/yr cost projection from the 2013 analysis. However, this $675/valve may have different internal components and functionality than what has been defined for SA's hydrogen integrated valve design. Furthermore, the production volume is unknown, but is assumed to be similar to the CNG Lyra CV valves OMB Saleri produces at 17,000 units/yr.

After investigating the BOP components for the hydrogen pressure vessel, the total BOP price changes between the 2013 analysis and 2014 analysis are very small at the high manufacturing rates, but differ by about 18% at

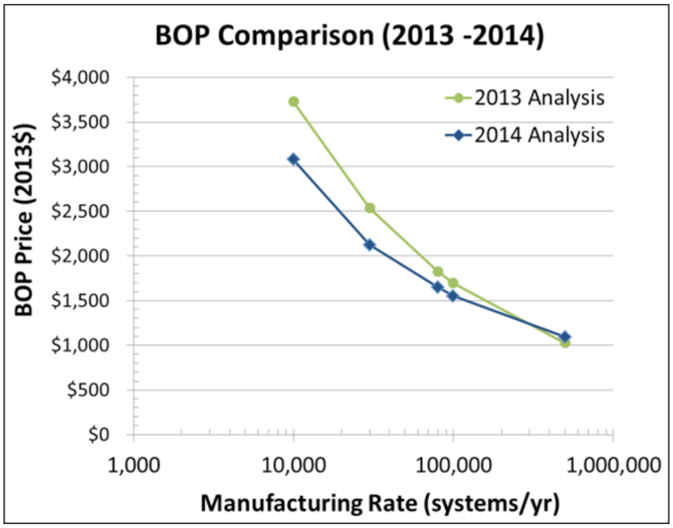

FIGURE 3. Graph of Total BOP Price for 2013 and 2014 Analyses (All prices are in 2013$.)

10,000 systems/yr (this includes the DFMA® cost results for fittings and integrated in-tank valves and quotations for pressure regulators). Figure 3 shows this comparison between 10,000 and 500,000 systems per year.

CONCLUSIONS AND FUTURE DIRECTIONS

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

- Validation of the hydrogen pressure vessel DFMA® cost model by adaptation of the DFMA® model to project CNG pressure vessel cost and subsequent agreement between model projected costs and vendor quotations (at 1,000 tanks/year).
- Identification of the BOP components as major contributors to total system cost and identification of fittings and the integrated in-tank valve as key cost drivers of the BOP subsystem.
- DFMA® analysis of both fittings and integrated in-tank valve suggest a small change in cost compared to 2013 analysis at 500,000 systems/yr, but an 18% lower cost at 10,000 systems/yr.

Future work will:

- Continue to refine the hydrogen pressure vessel cost analysis
- Gather further original equipment manufacturer data on BOP component costs
- Explore BOP component simplification and combined functionality as a pathway to lower cost
- Assess the cost impact of advanced tankage concepts such as use of strength-graded fibers, carbon nanotube addition between fiber layers to increase translational strength, and cold hydrogen storage (200 K)
- Conduct a DFMA® cost assessment of the Hawaii Hydrogen Carrier metal hydride storage system for fork lift applications
- Conduct a DFMA® cost assessment of an alane chemical hydrogen storage system used onboard a vehicle
- Conduct a DFMA® cost assessment of the sorbent based onboard systems as investigated by the Hydrogen Storage Engineering Center of Excellence

SPECIAL RECOGNITIONS & AWARDS/ PATENTS ISSUED

1. Hydrogen and Fuel Cells Program Award. Awarded to Brian D. James by the Director of the Fuel Cell Technologies Office, Sunita Satyapal June 17th 2014.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. James, B.D., Moton, J.M., Colella, W.G., "Ongoing Validation of the H_2 Pressure Vessel Storage System Cost Model," Presentation to the 2014 Hydrogen Storage Technical Team, presented remotely from Strategic Analysis Office in Arlington, Virginia, April 17, 2014.

2. James, B. D., Moton, J.M., Colella, W. G., "Ongoing Analysis of H_2 Storage System Costs," U.S. DOE's 2014 Annual Merit Review and Peer Evaluation Meeting (AMR) for the Hydrogen and Fuel Cells Program, Washington, D.C., June 16–20, 2014, Project ID ST100.

3. Moton, J.M., James, B.D., Colella, W.G. "Advances in Electrochemical Compression of Hydrogen," *Proceedings of the ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference (ESFuelCell2014)*, Boston, Massachusetts, June 30th- July 2nd , 2014 (ESFuelCell2014-6641).

4. Moton, J.M., James, B.D., Colella, W.G. "Advances in Electrochemical Compression of Hydrogen," *Presentation given at the ASME 2014 8th International Conference on Energy Sustainability & 12th Fuel Cell Science, Engineering and Technology Conference (ESFuelCell2014)*, Boston, Massachusetts, June 30th – July 2nd, 2014.

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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. European Patent (EP 0805295 B1).