# IV.E.2 Analyses of Hydrogen Storage Materials and On-Board Systems

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## Objectives

The overall objective for this project is 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 Fuel Cell 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 and/or updated assessments for several hydrogen storage systems. For each system assessment, we projected on-board system performance and high-volume (~500,000 units/year) manufactured cost, as well as determined the critical cost drivers and conducted single- and multi-variable sensitivity analyses to bound cost results. We also 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. Finally we compared performance and cost results to other baseline technologies and DOE targets for the on-board storage system. Specific accomplishments include:

- Completed preliminary, high-volume (500,000 units/yr) on-board system factory cost assessments of metal organic framework (MOF) 177 and liquid hydrogen tank systems. The MOF-177 system is projected to cost $16/kWh for a 5.6 kg hydrogen tank and $12/kWh for a 10.4 kg hydrogen tank. The liquid hydrogen system is projected to cost $8/kWh for a 5.6 kg tank and $5.4/kWh for a 10.4 kg tank.
- Revised high-volume on-board system factory cost assessments of cryo-compressed and 350 bar and 700 bar compressed tank systems. For the compressed systems, the analysis was extended to include Type 3 and Type 4 tanks, and single and dual tank systems.
- Supported the Storage Systems Analysis Working Group (SSAWG) evaluation of the well-to-tank energy use and greenhouse gas (GHG) emissions for MOF-177 tanks, cryo-compressed tanks, 350 and 700 bar tanks, and cold gas tanks.
- Completed review of Dow Chemical's Ammonia Borate 1$^{st}$ fill cost projections.

## Introduction

DOE is funding the development of a number of hydrogen storage technologies as part of its "Grand Challenge." 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 for four broad categories of on-board hydrogen storage. The four categories 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), and advanced physical storage (e.g., cryo-compressed hydrogen, liquid hydrogen). Evaluations are based on developers' on-going research, input from DOE and key stakeholders, and in-house expertise.

## Approach

This project utilizes an approach that is designed to minimize the risks associated with achieving the project objectives. In coordination with Argonne National Laboratory (ANL), system-level conceptual designs are developed for each on-board storage system and required fueling infrastructure. We work closely with ANL to develop a bill of materials consistent with their performance assessment. 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 SSAWG 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 storage technology options.

## Results

TIAX developed preliminary cost estimates for a MOF-177 storage system and a liquid hydrogen storage system, and updated previous cost estimates for compressed and cryo-compressed storage systems. Each of the storage system cost projections are estimated based on on-board system designs developed by ANL [1].

The high volume (~500,000 units per year) cost of the MOF-177 system was estimated to be $16/kWh for a 5.6 kg useable hydrogen tank and $12/kWh for a 10.4 kg useable hydrogen tank (Figure 1).[1] The modeled MOF-177 tank consists of a Type 3 carbon fiber pressure vessel surrounded by multi-layer vacuum insulation and an aluminum outer shell. The pressure vessel is filled with a metal organic framework storage media (Figure 2), which stores hydrogen at 250 bar and 100 K. The single biggest contributors to the system cost are the carbon fiber (19%), the aluminum tank liner (14%), and the storage media (14%). It should be noted that the MOF storage media is not yet available at high commercial volumes. As such, our preliminary estimate of the storage media is based on the high volume cost of activated carbon (AX-21); subsequent revisions will revisit this assumption.

The liquid hydrogen storage system was estimated to cost $8/kWh for a 5.6 kg tank and $5.4/kWh for a 10.4 kg tank (Figure 1). The liquid hydrogen tank consists of an aluminum inner shell and steel outer shell

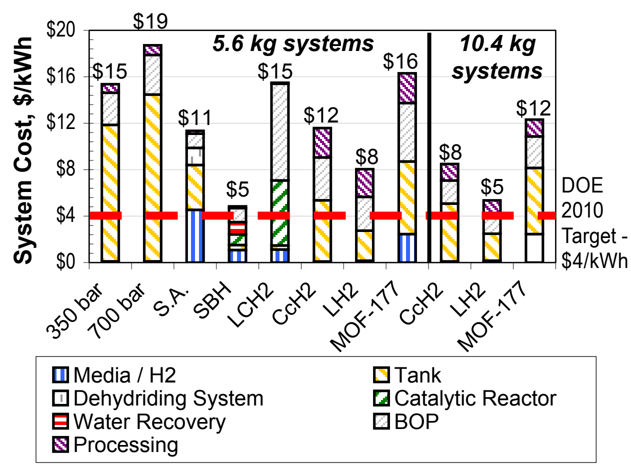


**FIGURE 1.** Preliminary On-board Storage System Cost Comparison Results

[1] Costs were estimated for both a 5.6 kg useable hydrogen tank and a 10.4 kg useable hydrogen tank for the cryogenic systems. Due to space constraints, only the results for the 5.6 kg tanks are shown. The two different tank sizes reflect two different bases for comparison that were suggested by various stakeholders: the 5.6 kg tank is consistent with other cost analyses performed as part of this project, and reflects the amount of hydrogen needed for a passenger vehicle to achieve 350 mile range. The larger tank is more consistent with the specifications of cryogenic tanks that have been tested to date, which tend to be larger to help mitigate the effects of boil-off.

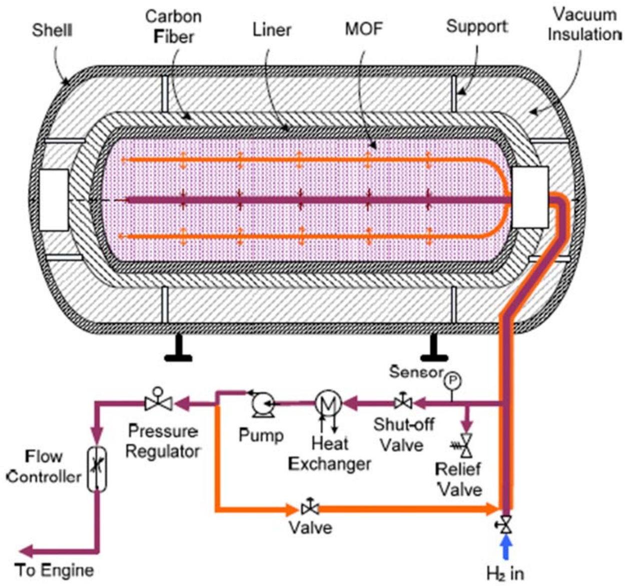


**FIGURE 2.** MOF-177 Storage System

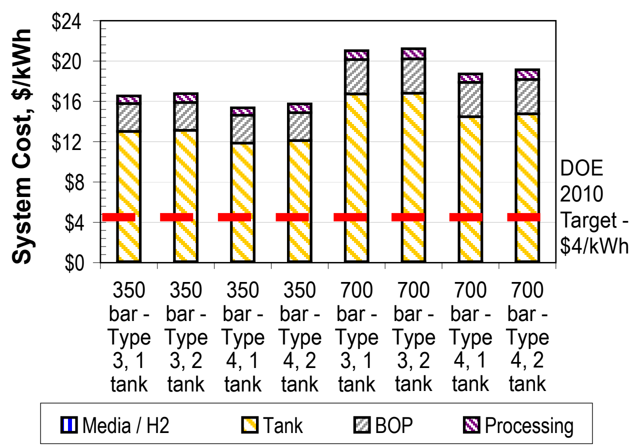


**FIGURE 3.** Preliminary Comparison of Compressed Storage System Configurations

with multi layer vacuum insulation sandwiched between. The tank is sized to include 7.5% ullage and assumes 40% boil off of hydrogen. The major costs are relatively evenly distributed between the tank (46%, primarily the liner and vacuum insulation), and the balance of plant (36%).

In addition to the new cost analyses described above, TIAX updated previous cost assessments of compressed and cryo-compressed storage systems. The revised cryo-compressed storage system is based on Lawrence Livermore National Laboratory's Gen 3 tank design [1]. Key changes between the current design and the Gen 2 design used for TIAX's prior assessment include an changes in the liner and vacuum insulation thickness, and a reduction to the system's nominal pressure (to 272 Bar). The updated estimates for the cryo-compressed system project a system cost of $12/kWh for a 5.6 kg tank and $8.4/kWh for a 10.4 kg tank (Figure 1). The tank, primarily due to the cost of carbon fiber and the aluminum liner, accounts for 55% of the total cost, while the balance of plant accounts for an additional 34% of the total.

The revised compressed hydrogen system cost estimates project that a 350 bar Type 4 tank will cost $15/kWh and a 700 bar Type 4 tank will cost $19/kWh (Figure 1). Both tanks were sized to store 5.6 kg of useable hydrogen. These calculations include a number of revised assumptions compared to TIAX's prior analysis, the net effect of which was a 10% decrease in the cost of the 350 bar system and a 30% decrease in the cost of the 700 bar system. The revised calculations continue to show that the cost of carbon fiber is the dominant cost component for the both the 350 and 700 bar systems, accounting for 75 to 80% of the system cost; the balance of plant accounts for an additional 18%.

In addition to the Type 4, single tank compressed hydrogen storage system, TIAX estimated the system costs for Type 3 tanks and for multi-tank systems. In total, eight different compressed hydrogen tanks were evaluated (i.e., each combination of 350 and 700 bar, Type 3 and Type 4, and single and multi-tank systems). The cost results of this analysis are shown in Figure 3. As shown, the multi-tank systems lead to a minor cost increase in system costs (approximately $0.5/kWh). Although the two tank system has additional surface area compared to a single tank, the carbon fiber thickness may be decreased due to the smaller dimensions. As such, the single and dual tank systems use a very similar quantity of carbon fiber. Moreover, it was assumed that the two tank system uses the same balance of plant as the one tank system.[2] The Type 3 tanks are projected to lead to a modest cost increase compared to the Type 4 baseline: for the 350 bar tank, the system cost increases by $1.3/kWh, while the 700 bar tank cost increases by $2.2/kWh compared to a Type 4 tank. This difference reflects a large increase in the cost of the aluminum Type 3 liner compared to the HDPE Type 4 liner, coupled with a minor decrease in the carbon fiber required.[3]

All of the results reported above should be considered in the context of meeting both on-board and off-board cost targets as well as other DOE targets, including on-board system weight, volume, durability/operability, charging/discharging rates; and off-board primary energy use/GHG emissions and fuel purity. While this project focuses on the onboard hydrogen storage system cost, the results of TIAX's onboard cost assessments were used as inputs to well-to-wheel lifecycle analysis of system performance cost conducted by the SSAWG (Table 1).

[2] i.e., none of the balance of plant components are duplicated.
[3] The aluminum liner is able to support a portion of the carbon fiber's pressure load.

**TABLE 1.** Hydrogen Storage System Performance and Cost Metrics for 5.6 kg Tanks

| Performance and Cost Metric | System Grav. Capacity | System Vol. Capacity | Storage System Cost | Fuel Cost | WTT Efficiency |
|---|---|---|---|---|---|
| **Units** | wt% | kg-$H_2$/$m^3$ | $/kWh | $/gge | % |
| **350-bar** | 5.5 | 17.8 | 13.4 | 4.2 | 56.5 |
| **700-bar** | 5.0 | 25.6 | 20 | 4.3 | 54.2 |
| **Liquid** | 5.7 | 23.0 | 8.0 | TBD | 22.3 |
| **Cryo-Compressed** | 5.7 | 44.0 | 11.6 | 4.8 | 41.1 |
| **MOF-177** | 4.9 | 34.3 | 16.3 | 4.6 | 41.1 |
| **2010 Targets** | 4.5 | 28 | 4 | 2 to 3 | 60 |
| **2015 Targets** | 5.5 | 40 | 2 | 2 to 3 | 60 |
| **Ultimate Targets** | 7.5 | 70 | TBD | 2 to 3 | 60 |

WTT = well-to-tank; TBD = to be determined

## Conclusions and Future Directions

The cost assessments conducted this year allow direct comparison with prior cost assessments and DOE targets. Our models allow us to identify critical cost components, which enables focused discussion with tank developers and manufacturers.

- None of the systems assessed meet the Department of Energy's 2010 cost target of $4/Wh. The cost of the 5.6 kg 350 bar, 700 bar, cryo-compressed, liquid, and MOF-177 storage systems range from 2 to 5 times the cost of the DOE target. Key factors influencing system costs are the carbon fiber material cost, the cost of aluminum, and in the case of the MOF system, the storage media.
- The MOF-177 system cost is 3 and 4 times the 2010 DOE target of $4/kWh for the 10.4 and 5.6 kg systems, respectively. Achieving the DOE cost targets will require large reductions in the cost of the storage media and the tank materials (aluminum and carbon fiber).
- The onboard liquid hydrogen system cost is 1.3 and 2 times the 2010 DOE target for the 10.4 and 5.6 kg systems, respectively. While the liquid system has amongst the lowest onboard storage system cost, it has low volumetric efficiency, well-to-tank efficiency, and high fuel costs. These shortcomings are a function of fuel boil-off and the high energy requirement associated with liquefaction.
- The cryo-compressed system is 2 and 3 times the 2010 DOE target for the 10.4 and 5.6 kg systems, but meets the 2010 volumetric and gravimetric targets. The base case 350 bar and 700 bar systems are 4 and 5 times higher than the 2010 DOE targets for the 350 bar Type 4 and 700 bar Type 4 systems, respectively, and both systems fall short of the 2010 volumetric capacity targets. Additional analysis of 350 and 700 bar dual tank systems showed minor cost increases of less than 5%; 350 and 700 bar Type 3 systems showed moderate cost increases on the order of 10%. The major cost driver for the compressed system is carbon fiber, while the cryo-compressed system cost is driven by carbon fiber, aluminum liner, and balance of plant component costs.

The rest of this fiscal year, we plan to continue to work with developers and stakeholders to improve the accuracy of the analyzed on-board and off-board system models and finalize our analysis of storage technology options. Specifically, we plan to:

- Incorporate feedback and finalize on-board cost assessments and reports (with ANL) for MOF177 and liquefied hydrogen options. In parallel, we will update previously completed final reports for 350 bar, 700 bar and cryo-compressed systems.
- Complete updated assessments and final reports (with ANL) for previously evaluated technologies, including liquid hydrogen carrier and Gen 4 cryo-compressed systems.
- Complete new assessments and final reports (with ANL) for activated carbon systems.
- Complete off-board cost review for ammonia borane and other technologies as requested by DOE and integrate with overall performance and on-board cost results.
- Continue to work with DOE, SSAWG, Centers of Excellence, other analysis projects, developers, Tech Teams and other stakeholders (as necessary) to revise and improve system models.

## FY 2010 Publications/Presentations

**1.** Ahluwalia, R et al. "Technical Assessment of Cryo-Compressed Hydrogen Storage Tank Systems for Automotive Applications." Argonne National Laboratory, ANL/09-33. December, 2009.

**2.** Lasher, S. et al, "Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications". TIAX, LLC. December 10, 2009.

**3.** Lasher, S. et al. "Updated Cryogenic and Compressed Hydrogen Storage System Cost Assessments." TIAX, LLC, presented at DOE Annual Hydrogen Merit Review, June 8, 2010, Washington, D.C.

## References

**1.** Ahluwalia, R.K., Hua, T.Q., Peng, J.K., "System Level Analysis of Hydrogen Storage Options," 2010 DOE Hydrogen Program Review, June 7–11, 2010 Washington, D.C.