DOE Hydrogen and Fuel Cells Program Record

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Title: On-Board Hydrogen Storage Systems – Projected Performance and Cost Parameters

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Item:

This record summarizes the current technical assessments of hydrogen (H_2) storage system capacities and projected manufacturing costs for the scenario of high-volume production (i.e., 500,000 units/year) for various types of "on-board" vehicular storage systems. These analyses were performed within the Hydrogen Storage sub-program of the DOE Fuel Cell Technologies (FCT) program of the Office of Energy Efficiency and Renewable Energy.

It is important to note that all system capacities are "net useable capacities" able to be delivered to the power plant. Capacities must be met at end of service life. "Net useful energy" excludes unusable energy (i.e., hydrogen left in a tank below minimum power train system pressure requirement, flow and temperature requirements) and hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g. fuel used to heat a hydride or material to initiate or sustain hydrogen release). The storage system includes interfaces with the fuel dispensing components of the refueling infrastructure, safety features, the storage vessel itself, all storage media, any required insulation or shielding, all necessary temperature/humidity management equipment, any regulators, electronic controllers, and sensors, all on-board conditioning equipment necessary to store the hydrogen (compressors, pumps, filters, etc.), as well as mounting hardware and delivery piping. Storage system capacity is only one of several performance criteria that storage systems must meet simultaneously including gravimetric and volumetric capacities, system cost, durability and operability, charging and discharging rates, fuel purity to the power plant, and environmental, health and safety attributes.

The DOE has recently revised the system targets for the net volumetric (g-H_2/L system) and gravimetric capacities (wt% = [g H_2/g system] x100) of various on-board storage vessels for hydrogen fuel cell-powered light-duty vehicles [1]. The storage capacities of high-pressure gas storage vessels used in 140 fuel cell vehicles are available from the DOE Fuel Cell Vehicle and Infrastructure Learning Demonstration Project initiated in FY2004 [2,3]. These gas cylinders are primarily early-phase pre-commercial H_2 storage systems (mainly 350 and 700 bar) and are reported to have gravimetric and volumetric capacities with ranges of 2.8-3.8 (2.5-4.4) wt% and 17-18 (18-25) g-H_2/L, respectively, at nominal filling pressures of 350 (700) bar. Since little or no publicly available information on prototypes currently exists for the other materials-based hydrogen storage systems, a series of independent reviews and evaluations were made at Argonne National Laboratory (ANL), TIAX LLC, and other organizations. These analyses were based upon evolving designs and configurations that included updates of both the type of storage media and balance-of-plant components as summarized in Table 1 with references to their original reports.

The progression in the gravimetric and volumetric capacities for several on-board systems, where each provides a nominal 5.6 kg of usable H_2, are shown in Figures 1 and 2, respectively. The projected costs in large volume manufacturing of 500,000 units/yr are given in Figure 3 as the probable range of manufacturing costs, which uses cost range bars to reflect impact of the interactions of various design, materials, and components options on projected costs. Summaries of the results from these analyses are given in Table 1 along with references.

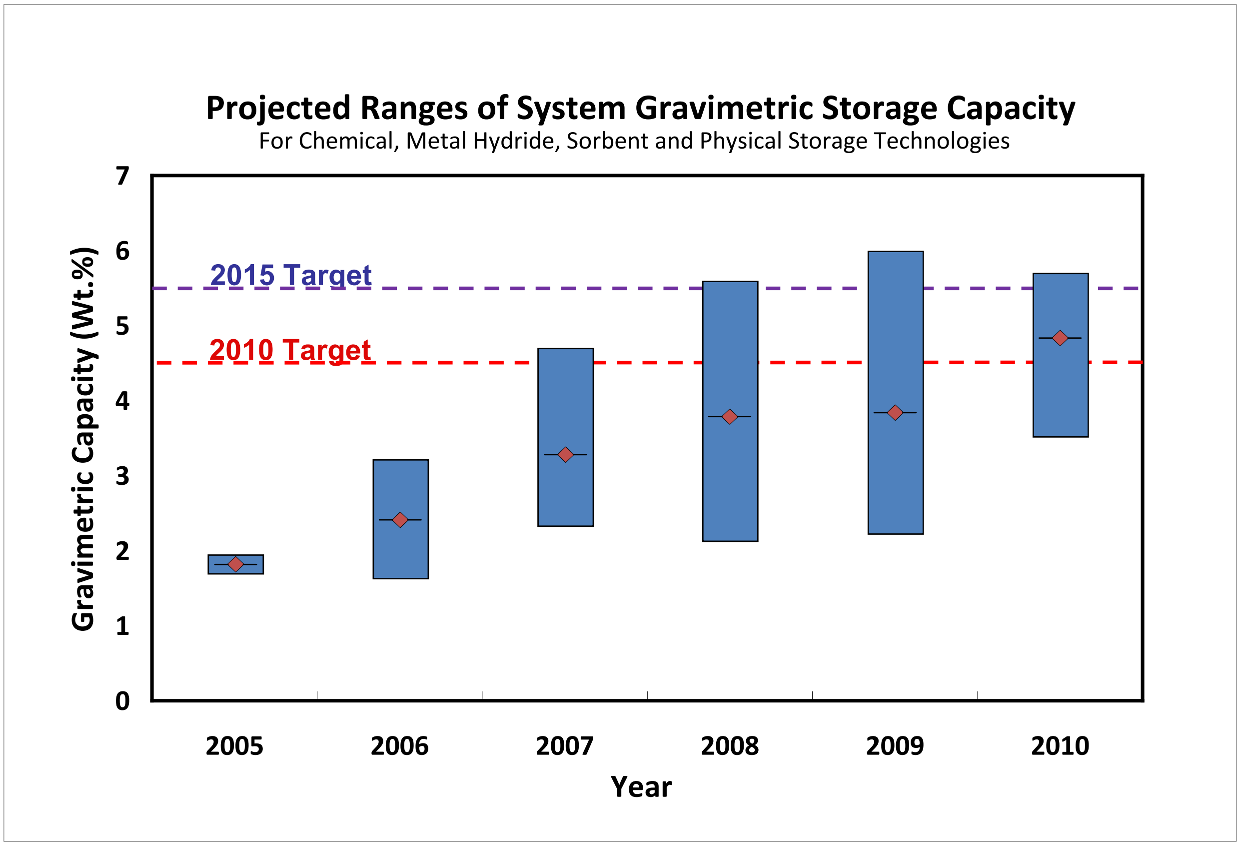

Figure 1. Estimates of gravimetric capacities projected for on-board storage systems that can supply 5.6 kg of usable hydrogen as compared to DOE targets (based upon engineering analyses). Note that the plotted data points are the average value for all systems analyzed during each year while the bars correspond to the range of maximum and minimum values obtained in each year. Also note that systems with predicted capacities exceeding the gravimetric targets do not meet other targets.

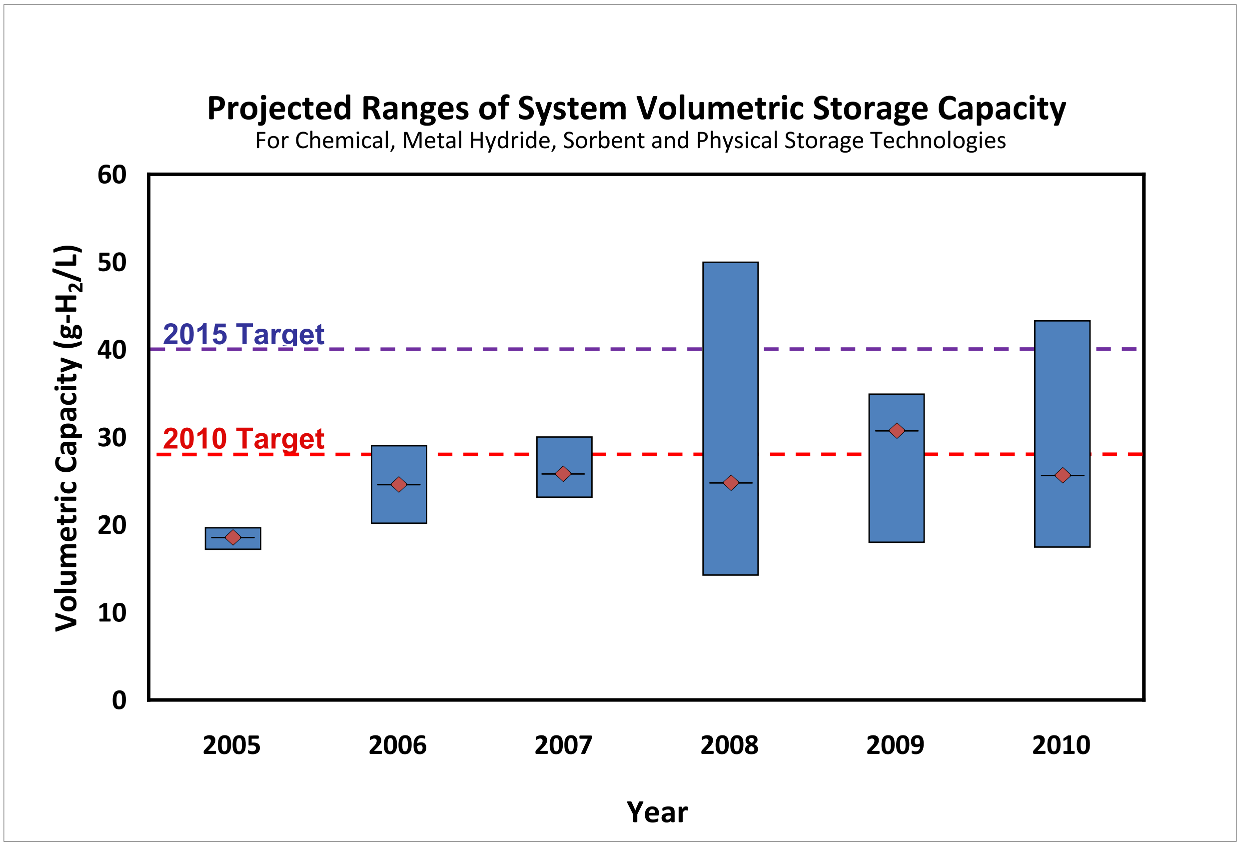

Figure 2. Estimates of volumetric capacities projected for on-board storage systems that can supply 5.6 kg of usable hydrogen as compared to DOE targets (based upon engineering analyses). Note that the plotted data points are the average value for all systems analyzed during each year while bars correspond to the range of maximum and minimum values obtained in each year. Also note that systems with predicted capacities exceeding the volumetric targets do not meet other targets.

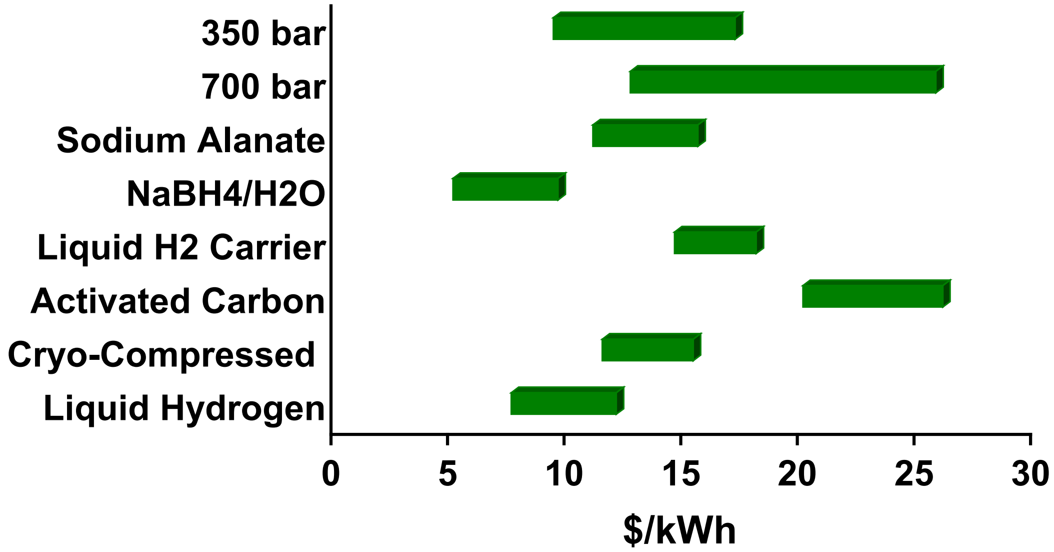

Figure 3. Estimated range of projected costs during high-scale production (i.e., 500,000 units/year) for several on-board storage systems with usable hydrogen capacities of 5.6 kg. These ranges include the most recent updated results for each system as reported through June 2010.

Data Sources, Assumptions, and Current Status

The gravimetric and volumetric capacities presented in Figures 1 and 2 include the hydrogen content, any storage media (i.e., metal hydrides, chemical hydrides, or sorbents), the containment vessel, as well as associated plumbing, valves, and auxiliary components required on the vehicle to supply hydrogen to the inlet of the fuel cell power system. The engineering assessments of these on-board hydrogen storage systems were based on information from prototypes (when publicly available), publicly released reports and documents on candidate storage materials, schematic designs of proposed configurations of vessels as integrated with any external components, and the operating requirements specified by the DOE [4]. As additional results and modified designs became publicly available and comments were received by various stakeholders, the assessments were updated to reflect these further inputs. Summaries of the evaluated capacities and projected costs for base case storage systems are compiled in Table 1 along with their sources and other details and comments that described assumptions and changes used in the different analyses. More complete descriptions of the assessment methodologies and results can be found in the published articles and reports along with the Proceedings of the DOE Hydrogen's Program Annual Merit Reviews (AMR) [5] and Annual Progress Reports (APR) [6] referenced in Table 1. (All of these documents can be found on the Fuel Cell Technologies Program Website, see references for specific website addresses).

Metal Hydrides

The prototype storage vessels containing Ti-catalyzed sodium alanate ($NaAlH_4$), fabricated and tested by the United Technologies Research Center (UTRC), served as examples during performance assessments [7-9] of reversible metal hydrides for on-board vehicle systems. While the theoretical maximum reversible H-content stored in undoped $NaAlH_4$ can reach 5.7 wt% during desorption at ~270 °C and ~1 bar to form Al metal and NaH products, the projected system capacities are ~2 wt% and 17-24 g-H_2/L due to various limitations including reduced stoichiometry from impurity phases arising from the Ti-additive, inefficient powder fill densities, components needed to improve heat transfer within the hydride bed, etc. In addition, the analyses by Ahluwalia [9] indicate that kinetics for hydrogen desorption should be at least a factor of 5-10 times faster than the rates published for the Ti-doped $NaAlH_4$ materials to satisfy minimum H_2 flow targets. In order to achieve the current 2015 system capacity targets of 5.5 wt% and 40 g-H_2/L, it is currently estimated by DOE that a hypothetical hydride should have materials capacities of at least 7.5 wt% and ~60 g-H_2/L assuming the scaling factors used by UTRC on extrapolating performance levels from their alanate beds [8]. Furthermore, the analyses by ANL [9] indicated this hypothetical hydride should also possess thermodynamic and kinetic properties to allow operation at temperatures at least 20-50K lower than the alanate used by UTRC. No hydride has yet been identified with these properties and there have been no further DOE system assessments performed on hydrogen storage using reversible hydrides to date.

Sorbents

Hydrogen storage via adsorption (i.e., using high surface area adsorbents or sorbents) can currently be accomplished with reasonable storage capacities only at cryogenic temperatures (i.e., ~77-100K) due to low binding energies of H_2 molecules on the surface. System level assessments [10] have been performed on storage vessels containing activated carbon type AX-21 and those containing the metal organic framework (MOF) compound Zn_4O(1,3,5-benzenetribenzoate), which is identified as MOF-177. The storage capacities of these sorption systems are dependent upon the residual pressure in the tank with substantial portions coming from the cryogenically compressed gas. However, the performance analyses by Ahluwalia and Peng [10] showed the storage capacities of the AX-21 sorbent system do not exceed those for the cryo-compressed gaseous H_2 system under identical conditions. Due to its higher gravimetric and volumetric capacities, the MOF-177 sorbent is projected to provide improved capacities over the activated carbon but is still not as good as the best cryo-compressed H_2 gas-only vessels, as shown in Figures 1 and 2 and in Table 1.

Chemical Hydrogen Storage Materials

Chemical hydrides store hydrogen via strong chemical bonds and typically, cannot be directly recharged with H_2 gas on-board the vehicle under practical temperature and/or pressure. A separate chemical process [11] must be performed off-board to regenerate this storage media to its “hydrogenated” form.

Chemical hydrogen storage systems are also different from other approaches since the on-board system must move the fuel itself at various stages, requiring additional components for the release of hydrogen as well as the collection and removal of the spent fuel from the vehicle. The hydrogen release mechanisms and thermodynamics of potential chemical hydrides vary widely and can range from strongly exothermic (e.g., hydrolysis reactions of LiH or $NaBH_4$) to endothermic decomposition of liquid or solid compounds assisted by catalysts and heating [11]. The configurations of the on-board chemical storage systems are thus highly dependent on the nature of these reactions as well as the characteristics of all the materials involved [11].

To date, detailed system engineering analyses have been performed on three chemical hydride storage concepts: (1) Catalytically controlled exothermic reactions of $NaBH_4/H_20$ solutions, (2) Endothermic release (dehydrogenation reactions) from liquid n-ethyl carbazole using heating and catalysts, and (3) Decomposition of metastable alane (AlH_3) in a concentrated mineral oil slurry [12]. The projected on-board storage capacities and predicted high volume production costs for these three chemical hydrides are compiled in Table 1 and compared with other storage systems in Figures 1 – 4. Although the on-board cost is predicted to be $5/kWh for storage using hydrolysis of $NaBH_4/H_20$ solutions, the system capacities are below the 2010 targets of 4.5 wt% and 28 g-H_2/L. In addition, a number of serious engineering issues associated with maintaining the fuel in liquid phase as well as collecting and controlling the spent fuel products are summarized in Reference 13. Because of the low thermodynamic efficiency (~20% compared to the DOE target [1] of at least 60%) for the regeneration of the $NaBH_4$ phase from the very stable borate decomposition product, in addition to the complexities noted above, DOE discontinued further support for developing the hydrolysis of $NaBH_4$ as a light-duty vehicular hydrogen storage option [13]. Assessments of the liquid organic n-ethyl carbazole for vehicular storage yielded capacities in the range of 2.1-2.8 wt% and 18-21 g-H_2/L that are also below the 2010 system targets indicating this will not be a viable vehicular option unless materials with much greater quantities of releasable hydrogen and lower reaction temperature can be found. Higher usable capacities of 4.3 wt% and 50 g-H_2/L have been projected during the ANL analysis for a storage system containing a 70 wt% solid of AlH_3/mineral oil slurry [12]. Improvements in system performance will require optimization of the alane content and particle sizes dispersed in the carrier liquid along with faster desorption kinetics at lower operating temperature but without decreasing hydride stability during ambient storage. Beyond better on-board properties, alane storage systems would benefit from more efficient and less costly regeneration processes of the residual spent Al material/Al metal such as the recently published electrochemical synthesis route [14].

Physical Storage

Nearly all of the fuel cell vehicles participating in the DOE technology demonstration validation project [2,3] store hydrogen as compressed gas in either Type III (i.e., metal inner liner) or Type IV (i.e., polymer liner) carbon-wrapped vessels at ambient temperatures with 350 bar or 700 bar initial operating pressure. None of these “Learning Demo” gas storage systems can meet the 2010 system targets for capacities. The assessments of modified configurations (i.e., optimized single tanks) of the Type IV vessels presented in Figure 1 and Table 1 do indicate some improvements are possible for the gravimetric capacities at both operating pressures. However, almost no increase in the volumetric capacity was found primarily due to the fact that the density of just the compressed H_2 gas itself at room temperature is 23 g-H_2/L and 39 g-H_2/L at 350 bar and 700 bar, respectively, without any container or necessary valves or plumbing of the system. Although the manufacturing technology of carbon fiber is well established, improvements are needed in the fiber properties and significant cost reductions of high pressure tanks. A comprehensive assessment of both "on-board" and "off-board" metrics for hydrogen storage as a compressed gas has been recently completed by the ANL and TIAX team in which the analysis methodology, assumptions, key performance parameters are given [15].

Cryo-compressed hydrogen storage involves using a vessel that can be pressurized (e.g., to ~350 bar) for the storage of H_2 at cryogenic temperature [16]. The hydrogen may be stored in the liquid phase, cold compressed H_2 gas, or a saturated liquid/vapor mixture depending on variation in temperature and pressure. Systems analyses have been performed on two designs (i.e., Gen-2 and Gen-3) of automotive storage vessels storing cryo-compressed liquid phase hydrogen and prototypes developed at the Lawrence Livermore National Laboratory (LLNL) [16]. The predicted capacities of the Gen-3 cryo-compressed storage vessels can meet the 2015 capacity targets and may come close to the ultimate capacity targets if these configurations can be successfully optimized. While the projected costs of on-board cryo-compressed vessels are similar to those of 350-bar tanks, the energy needed to liquefy hydrogen used for refilling cryo-compressed tanks leads to higher operating costs. A detailed report summarizing their assessments of on-board and off-board performance and cost of cryo-compressed hydrogen storage based upon the LLNL Gen-3 prototype system has been prepared by ANL and TIAX [17].

Current Status and Summary

The gravimetric and volumetric capacities and costs given in Table 1 and plotted in Figures 1-3 include essentially all major results produced by the FCT Hydrogen Storage sub-program that have been reported publicly through June 2010. As indicated in Fig. 1, steady increases in the predicted gravimetric capacities are being obtained. Improvement in the mean volumetric capacities shown in Fig. 2 has been less, which is mainly due to limitations of compressed gas storage tanks at 350 bar and 700 bar as described above. Nevertheless, projected volumetric capacities of storage via alane slurries and cryo-compressed storage systems would exceed the 2015 target of 40 g-H_2/L . Over the past several years ANL has examined variations in the performance of several on-board storage systems beyond base case designs [9, 10, 16, 17, 18, 19]. Many of these results are compared in Fig. 4, which show the sensitivity of gravimetric and volumetric capacities to designs and other variations [18, 19]. Fig. 4 also includes the performance parameters from the "Learning Demo" compressed gas storage vessels [2, 3], which are consistent with the ANL predictions for similar configurations.

Finally, the Hydrogen Storage Engineering Center of Excellence (HSECoE) was initiated by the FCT in 2009, which includes in its objectives assessments of the requirements and performance potential of condensed phase hydrogen storage systems for light duty vehicles [20]. Some preliminary results for storage systems using $NaAlH_4$ and activated carbon were presented at the 2010 AMR [21].

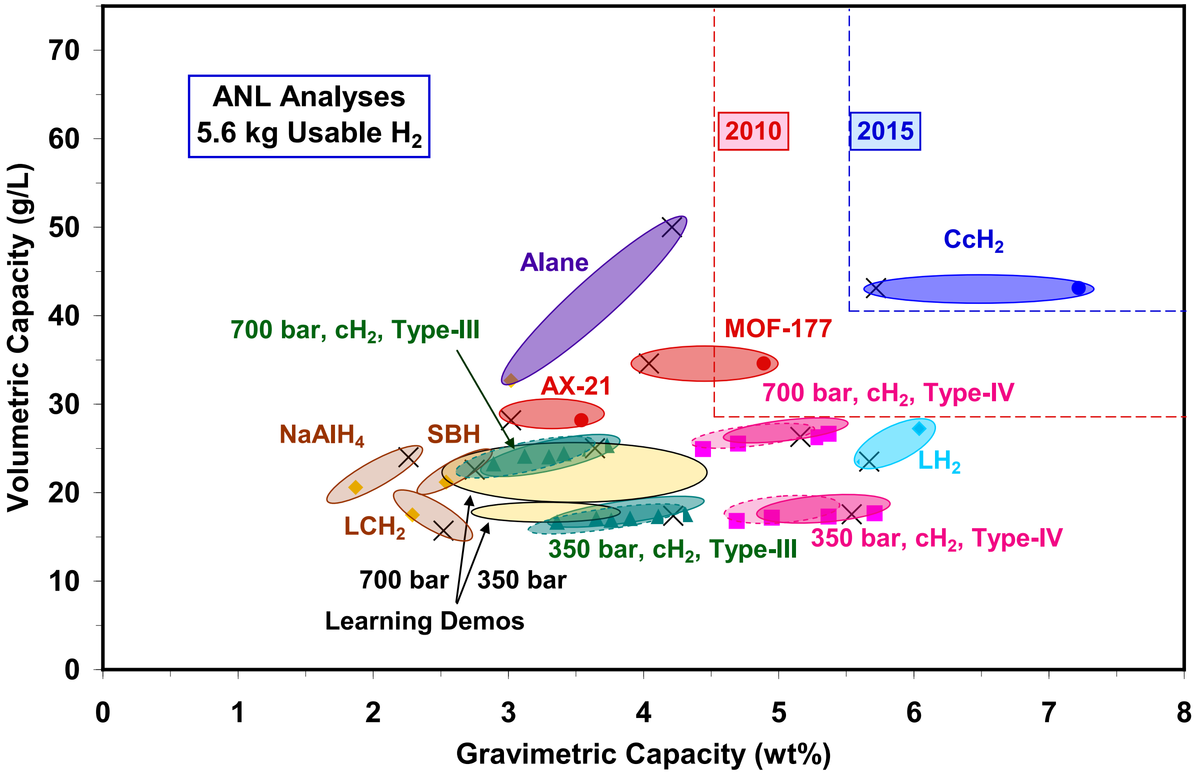

Figure 4. The gravimetric and volumetric capacities predicted for several hydrogen storage systems by Argonne National Laboratory (ANL). The symbols (X) denote base case configurations while other symbols correspond to design and materials variations (See References 18 and 19). The parameters of compressed gas storage systems from the "Learning Demos" Technology Validation project are also included.

References

[1] DOE Targets for On-Board Hydrogen Storage Systems for Light-Duty Vehicles, February 2009, published on DOE/FCT website: http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf

[2] K. Wipke, S. Sprik, J. Jurtz, H. Thomas, and J. Garbak, "FCV Learning Demonstration: Project Midpoint Status and First-Generation Vehicle Results", World Electric Vehicle Journal 2(No.3) (2008) 4-17. http://www.nrel.gov/hydrogen/pdfs/ja-560-45468.pdf

[3] K. Wipke, S. Sprik, J. Kurtz, and J. Garbak, "Field Experience with Fuel Cell Vehicles" in Handbook of Fuel Cells – Fundamentals, Technology and Applications, Edited by W. Vielstich, H. Yokokawa, and H. A.

Gasteiger. Volume 6: Advances in Electrocatalyst, Materials, Diagnostics and Durability (2009, Wiley, New York), Chapter 60. http://www.nrel.gov/hydrogen/pdfs/43589.pdf

[4] S. Satyapal, J. Petrovic, C. Read, G. Thomas, and G. Ordaz , “The U.S. Department of Energy’s National Hydrogen Storage Project: Progress towards meeting hydrogen-powered vehicle requirements,” Catalysis Today **120** (2007) 246–256.

[5] DOE Hydrogen Program Annual Merit Review and Peer Evaluation, Proceedings published on the DOE/FCT website: http://www.hydrogen.energy.gov/annual_review.html

[6] DOE Hydrogen Program Annual Progress Reports, published on the DOE/FCT website: http://www.hydrogen.energy.gov/annual_progress.html

[7] D. A. Mosher, et al., “Design, Fabrication and Testing of $NaAlH_4$ based Hydrogen Storage Systems”, J. Alloys Compds. **446-447** (2007) 707-712.

[8] D. Mosher, et al., “High Density Hydrogen Storage System Demonstration Using $NaAlH_4$ Complex Compound Hydrides”, A Report to the DOE (December 19, 2006), published on the DOE/FCT website; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/storage_system_prototype.pdf

[9] R. K. Ahluwalia, “Sodium Alanate Hydrogen Storage System for Automotive Fuel Cells”, Int. J. Hydrogen Energy **32** (2007) 1251-1261.

[10] R. K. Ahluwalia and J. K. Peng, “Automotive Hydrogen Storage System Using Cryo-Adsorption on Activated Carbon”, Int. J. Hydrogen Energy **34** (2009) 5476-5487.

[11] C. L. Aardahl and S. D. Rassat, “Overview of Systems Considerations for On-Board Chemical Hydrogen Storage”, Int. J. Hydrogen Energy **34** (2009) 6676-6683.

[12] R. K. Ahluwalia, T. Q. Hua, and J. K. Peng, “Automotive Storage of Hydrogen in Alane”, Int. J. Hydrogen Energy **34** (2009) 7731-7740.

[13] DOE Independent Review “Go/No-Go Recommendation for Sodium Borohydride for On-Board Vehicular Hydrogen Storage”, NREL Report NREL/MP-150-4220 (November 2007) published on the DOE/FCT website: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/42220.pdf

[14] R. Zidan, B. Garcia-Diaz, C. S. Fewox, A. C. Stowe, J. R. Gray, and A. G. Harter, “Aluminium Hydride: A Reversible Material for Hydrogen Storage” Chem. Commun. (2009) 3717-3719.

[15] S. Lasher, K. McKenney, J. Sinha, R. K. Ahluwalia, T. Q. Hua, and J.-K. Peng, “Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Appliations”, DOE-2009/XXX Report, Final Draft (December, 2009)

[16] Department of Energy Hydrogen Program Report "Technical Assessment: Cryo-Compressed Hydrogen Storge for Vehicular Applications" (October 30, 2008) published on the DOE/FCT website: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/cryocomp_report.pdf

[17] R. K. Ahluwalia, T. Q. Hua, and J-K Peng, S. Lasher, K. McKenney, J. Sinha, "Technical Assessment of Cryo-Compressed Hydrogen Storage Tank Systems for Automotive Applications", ANL Report ANL/09-33, (December, 2009).

[18] R. K. Ahluwalia, et al., "System Level Analysis of Hydrogen Storage Options", Proceedings of 2010 Annual Merit Review, Project ID: ST-001. http://www.hydrogen.energy.gov/pdfs/review10/st001_ahluwalia_2010_o_web.pdf

[19] R. K. Ahluwalia, et al., "Performance and Cost Analyses of Type 3 and Type 4 Compressed Hydrogen Tanks', presentation to the DOE/EERE Storage System Analysis Working Group (SSAWG) Meeting, June, 2010.

[20] D. L. Anton and T. Motyka, "Hydrogen Storage Engineering Center of Excellence", Proceedings of 2010 Annual Merit Review, Project ID: ST-004. http://www.hydrogen.energy.gov/pdfs/review10/st004_anton_2010_o_web.pdf

[21]. D. Kumar, "System Design and Media Structuring for On-Board Hydrogen Storage Technologies", Proceedings of 2010 Annual Merit Review, Project ID: ST-009. http://www.hydrogen.energy.gov/pdfs/review10/st009_kumar_2010_o_web.pdf

Table 1. Summary of the projected system gravimetric and volumetric capacities and production costs during high-volume production of "on-board" hydrogen storage systems in vehicles. The year and reference sources for these results are given along with key assumptions and other comments. Note: N/A denotes a parameter was not evaluated in that referenced study.

(a) Compressed Hydrogen Gas Tanks (Part 1)

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	System Cost ($/kWh)	Year	Source	Assumptions and Notes
Compressed Hydrogen (700 bar)	3.50%	24.7	21.4	2010	ANL Presentation at Storage System Analysis Working Group Meeting, June 2010 (Slides 4 & 11)	Two Type III tanks with 9.6 mm Al metal liner and 90% of stress load in carbon fiber (CF) storing 5.6 Kg of usable hydrogen at 700 bar. CF strength is 90% of value that was used in 2009 analyses of type IV tanks as a safety margin to account for variations in manufacturing. CF translation efficiency of 80% was used. The other design parameters were the same as in the 2009 analyses. Also includes metal fatigue impact from 5,500 pressure cycles. Cost Analyses were performed by TIAX.
Compressed Hydrogen (700 bar)	4.80%	25.6	19.2	2010	ANL Presentation at Storage System Analysis Working Group Meeting, June 2010 (Slides 4 & 11)	Two Type IV tanks with 5-mm HDPE liner and 100% of stress load in carbon fiber (CF) storing 5.6 Kg of usable hydrogen at 700 bar. CF strength is 90% of value that was used in 2009 analyses of type IV tanks as a safety margin to account for variations in manufacturing. CF translation efficiency of 80% was used. The other design parameters were the same as in the 2009 analyses. Cost Analyses were performed by TIAX.
Compressed Hydrogen (350 bar)	4.00%	17.2	16.9	2010	ANL Presentation at Storage System Analysis Working Group Meeting, June 2010 (Slides 4 & 11)	Two Type III tanks with 5.9 mm Al metal liner and 90% of stress load in carbon fiber (CF) storing 5.6 Kg of usable hydrogen at 700 bar. CF strength is 90% of value that was used in 2009 analyses of type IV tanks as a safety margin to account for variations in manufacturing. CF translation efficiency of 85% was used. The other design parameters were the same as in the 2009 analyses. Also includes metal fatigue impact from 5,500 pressure cycles. Cost Analyses were performed by TIAX.
Compressed Hydrogen (350 bar)	5.00%	17.2	15.8	2010	ANL Presentation at Storage System Analysis Working Group Meeting, June 2010 (Slides 4 & 11)	Two Type IV tanks with 5-mm HDPE liner and 100% of stress load in carbon fiber (CF) storing 5.6 Kg of usable hydrogen at 700 bar. CF strength is 90% of value that was used in 2009 analyses of type IV tanks as a safety margin to account for variations in manufacturing. CF translation efficiency of 85% was used. The other design parameters were the same as in the 2009 analyses. Cost Analyses were performed by TIAX.
Compressed Hydrogen (700 bar)	3.60%	25.0	21.2	2010	ANL Presentation at Storage System Analysis Working Group Meeting, June 2010 (Slides 3, 4 & 11)	Single Type III vessel with 12.1 mm Al metal liner and 90% of stress load in carbon fiber (CF) storing 5.6 Kg of usable hydrogen at 700 bar. CF strength is 90% of value that was used in 2009 analyses of type IV tanks as a safety margin to account for variations in manufacturing. CF translation efficiency of 80% was used. The other design parameters were the same as in the 2009 analyses. Also includes metal fatigue impact from 5,500 pressure cycles. Cost Analyses were performed by TIAX.

(a) Compressed Hydrogen Gas Tanks (Part 2)

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	System Cost ($/kWh)	Year	Source	Assumptions and Notes
Compressed Hydrogen (700 bar)	5.20%	26.3	18.9	2010	ANL Presentation at Storage System Analysis Working Group Meeting, June 2010 (Slides 3, 4 & 11)	Single Type IV vessel with 5-mm HDPE liner and 100% of stress load in carbon fiber (CF) storing 5.6 Kg of usable hydrogen at 700 bar. CF strength is 90% of value that was used in 2009 analyses of type IV tanks as a safety margin to account for variations in manufacturing. CF translation efficiency of 80% was used. The other design parameters were the same as in the 2009 analyses. Cost Analyses were performed by TIAX.
Compressed Hydrogen (350 bar)	4.20%	17.4	16.8	2010	ANL Presentation at Storage System Analysis Working Group Meeting, June 2010 (Slides 3, 4 & 11)	Single Type III vessel with 7.4 mm Al metal liner and 90% of stress load in carbon fiber (CF) storing 5.6 Kg of usable hydrogen at 700 bar. CF strength is 90% of value that was used in 2009 analyses of type IV tanks as a safety margin to account for variations in manufacturing. CF translation efficiency of 85% was used. The other design parameters were the same as in the 2009 analyses. Also includes metal fatigue impact from 5,500 pressure cycles. Cost Analyses were performed by TIAX.
Compressed Hydrogen (350 bar)	5.50%	17.6	15.5	2010	ANL Presentation at Storage System Analysis Working Group Meeting, June 2010 (Slides 3, 4 & 11)	Single Type IV vessel with 5-mm HDPE liner and 100% of stress load in carbon fiber (CF) storing 5.6 Kg of usable hydrogen at 700 bar. CF strength is 90% of value that was used in 2009 analyses of type IV tanks as a safety margin to account for variations in manufacturing. CF translation efficiency of 85% was used. The other design parameters were the same as in the 2009 analyses. Cost Analyses were performed by TIAX.
Compressed Hydrogen (700 bar)	4.80%	25.6	20.0	2009	TIAX/ANL Final Report "H_2 Storage Compressed Gas at 350 and 700 bar" (Reference 15)	Theoretical values that are based upon an optimized design for a single Type IV vessel with HDPE polymer liner storing 5.6 Kg of usable H_2 at 10,153 psi (700 bar) with 25% over nominal tank pressure for fast fills. Pressure Factor of Safety (FS) reduced from 2.35 to 2.25. Carbon fiber translation efficiency of 63% and composite strength of 2550 MPa.
Compressed Hydrogen (350 bar)	6.00%	17.8	13.4	2009	TIAX/ANL Final Report "H_2 Storage Compressed Gas at 350 and 700 bar" (Reference 15)	Theoretical values that are based upon an optimized design for a single Type IV vessel with HDPE polymer liner storing 5.6 Kg of usable H_2 stored at 5,076 psi (350 bar)with 25% over nominal tank pressure for fast fills. Pressure Factor of Safety (FS) reduced from 2.35 to 2.25 Carbon fiber translation efficiency of 82.5% and composite strength of 2550 MPa.

(a) Compressed Hydrogen Gas Tanks (Part 3)

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	System Cost ($/kWh)	Year	Source	Assumptions and Notes
Compressed Hydrogen (~700 bar)	4.20%	23.0	27.0	2008	IV.E.1 Analyses of Hydrogen Storage Materials and On-Board Systems FY2008 Annual Progress Report Stephen Lasher, TIAX LLC	Single Type IV vessel with 5.6 Kg of usable H_2 stored at 10,000 psi (690 bar). Carbon fiber cost accounts for 80% of total system cost. Detailed design assumptions were not specified but are based upon a theoretical configuration for the vessel.
Compressed Hydrogen (~350 bar)	5.60%	17.0	17.0	2008	IV.E.1 Analyses of Hydrogen Storage Materials and On-Board Systems FY2008 Annual Progress Report Stephen Lasher, TIAX LLC	Single Type IV vessel with 5.6 Kg of usable H_2 stored at 5,000 psi (345 bar). Carbon fiber cost accounts for 75% of total system cost. Detailed design assumptions were not specified but are based upon a theoretical configuration for the vessel.
Compressed Hydrogen (~700 bar psi)	4.50%	24.0	18.6	2006	IV.F.2 Cost Analysis of Hydrogen Storage Systems FY2006 Annual Progress Report Stephen Lasher, TIAX LLC (Figures 4, 5, and 6)	Based on results of previous TIAX analysis [E. Carlson, "Cost Analyses of Fuel Cell Stacks/Systems", 2004 Annual Merit Review Proceedings, Fuel Cell Poster #2] for H_2 stored at 10,000 psi (690 bar) adjusted for < 100% carbon fiber translation strength. Results are not included in Figures 1, 2, and 3 as input assumptions are incomplete.
Compressed Hydrogen (~350 bar)	6.10%	18.0	12.0	2006	IV.F.2 Cost Analysis of Hydrogen Storage Systems FY2006 Annual Progress Report Stephen Lasher, TIAX LLC (Figures 4, 5, and 6)	Based on results of previous TIAX [E. Carlson, "Cost Analyses of Fuel Cell Stacks/Systems", 2004 Annual Merit Review Proceedings, Fuel Cell Poster #2] analysis for H_2 stored at 5,000 psi (345 bar) adjusted for < 100% carbon fiber translation strength. Results are not included in Figures 1, 2, and 3 as input assumptions are incomplete.

(b) Cryo-compressed storage vessels

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	System Cost ($/kWh)	Year	Source	Assumptions and Notes
Cryo-Compressed (5.6 Kg H_2)	5.70%	43.3	N/A	2010	FY2010 AMR Project ST-001 "System Level Analysis of Hydrogen Storage Options" R. Ahluwalia, ANL (Slides 9 & 21)	Revise modified LLNL design with 276 bar pressure rating, single flow nozzle, liquid H2 pump, Type III tank with 9.3-mm Al liner, 85% load in CF, 3.2 mm steel shell, and 5500 cycles safety factor
Cryo-Compressed (10.4 Kg H_2)	6.85%	44.6	N/A	2010	FY2010 AMR Project ST-001 "System Level Analysis of Hydrogen Storage Options" R. Ahluwalia, ANL (Slide 9)	Revise modified LLNL design with 276 bar pressure rating, single flow nozzle, liquid H2 pump, Type III tank with 11.4-mm Al liner, 85% load in CF, 3.2 mm steel shell, and 5500 cycles safety factor
Cryo-Compressed (5.6 Kg H_2)	5.50%	43.0	12.0	2009b	TIAX Final Report "H_2 Storage using Cryo-compressed On-board System and Ownership Cost Assessment of Gen 3 Tank" (Slides 4-7); Appendix B in Reference #17.	Updated estimate for modified LLNL Gen-3 design that was scaled for storing 5.6 Kg of usable H_2. Maximum pressure of 272 bar in carbon wrapped inner tank with Al liner. Capacities from ANL.
Cryo-Compressed (5.6 Kg H_2)	4.00%	28.0	20.0	2009a	IV.E.1 Analyses of Hydrogen Storage Materials and On-Board Systems FY2008 Annual Progress Report Stephen Lasher, TIAX LLC and TIAX presentation to SSAWG Meeting June 17, 2009 (Slides 7, 9, & 10)	Updated estimate for LLNL Gen-2 design that was scaled for 5.6 Kg of usable H_2 capacity. Maximum pressure of 350 bar in carbon wrapped inner tank with Al liner.
Cryo-Compressed (10.4 Kg H_2)	7.10%	44.5	8.0	2009	TIAX Final Report "H_2 Storage using Cryo-compressed On-board System and Ownership Cost Assessment of Gen 3 Tank" (Slides 4-7); Appendix B in Reference #17.	Updated estimate for Gen-3 design storing 10.4 Kg of usable H_2 with reduced costs for cryogenic components. Maximum pressure of 272 bar in carbon wrapped inner tank with Al liner.
Cryo-Compressed (10.1 Kg H_2)	5.50%	33.0	13.5	2008	IV.E.1 Analyses of Hydrogen Storage Materials and On-Board Systems FY2008 Annual Progress Report Stephen Lasher, TIAX LLC	Updated estimate of Gen-2 design for 10.1 Kg of usable H_2 Carbon Fiber and Cryogenic control valves account for about 50% of the total cost. Maximum pressure of 350 bar in carbon wrapped inner tank with Al liner.
Cryo-Compressed (10.1 Kg H_2)	4.70%	30.0	8.4	2007	IV.F.2 Cost Analysis of Hydrogen Storage Systems FY2007 Annual Progress Report Stephen Lasher, TIAX LLC IV.F.1 System Level Analysis of Hydrogen Storage Options FY2007 Annual Progress Report Rajesh K. Ahluwalia, Argonne National Lab	Used LLNL second generation (Gen-2) cryo-compressed tank as design basis for cyro-compressed system cost estimate 151 L Tank, 10.1 kg of usable H_2, 94% drive cycle utilization calculated by ANL Used fixed tank processing cost factor of 50% on top of the total tank material cost

(c) Liquid hydrogen storage vessels

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	System Cost ($/kWh)	Year	Source	Assumptions and Notes
Liquid Hydrogen (5.6 Kg H_2)	5.60%	23.5	8.0	2010	FY2010 AMR Project ST-001 "System Level Analysis of Hydrogen Storage Options" R. Ahluwalia, ANL (Slide 21) FY2010 AMR Project ST-002 "Analyses of Hydrogen Storage Materials and On-Board Storage" S. Lasher, TIAX (Slides 7 & 48).	Updated estimates for 5.6 Kg of usable H_2 capacity
Liquid Hydrogen (5.6 Kg H_2)	4.40%	28.0	14.0	2009	Stephen Lasher, TIAX LLC presentation to SSAWG Meeting June 17, 2009 (Slides 7, 9, & 10)	Updated estimate scaled for 5.6 Kg of usable H_2 capacity
Liquid Hydrogen (10.1 Kg H_2)	6.50%	33.0	8.0	2008	IV.E.1 Analyses of Hydrogen Storage Materials and On-Board Systems FY2008 Annual Progress Report Stephen Lasher, TIAX LLC	For 10.1 Kg of usable H_2 Cryogenic control and relief valves account for 30% total cost
Liquid Hydrogen (10.1 Kg H_2)	N/A	N/A	4.9	2007	IV.F.2 Cost Analysis of Hydrogen Storage Systems FY2007 Annual Progress Report Stephen Lasher, TIAX LLC	Preliminary cost numbers for 10.1 kg of usable hydrogen The assumed tank processing cost contains high level of uncertainty

(d) Chemical Hydrogen Storage Systems:

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	System Cost ($/kWh)	Year	Source	Assumptions and Notes
Alane Slurry	4.30%	50.0	N/A	2008	IV.E.2 System Level Analysis of Hydrogen Storage Options FY2008 Annual Progress Report Rajesh K. Ahluwalia, Argonne National Lab	(1) Estimated system efficiency of ~80% after accounting for ~13% of stored H_2 being consumed during start-up and ~7% of H_2 being consumed by the burner. (2) Slurry contains 70 wt.% AlH_3. (3) Off-board regeneration required with estimated well-to-tank efficiency range of 40-55%.
Liquid/organic Carrier	2.20%	19.0	15.4	2009	DOE FreedomCAR Tech Team Presentation "Liquid Hydrogen Carrier On-Board and Off-board H2 Storage System Cost Assessment" June 18, 2009 S. Lasher, TIAX LLC (Slides 19, 26, & 27)	(1) For 5.6 kg of usable H_2 and total of 8.8 kg stored H_2. (2) media is N-ethylcarbazole with tank assumptions and specifications inputs from APCI and ANL.
Liquid/organic Carrier	2.10%	18.0	15.5	2008	IV.E.1 Analyses of Hydrogen Storage Materials and On-Board Systems FY2008 Annual Progress Report Stephen Lasher, TIAX LLC IV.E.2 System Level Analysis of Hydrogen Storage Options FY2008 Annual Progress Report Rajesh K. Ahluwalia, Argonne National Lab	(1) For 5.6 kg of usable H_2. (2) Based on Air Products' liquid carrier N-ethylcarbazole and a baseline on-board system design developed by ANL. (3) Assumes 67% storage efficiency & 95% conversion efficiency. (4) ANL estimated a ~60+ % well-to-tank efficiency for regeneration.
Liquid /organic Carrier	2.80%	23.0	N/A	2007	IV.F.1 System Level Analysis of Hydrogen Storage Options FY2007 Annual Progress Report Rajesh K. Ahluwalia, Argonne National Lab	Total hydrogen storage of 10 kg. System capacities are based on materials values of 4.4wt% and 35 g H_2/L for N-ethylcarbazole. Assumes 95% conversion in the dehydrogenation reactor and 68% storage system efficiency.
Sodium borohydride hydrolysis chemical storage	3.30%	26.0	4.8	2008	IV.E.1 Analyses of Hydrogen Storage Materials and On-Board Systems FY2008 Annual Progress Report Stephen Lasher, TIAX LLC IV.E.2 System Level Analysis of Hydrogen Storage Options FY2008 Annual Progress Report Rajesh K. Ahluwalia, Argonne National Lab	(1) for 5.6 kg of usable H_2 (2) Incorporated updated system design assumptions using information from Millennium Cell and ANL (3) Conversion efficiency 100%, operating pressure 12 bar and integrated active water/glycol cooling loop $NaBH_4$ concentration of 24 wt% (4) ANL reports estimated off-board regeneration well-to-tank efficiency ranges between 15-23% for various processes.
Sodium borohydride hydrolysis chemical storage	3.20%	29.0	4.7	2006	IV.F.2 Cost Analysis of Hydrogen Storage Systems FY2006 Annual Progress Report Stephen Lasher, TIAX LLC (Figs: 4, 5, and 6) IV.E.2 System Level Analysis of Hydrogen Storage Options FY2008 Annual Progress Report Rajesh K. Ahluwalia, Argonne National Lab	(1) for 5.6 kg of usable hydrogen. (2) Evaluated the Millennium Cell approach to storing and transporting sodium borohydride. (3) Assume sodium borohydride material can achieve 21.3 wt% hydrogen storage capacity (not including water) & based on 1 mole of sodium borohydride with 4 moles of water. (4) Assumed concentration of 26% in water and NaOH.

(d) Sorbent Hydrogen Storage Systems

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	System Cost ($/kWh)	Year	Source	Assumptions and Notes
Activated Carbon	4.50%	31.0	N/A	2009	R. K. Ahluwalia & J. K. Pen, "Automotive hydrogen storage system using cryo-adsorption on activated carbon", Int. J. Hydrogen Energy 34 (2009) 5476-5487	Analysis by ANL based on Activated Carbon AX-21 for 5.6 kg of usable H_2 stored at 350 bar pressure and 100 K temperature, 8-bar minimum discharge, 50 K temperature swing, and 11.2 minutes refueling time.
Activated Carbon	4.80%	28.0	15.6	2007	IV.F.2 Cost Analysis of Hydrogen Storage Systems FY2007 Annual Progress Report Stephen Lasher, TIAX LLC IV.F.3 System Level Analysis of Hydrogen Storage Options FY2006 Annual Progress Report Rajesh K. Ahluwalia, Argonne National Lab	Based on Activated Carbon AX-21 as an in-tank absorbent, modeled by ANL Operates at 100K and pressures up to 3,000 psi will have gravimetric and volumetric capacities from Figure 4 in 2006 ANL Report Based on ANL's estimated 42 kg/m^3 recoverable hydrogen 175 L tank for 5.6 kg of usable hydrogen storage
Activated Carbon	3.10%	14.0	N/A	2007	R. K. Ahluwalia, "System Level Analysis of Hydrogen Storage Options: Status Report" Joule Target Review October 10, 2007 (Slides 2 & 3)	Analysis by ANL based on Activated Carbon AX-21 for 5.6 kg of usable H_2 stored at 50 bar pressure and 100 K temperature, 8-bar minimum discharge, 50-K temperature swing
MOF-177	4.00%	34.6	18.0	2010	FY2010 AMR Project ST-001 "System Level Analysis of Hydrogen Storage Options" R. Ahluwalia, ANL (Slides 12, 21, 26)	Updated estimate of FY2009 engineering results by ANL for 5.6 Kg of usable H_2 capacity. Analysis by TIAX assumed costs for large scale quantities of raw MOF-177 material are identical to AX-21 carbon, which will mostly likely higher by TBD amounts. Hence, current system cost is a lower bound.
MOF-177	5.90%	36.6	N/A	2009	On-Board Storage of Hydrogen in Metal-Organic Frameworks at Cryogenic Temperatures (Slide 21) Hydrogen Storage Tech Team Meeting, 18 June 2009 R. K. Ahluwalia, Argonne National Lab.	(1) For 5.6 kg of usable hydrogen for presumed operating conditions of 100 K and ~250 bar H_2 pressure. (2) MOF-177 is Zn_4O(1,3,5-benzenetribenzoate) with adiabatic refueling using liquid H_2
MOF-177	4.50%	31.0	N/A	2009	System Level Analysis of Hydrogen Storage Options 2009 Annual Merit Review Rajesh K. Ahluwalia, Argonne National Lab ST13_Ahluwalia (Slides 9, 10)	(1) For 5.6 kg of usable hydrogen for presumed operating conditions of 100 K and ~250 bar H_2 pressure. (2) MOF-177 is Zn4O(1,3,5-benzenetribenzoate) with a peak excess H_2 adsorption of 7.5 wt% at 77 K and 10 bar
MOF-177	3.40%	17.0	N/A	2009	IV.E.2 System Level Analysis of Hydrogen Storage Options FY2009 Annual Progress Report (Fig. 2) R. K. Ahluwalia, Argonne National Lab	(1) Estimated from Figure 2 for 5.6 kg of usable hydrogen at presumed operating conditions of 100 K and ~50 bar H_2 pressure. (2) MOF-177 is Zn_4O(1,3,5-benzenetribenzoate) with a peak excess H_2 adsorption of 7.5 wt% at 77 K and 10 bar

(e) Metal Hydride Hydrogen Storage Systems and 2009 Revised DOE System Targets

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	System Cost ($/kWh)	Year	Source	Assumptions and Notes
Sodium Alanate	2.30%	24.0	N/A	2007	IV.A.3 High Density Hydrogen Storage System Demonstration Using NaAlH4 Based Complex Compound Hydrides FY2007 Annual Progress Report Daniel A. Mosher, UTRC (Table 2)	More detailed descriptions & analyses of systems in (1) D. A. Mosher, et al. "Design, fabrication and testing of NaAlH4 based hydrogen storage systems", J. Alloys Compds. **446-447** (2007) 707-712. (2) R. K. Ahluwalia, "Sodium alanate hydrogen storage system for automobile fuel cells", Int. J. Hydrogen Energy **32** (2007) 1251-1261.
Sodium Alanate	1.60%	20.0	11.3	2006	IV.F.2 Cost Analysis of Hydrogen Storage Systems FY2006 Annual Progress Report Stephen Lasher, TIAX LLC (Slides 4, 5, and 6)	For 5.6 kg of usable hydrogen Based on UTRC technology Media density of 1.39 g/cc (accounts more accurately for the Ti catalyst & by products) Cost calculation uses bottom-up method for BOP purchased component costs
Sodium Alanate	1.70%	17.0	N/A	2005	VI.A.2 High Density Hydrogen Storage System Demonstration Using NaAlH4 Based Complex Compound Hydrides FY2005 Annual Progress Report Donald L. Anton, UTRC (Table 1)	Projected capacities based upon prototype 1 design and NaAlH$_4$+4 wt% TiCl$_3$ sorbent media
2010 Targets (New)	4.50%	28.0	TBD	2009	http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf	Storage system cost to be determined in conjuntion with other Partnership cost target changes.
2015 Targets (New)	5.50%	40.0	TBD	2009	http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf	Storage system cost to be determined in conjuntion with other Partnership cost target changes.
Ultimate Targets	7.50%	70.0	TBD	2009	http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf	Storage system cost to be determined in conjuntion with other Partnership cost target changes.

Note: Annual Merit Review Proceedings are available on the DOE/FCT website: http://www.hydrogen.energy.gov/annual_review.html and Annual Progress Reports are available on the DOE/FCT website: http://www.hydrogen.energy.gov/annual_progress.html