IV.0 Hydrogen Storage Program Overview

INTRODUCTION

The Hydrogen Storage program supports research and development (R&D) of materials and technologies for compact, lightweight, and inexpensive storage of hydrogen for automotive, portable, and material handling equipment (MHE) applications. The Hydrogen Storage program has developed a two-prong strategy, with a near-term focus on improving performance and lowering the cost of high-pressure compressed hydrogen storage systems and a long-term focus on developing advanced cold/cryo-compressed hydrogen storage systems and materials-based technologies for hydrogen storage.

In Fiscal Year (FY) 2013, the program focused on development of lower cost precursors and fillers for carbon fiber composites to lower the cost of high-pressure compressed hydrogen systems, system engineering for transportation applications, and continued R&D efforts in materials-based storage including metal hydrides, chemical hydrogen storage materials, and hydrogen sorbents.

GOAL

The program's goal is to develop and demonstrate commercially viable hydrogen storage technologies for transportation, portable power, and MHE applications.

OBJECTIVES[1]

The Hydrogen Storage program's objective regarding light-duty vehicles is to provide sufficient onboard hydrogen storage to allow for a driving range of more than 300 miles (500 km), while meeting packaging, cost, safety, and performance requirements to be competitive with current vehicles. Although some fuel cell electric vehicles (FCEVs) have been demonstrated to travel more than 300 miles on a single fill using high-pressure tanks, this driving range must be achievable across the full range of vehicle models without compromising space, performance, or cost.

By 2017, the program aims to develop and verify onboard automotive hydrogen storage systems achieving the following targets that will allow some hydrogen-fueled vehicle platforms to meet customer performance expectations:

- 1.8 kWh/kg system (5.5 wt%),
- 1.3 kWh/L system (0.040 kg hydrogen/L), and
- $12/kWh ($400/kg stored hydrogen capacity)

The following ultimate targets are intended to facilitate the introduction of hydrogen-fueled propulsion systems across the majority of vehicle classes and models. Advanced storage materials and concepts will be needed to meet the 2017 and ultimate targets.

- 2.5 kWh/kg system (7.5 wt%),
- 2.3 kWh/L system (0.070 kg hydrogen/L), and
- $8/kWh ($266/kg stored hydrogen capacity)

[1] Note: Targets and milestones were recently revised; therefore, individual project progress reports may reference prior targets.

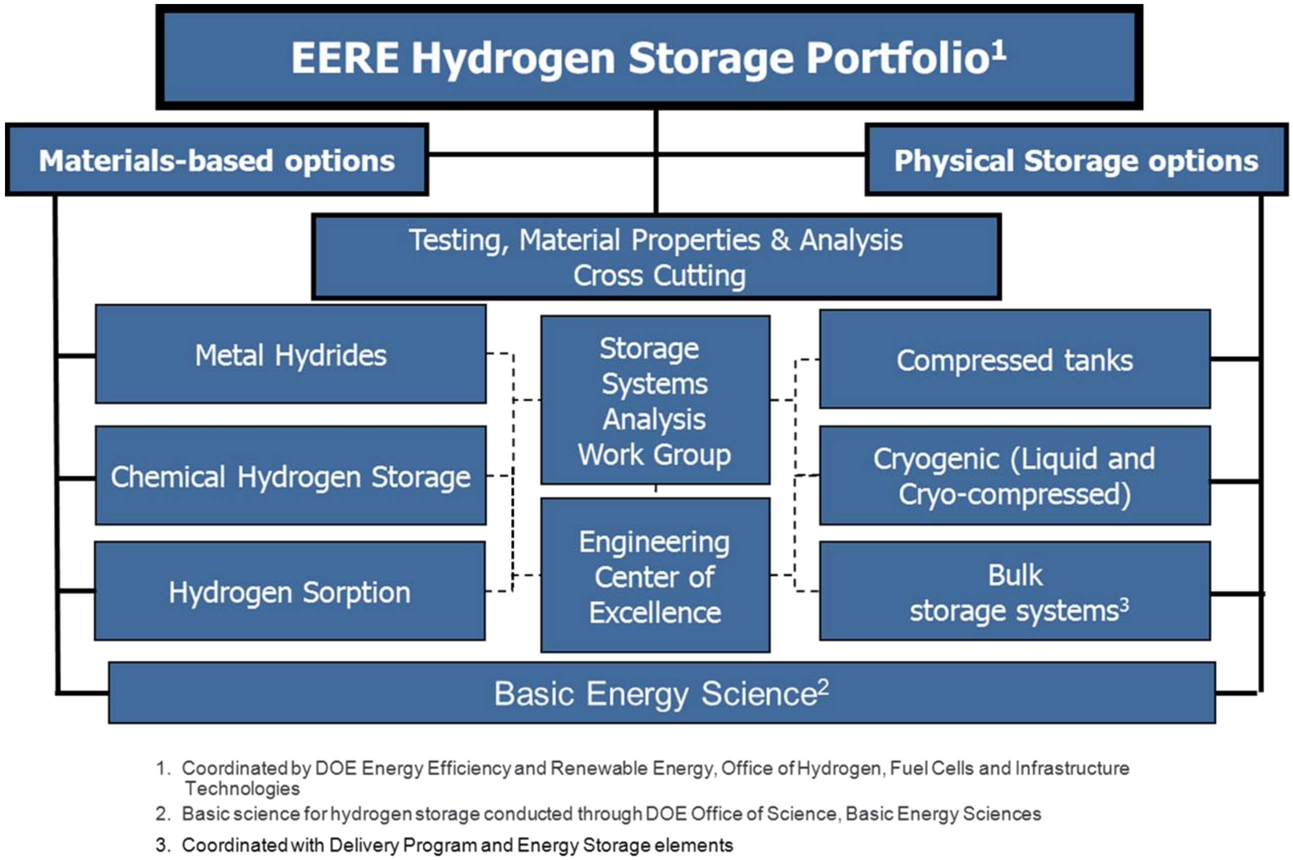


FIGURE 1. The EERE Hydrogen Storage Portfolio of Technologies and their Interrelationships

FY 2013 STATUS

The Hydrogen Storage program has developed comprehensive sets of hydrogen storage targets for onboard automotive, portable power, and MHE targets. The targets can be found in the *Multi-Year Research Development and Deployment Plan* (MYRD&DP). The status of the various storage technologies pursued is evaluated through analysis within individual projects, but also through independent analysis carried out through the program.

In the near-term, automotive companies plan to commercialize FCEVs that use compressed hydrogen systems onboard, with system cost being one of the most important challenges to commercialization. The program, working with automotive original equipment manufacturers through the U.S. DRIVE Partnership, established onboard automotive hydrogen storage system cost targets of $12/kWh of usable stored hydrogen to be reached by 2017, with $8/kWh of usable storage hydrogen as an Ultimate Full Fleet target. In 2013 Strategic Analysis Inc. (SA), working with Argonne National Laboratory (ANL) and the National Renewable Energy Laboratory (NREL), completed a thorough cost analysis for baseline Type IV 350 and 700 bar compressed hydrogen storage systems, for both single- and multi-tank configurations. The cost analysis used a Design for Manufacturing and Assembly (DFMA®) methodology and included considerable input from appropriate stakeholders. A complete description of the methodology, key assumptions and results, along with a performance analysis by ANL, has been published in program data record 13010: *Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost*.[2] Figure 2 shows the projected variable volume manufacturing costs for 700 bar, Type IV onboard system with a 5.6 kg hydrogen usable capacity and includes the component breakdown costs. Current high volume costs are projected to be approximately 50% and 100% higher than the 2017 and Ultimate Full Fleet targets, respectively.

2 DOE Fuel Cell Technologies Office Record 13010: *Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost* [http://hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf].

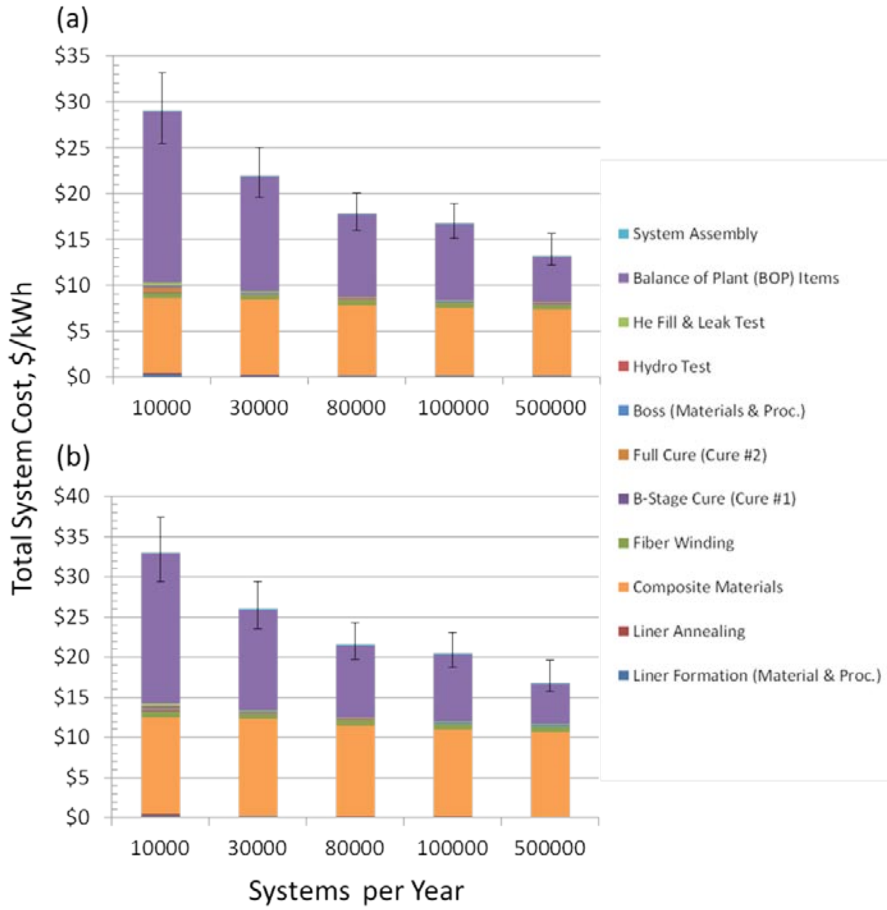
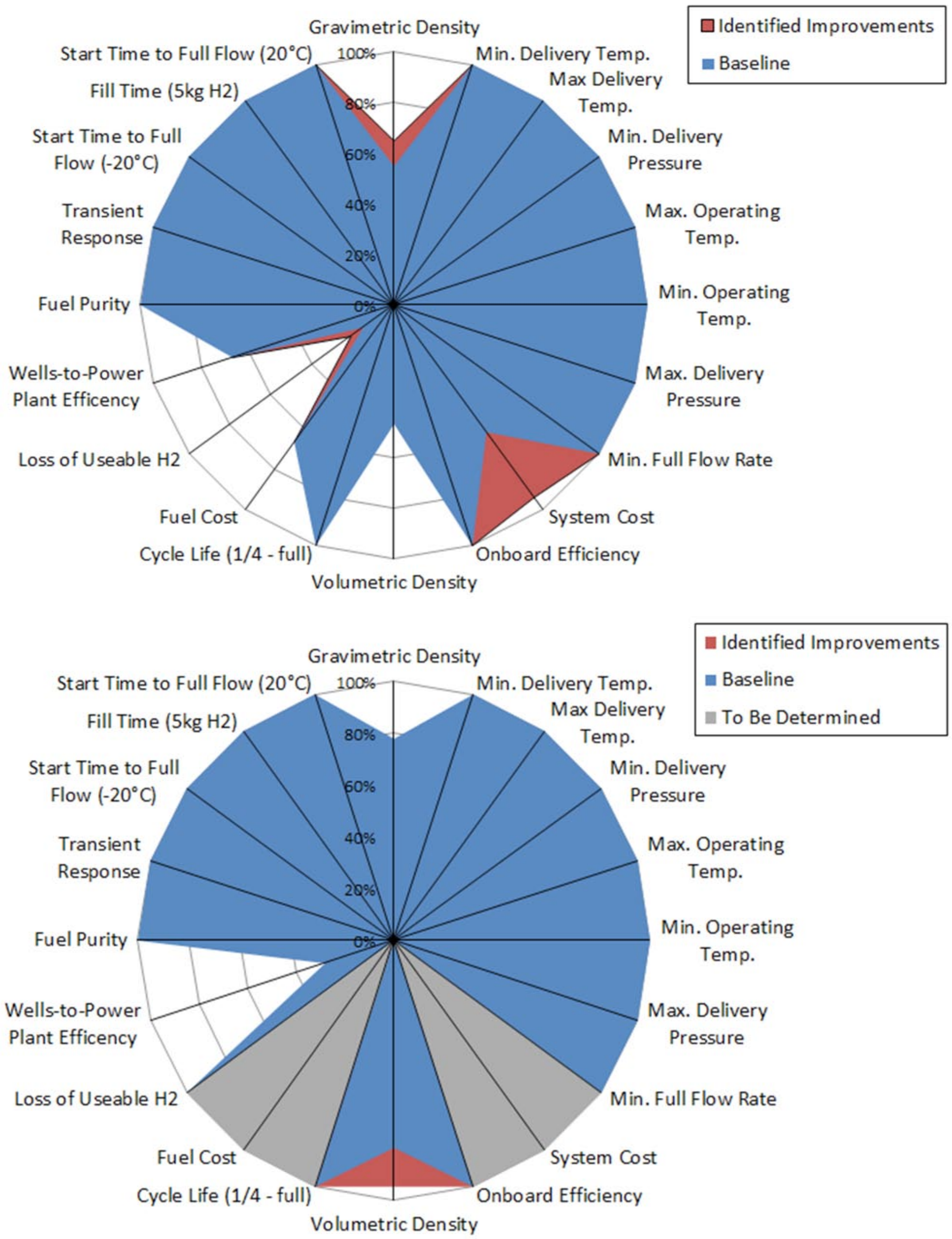


FIGURE 2. Projected costs in 2007$, at various annual manufacturing volumes, for (a) 350 bar and (b) 700 bar compressed hydrogen storage systems, sized to deliver 5.6 kg of hydrogen to the vehicle fuel cell powerplant. Cost analysis performed by SA in 2013.

As a longer-term strategy, the Hydrogen Storage program continues to pursue less mature hydrogen storage technologies that have the potential to satisfy all onboard hydrogen storage targets. These technologies include cold (temperatures as low as ~150-200 K) and cryo–compressed (temperatures <150 K) hydrogen and materials-based storage technologies. The materials-based efforts include total systems engineering and hydrogen storage materials discovery, including adsorbents, metal hydrides, and chemical hydrogen storage materials. A major effort in this area the last several years has been through the Hydrogen Storage Engineering Center of Excellence (HSECoE). In 2013 the HSECoE completed Phase II and is transitioning into Phase III – sub-scale system prototype development and evaluation. As part of the Phase II-III transition decisions, a thorough review of the projected status of both system performance and material availability was carried out. Figure 3 compares the modeled systems performance at the end of Phase I and Phase II for the sorbent and chemical systems, respectively. Neither system is projected to meet the program targets for onboard hydrogen storage with currently available materials. However, these efforts are able to help define the material properties that are needed for a complete system to meet the targets. The results will be used to help guide future hydrogen storage material development efforts. For Phase III of the HSECoE efforts, the decision was made to continue only with the sorbent system prototypes. This decision was partially based on the fact that neither of the two primary chemical hydrogen storage materials investigated by the HSECoE, namely ammonia borane (NH_3BH_3) and alane (AlH_3), are widely available in bulk nor is there a low-cost, energy-efficient process available for their regeneration. Therefore, it was decided to not continue towards sub-scale system prototype evaluation until materials are available that are projected to be low-cost and are able to be efficiently regenerated.

(a)

(b)



FIGURES 3a and 3b. Status of projected sorbent (3a) and chemical hydrogen storage (3b) system performance versus 2017 onboard system targets. Note that the systems were sized to provide 5.6 kg of usable hydrogen. Blue areas indicate projected status at end of Phase I, red areas indicate identified improvements as of the end of Phase II, and the grey areas indicates performance metrics which still must be determined.

Advanced Materials Development

In FY 2013 the program continued efforts in developing and improving hydrogen storage materials with potential to meet the 2017 onboard storage targets in addition to the 2015 portable power and MHE targets. In the area of metal hydrides, efforts emphasized material discovery coupled with reducing desorption temperatures and improving kinetics. For chemical hydrogen storage materials, much of the focus was on developing reversible or regenerable liquid phase materials, such as slurries or solutions, and also increasing efficiency of regeneration routes for solid-phase materials. For hydrogen sorbents, efforts were focused on increasing the isosteric heat of adsorption mainly through metallization to increase the adsorbed capacity at higher temperatures and improving standard measurement practices for hydrogen capacity. Also in FY 2013, the Hydrogen Storage program maintained efforts to collect and disseminate materials data on advanced hydrogen storage materials that comprise the hydrogen storage materials database (http://hydrogenmaterialssearch.govtools.us/).

- Developed an ad hoc working standard of an activated-carbon material to test instrumentation and measurement protocols for hydrogen capacity. (NREL)
- Demonstrated direct spectroscopic evidence of a reversible room temperature sorption/desorption from a unique C-H interaction via diffuse reflectance infrared Fourier transform spectroscopy and neutron scattering. (NREL)
- Identification of a higher performance Liquid Organic Carrier, butylperhydropyrolidine, that undergoes pincer complex catalyzed dehydrogenation at practical turnover rates at 140ºC (Hawaii Hydrogen Carriers, LLC)
- Demonstrated regeneration of $LiAlH_4$ electrolyte material for electrochemical formation of alane and identified diglyme as an inexpensive additive to increase rate (3X) and efficiency of alane production (Savannah River National Laboratory, SRNL)

Engineering

In FY 2013, the HSECoE completed assessment of hydrogen storage systems for cryo-sorbents and liquid-phase off-board regenerable chemical hydrogen storage material systems which allowed the HSECoE to successfully transition from Phase II into Phase III. Assessments included model validation through component level testing and tradeoff analyses that compared novel system designs and candidate storage materials. Based on these results, the center chose to terminate work on chemical hydrogen storage material systems and focus Phase III efforts on cryo-sorbent systems based on a metal organic framework (MOF)-5 material. The Phase III evaluations will include designing, constructing, and testing subscale prototype concepts such as the Hexcel and modular adsorbent tank insert heat exchanger designs.

- Completed assessment of chemical hydrogen storage materials and systems and will terminate work on these systems due to low probability of identifying materials that meet 8.5 wt% fluid gravimetric requirements and regeneration efficiencies. Developed a 6 wt% H_2 liquid phase chemical hydrogen storage media having a viscosity before and after dehydrogenation below 1,500 cP. (HSECoE)
- Developed an ammonia scrubber resulting in a minimum ammonia outlet concentration of 0.1 ppm/v (inlet concentration = 500 ppm/v) having a maximum mass of 1.2 kg and a maximum volume of 1.6 liters. (HSECoE)
- Completed assessment of adsorbent system and downselected both the Hexcel and modular adsorbent tank insert heat exchanger designs for subscale prototype adsorbents systems to be evaluated in Phase III. (HSECoE)
- Completed cryogenic pressure vessel burst testing of Type I (all metal) and IV (composite overwrapped) tanks. Tanks burst at 77 K and pressures above the design limits, proving the efficacy of both types of tanks at cryogenic temperatures. (Hexagon Lincoln)
- Demonstrated an internal flow-through heat exchanger system based on compacted media capable of allowing less than 3-minute scaled refueling time and hydrogen release rate of 0.02 $g_{hydrogen}$/(sec-kW) with a mass less than 6.5 kg and a volume less than 6 liters. (SRNL)
- Developed an adsorbent acceptability envelope that identifies coupled material properties and system dimensions that affect gravimetric and volumetric capacity, charging, and discharging rates. (SRNL)
- Completed costing of 135 cryo-sorbent tanks configurations and identified a 100-bar, Type I vessel with MOF-5 as the lowest cost option. (Pacific Northwest National Laboratory, PNNL)
- Identified balance-of-plant components for a cryo-sorbent hydrogen storage system with a total mass of less than 9.4 kg and volume of less than 11.6 L exceeding the system targets of 17 kg and 18.5 L (PNNL)
- Completed fabrication and testing of a microchannel combustor/heat exchanger to provide hydrogen preheating in an adsorption hydrogen storage system. (Oregon State University)

Advanced Physical Storage

In FY 2013, the program continued to reduce the cost of compressed hydrogen gas storage tanks with efforts focused on low-cost, high-strength carbon fiber and advanced tank designs. Lightweight compressed gas storage vessels requiring a composite overwrap to contain hydrogen gas are considered the most likely near-term hydrogen storage solution for the initial commercialization of FCEVs, as well as for other early market applications. Carbon fiber composite overwraps can currently contribute as much as 75% or more to the overall cost of advanced Type IV tanks. The Hydrogen Storage program supported efforts at Oak Ridge National Laboratory (ORNL) to reduce the cost of polyacrylonitrile-based (PAN) fibers used as precursors to produce high-strength carbon fibers. The ORNL efforts focused on advanced precursor materials and processing since precursors have been shown to contribute approximately 50% of the total cost of high-strength carbon fibers. The team investigated the use of low-cost textile-grade fibers made from PAN blended with a methyl acrylate comonomer (PAN-MA) as lower cost precursors and continued to improve on the development of melt-spinnable PAN precursors and processing techniques to replace the current more costly wet processing methods. Additionally, a team lead by PNNL, focused on reducing the cost of a Type IV tank system by developing novel alternative resins and resins matrix modification, modifying the carbon fiber surface to improve composite translational efficiency, developing methods for alternative fiber placement and enhanced operating conditions that demonstrated routes to increase carbon fiber usage efficiency. Two new Small Business Innovation Research (SBIR) Phase I awards were made that focused on alternative fiber placement and novel resin modifications to reduce the usage of carbon fiber in Type IV tanks. Through an SBIR Phase II project, Applied Nanotech, Inc. continued the development of lightweight, high-strength carbon nanotube reinforced composite overwraps to reduce the cost of tanks.

- Downselected to a single PAN-MA precursor fiber composition and refined the conversion protocol to achieve a 35% improvement in tensile strength (405 ksi) and 10% improvement in tensile modulus (33 Msi) compared to 2012 results. (ORNL)
- Improved spinning and drawing equipment and developed and implemented processes for producing sample quantities of melt-spun PAN-MA precursor that achieved the Go/No-Go milestone of 150 ksi tensile strength and 15 Msi tensile modulus. (ORNL)
- Demonstrated strategies to reduce the cost of pressure vessels by 15% through modeling and material testing consisting of:
  - Testing properties of low-cost resins (4% cost reduction)
  - Testing properties of additives to enhance resin properties (5% cost reduction)
  - Modeling to demonstrate alternative fiber placement and fiber types (6% cost reduction) (PNNL)

Testing & Analysis

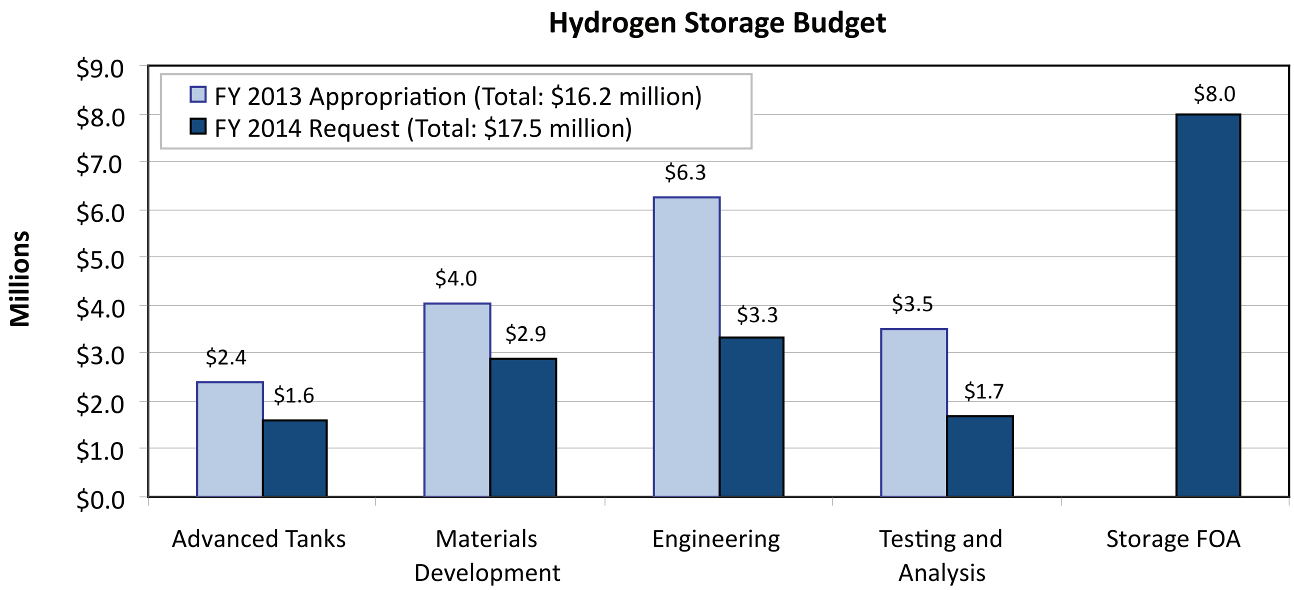
In FY 2013, the Hydrogen Storage program continued carrying out assessments of hydrogen storage technologies and to disseminate proper hydrogen storage material testing and characterization procedures to evaluate material/system performance against requirements of hydrogen fuel cell applications. Technical analysis and cost modeling of Type IV pressure vessel systems remained a critical focus during FY 2013, with a baseline cost and validation of the performance costs with tank manufacturers' data.

- Refined the ABAQUS finite-element model of carbon fiber filament wound Type IV vessel for hydrogen storage at 350 and 700 bar. Calibrated and validated the ABAQUS model against other models based on modified netting analysis and transfer functions derived from data supplied by tank manufacturers. (ANL)
- Formulated models and performed reverse engineering to determine thermodynamic and kinetic properties of metal hydride materials needed to meet system targets and compared to metal hydride acceptability envelope developed by the HSECoE. (ANL)
- Updated DFMA® cost analysis and validated key performance parameters for pressure vessels based on discussions with industry, the U.S. DRIVE Partnership Hydrogen Storage Tech Team, the Storage System Analysis Working Group, ANL, PNNL, HSECoE, and project collaborators where the key parameters included (1) the composite fiber and resin masses as a function of tank capacity, (2) fiber and resin material costs, and (3) cost of the balance-of-plant components. (SA)
- Completed cost analysis of the off-board regeneration of spent ammonia borane and alane slurries for use by the HSECoE. (SA)
- Updated, completed, and posted online Section 6: Thermal Properties of the Best-Practices Document on the Characterization of Hydrogen Storage Materials[3]. (Hydrogen Technology Consulting through NREL)

[3] http://www1.eere.energy.gov/hydrogenandfuelcells/hydrogen_publications.html#h2_storage

BUDGET

$17.5 million from the President's FY 2014 budget request is planned for hydrogen storage—compared with $16.2 million from the FY 2013 congressional appropriation. In FY 2014, the Hydrogen Storage program will continue to focus on nearer-term R&D to lower the cost of high-pressure storage systems and longer-term technology development including cold/cryo-compressed hydrogen and materials discovery and system engineering for materials-based storage technologies. The program will also continue to carry out systems analyses. The program plans to initiate new activities in these areas for onboard automotive and non-automotive applications.



FY 2014 PLANS

The technology portfolio for Hydrogen Storage emphasizes materials R&D to meet system targets for onboard automotive and non-automotive applications. While a focus on light-duty vehicle applications will continue, increased emphasis will be placed on new materials and novel concepts to meet performance requirements for portable power and material handling equipment applications. The increased emphasis on developing lower-cost physical storage technologies will continue to be expanded. Specifically, the program will coordinate with and leverage other efforts (e.g., Advanced Manufacturing, Vehicle Technologies, DARPA, etc.) to develop approaches to produce low-cost carbon fiber for composite cylinders. System engineering and analysis will continue through the HSECoE, ANL, and SA. Coordination with basic science efforts, including theory, characterization, and novel concepts, will continue during FY 2014.

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