VI Storage

VI.1 Hydrogen Storage Sub-Program Overview

Introduction

Hydrogen Storage continues to be a key enabling technology for the advancement of hydrogen and fuel cell power technologies in transportation, stationary power and portable power applications. The Hydrogen Storage activity focuses primarily on the research and development of on-board vehicular systems that will allow for a driving range of more than 300 miles while meeting packaging, cost, safety, and performance requirements. Technologies developed under this effort may also be applicable to hydrogen delivery and off-board storage of hydrogen and will be closely coordinated with the Hydrogen Delivery sub-program element.

In FY 2005, the awards from the Hydrogen Storage "Grand Challenge" solicitation were initiated with three Centers of Excellence (CoEs) in advanced metal hydrides, carbon-based/sorbent materials and chemical hydrogen storage, as well as 15 new independent projects. Awardees include 30 universities, 10 companies and 10 federal laboratories. Also in FY 2005, the Hydrogen Storage Systems Analysis Working Group was formed to coordinate systems analysis work across the storage sub-program and to aid in assessing technologies on a systematic basis in terms of life cycle cost, performance, energy efficiency and environmental impact. The group will meet semi-annually with monthly interim progress meetings. The DOE Office of Energy Efficiency and Renewable Energy Hydrogen Storage activity will continue to coordinate with the DOE Office of Science (Basic Energy Sciences) as 17 new hydrogen storage basic research projects are initiated in FY 2005.

The hydrogen storage effort will continue to increase longer-term, multidisciplinary exploratory research for breakthrough approaches to overcome the hydrogen storage technical barriers as advised by the National Research Council (NRC). In addition, as a result of the NRC's recent review of the FreedomCAR and Fuel Partnership, DOE will report annually to all program participants, the FreedomCAR and Fuel Partnership and Congress on the state of hydrogen storage technology worldwide relative to DOE goals and targets for the program.

Goal

- Develop and demonstrate viable hydrogen storage technologies for transportation and stationary applications.

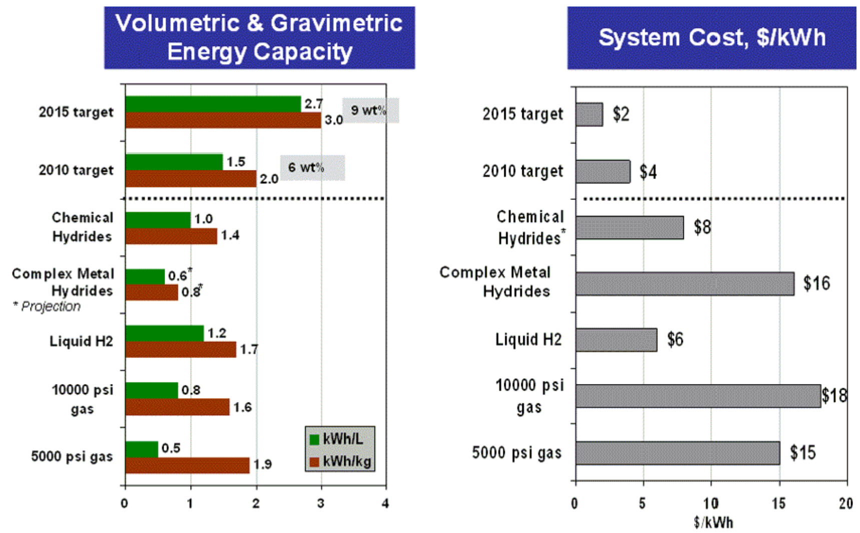
Objectives

- By 2010, develop and verify on-board hydrogen storage systems achieving 2 kWh/kg (6 wt.%), 1.5 kWh/L, and $4/kWh
- By 2015, develop and verify on-board hydrogen storage systems achieving 3 kWh/kg (9 wt.%), 2.7 kWh/L, and $2/kWh

FY 2005 Technology Status

On-board hydrogen storage approaches under investigation include advanced metal hydrides, carbon-based materials and other high-surface-area sorbents, chemical hydrogen storage, low-cost and conformable tanks, compressed/cryogenic hydrogen tanks, and new materials or processes, such as clathrates and conducting polymers. Compressed/cryogenic tanks, metal hydrides, high-surface-area sorbents and carbon-based materials constitute on-board reversible hydrogen storage systems because hydrogen regeneration or hydrogen uptake can take place on-board the vehicle. For chemical hydrogen storage approaches as well as certain metal hydrides, hydrogen regeneration is not possible on-board the vehicle; thus, these systems must be regenerated off-board.

The current system status values, as shown below, are estimates provided by developers and by the R&D community and will be updated as information becomes available. Because it is often difficult to estimate system-level weight and volume when research is still at the stage of materials development, the current status data will be revisited periodically. However, it is clear that none of the current systems meets the combined gravimetric, volumetric, and system cost targets for either 2010 or 2015.



Estimates from developers- to be continuously updated

* Regeneration costs excluded

To gauge the progress of materials development, Table 1 shows gravimetric capacity data for materials under development in FY 2004 and FY 2005. Note that these values do not include any balance-of-plant components needed to estimate system values. Although these promising results show potential materials-based capacities of 5 to 9 wt.%, the targets of 6 wt.% by 2010 and 9 wt.% by 2015 are system-level capacities which include the storage media, tank and all balance-of-plant components needed for a vehicular storage system. Significant work is still needed to reduce operating temperatures and pressures to the required range.

Table 1. Hydrogen Storage Capacity Status for FY 2004 and FY 2005

	Material Capacities for Hydrogen Storage			
	Metal Hydrides	**Chemical H_2 Storage**	**Carbon Materials**	**New Materials & Concepts**
Status 2004	Sodium alanate ~3.5 to 4 wt% SNL & U. Hawaii	Organic liquid ~5.5 wt% APCi	Nanotubes ~2 to 3 wt% NREL	Not initiated in FY04
Status 2005	Amides ~5.5 wt%, >100 cycles: Sandia	Ethyl carbazole/ organic liquids up to 6.9 wt%: APCi	Metal/fullerene hybrids potential > 8 wt% from theory: NREL	MOFs: IRMOF-1: 4.5 wt% at 30 bar, 77K: CalTech/UMich
	LiBH4 - MgH2: ~9 wt% at 350°C: HRL	Ammonia borane ~6 wt%, PNNL	Carbide-derived carbons: 3.5 wt% at 77K, 8 atm: Penn/Drexel	**OTHER APPROACHES:** MOFs Conducting polymers Clathrates Glass microspheres Perhydrides
	Alane, 6 to 7 wt% at <100°C: BNL, Sandia, & SRNL			
	Destabilized binary hydrides, ~5 to 7 wt%, HRL			

FY 2005 Accomplishments

<u>Compressed and Cryogenic Tanks</u>

- Completed preliminary optimization of low-cost 10,000 psi tanks to achieve 1.3 kWh/kg specific energy. Identified approaches with potential to lower cost from $18/kWh to $10/kWh.
- Completed design of cryo-compressed tank system with potential to meet 1.2 kWh/L (2007 target).

Advanced Metal Hydrides

- Completed preliminary lab-scale experiments identifying alane (AlH_3, theoretical materials-based capacity of 10 wt.%) as a promising candidate with potential to meet 2010 targets. Lowered the desorption temperature of the as-received α-AlH_3, which ranged from 175-200°C, to 100-150°C (6-7 wt.% hydrogen evolved) by mechanically milling the material with a LiH dopant (Brookhaven National Laboratory and Sandia National Laboratories as part of the Metal Hydride CoE).
- Achieved 5.5 wt.% reversible hydrogen storage through the development of a destabilized Mg-modified Li-imide material (Sandia). Demonstrated over 100 cycles of use of this material and characterized loss of activity over period due to a combination of material loss and material degradation.
- Developed and demonstrated $LiBH_4$/Mg(X) as a class of promising high-capacity destabilized systems, with partial to complete reversibility demonstrated for X = H, F, and S ($LiBH_4$/MgH_2 ~9 wt.% at 350°C). However, these systems also display slow kinetics; future work will focus on enhanced reaction rates in nanoscale materials (HRL, as part of the Metal Hydride CoE).

Chemical Hydrogen Storage

- Developed and demonstrated ethyl carbazole-based and similar organic liquid carriers with hydrogen storage capacities of 5 to 6.9 wt.% (Air Products & Chemicals).
- Discovered non-metal, non-precious metal and general classes of transition metal catalysts for releasing hydrogen from ammonia-borane, which has a potential material hydrogen storage capacity of 19.6 wt.% (LANL, PNNL, Univ. Penn, and Univ. WA; partners of the Chemical Hydrogen Storage CoE).
- Discovered that ammonia-borane in inorganic scaffolds leads to increased kinetics of hydrogen release with no borazine formation; showed ~6 wt.% hydrogen storage at low temperatures (PNNL, partner of the Chemical Hydrogen Storage CoE).
- Demonstrated hydrogen release from a hetero-atom containing "organic hydride" (LANL and Univ. of Alabama, partners of the Chemical Hydrogen Storage CoE).
- Demonstrated a coupled reaction with potential hydrogen storage capacity of > 6 wt % (LANL, partner of the Chemical Hydrogen Storage CoE).

Carbon-based Materials and Sorbents

- Using theory, designed fullerene derivative/metal hybrids with the potential to store >8 wt.% at room temperature (National Renewable Energy Laboratory – NREL).
- Optimized synthesis and purification processes to reproducibly produce metal-doped single-walled nanotubes, with 2 to 3 wt.% and 2.9 wt.% demonstrated at an independent test facility (NREL).
- Developed polyaniline-based conducting polymers for hydrogen adsorption to test claims of ~6 wt.% materials-based hydrogen storage capacity (Univ. of Pennsylvania as part of the Carbon CoE).
- Determined that the binding energy for hydrogen zinc oxide corner units in metal organic frameworks increases the overall sorption enthalpy from 4.1 kJ/mol to 6.1 kJ/mol by changing the organic linker (Caltech as part of the Carbon CoE).
- Incorporated boron into carbon materials, demonstrating greater than three-fold improvement in hydrogen adsorbed at ambient temperature (from <0.2 to 0.7 wt.%) (Penn. State Univ. as part of the Carbon CoE).

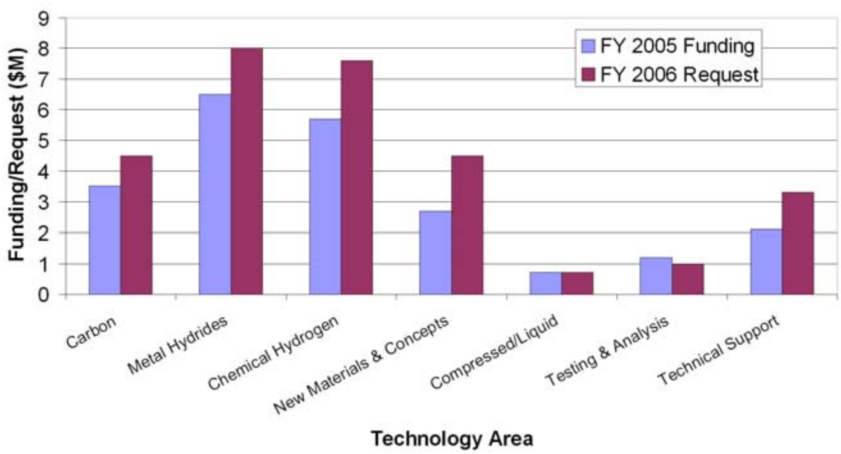
Testing and Analysis

- Completed independent test capabilities at Southwest Research Institute and preliminary validation of facility for sorbent materials.
- Formed Storage Systems Analysis Working Group and completed baseline, independent analysis of sodium alanate system.

FY 2006 Plans and Budget

The FY 2006 hydrogen storage activities will comprise the first full year of effort within the "National Hydrogen Storage Project" since the launch of the DOE Centers of Excellence and "Grand Challenge" awards. Subject to congressional appropriations, the budget will increase from about $22 million in FY 2005 to nearly $30 million in FY 2006.

The requested FY 2006 funding profile and the DOE Centers of Excellence address the NRC Report's emphasis on the importance of storage and recommendation to "shift…away from some development areas towards more exploratory work", as well as the recommendation that "the probability of success is greatly increased by partnering with a broader range of academic and industrial organizations…". A thorough review of the Centers of Excellence will be conducted in FY 2006, to develop lessons learned and apply them to other areas of the Hydrogen Program, as advised by the NRC. Continued funding, at a low level, for compressed hydrogen/cryogenic tanks emphasizes cost reduction and novel conformable designs. In addition, it is recognized that materials-based solutions will require low-cost, conformable tanks and would benefit from current R&D in this area. A major milestone in FY 2006 will be the go/no-go decision on R&D for single-walled carbon nanotubes with a metric of reproducibly achieving 6 wt.% (material basis) hydrogen storage capacity. In addition, an independent analysis of cryo-compressed tanks will be conducted in FY 2006 to determine gravimetric and volumetric capacities as well as cost.



The R&D planned on metal hydrides will focus on the development of high-capacity materials, including complex hydrides, destabilized binary hydrides, alane, intermetallic hydrides, modified lithium amides and other new materials, using theory and combinatorial methods to increase the efficiency of materials identification and screening. The R&D planned on chemical hydrogen storage focuses on three "tiers" of R&D: borohydride-water, novel boron chemistries, and innovation beyond boron such as liquid carriers. In the area of carbon-based materials, the planned R&D will focus on breakthrough concepts for storing hydrogen at room temperature, such as hybrid metal/carbon nanotubes and metal/fullerene hybrids, aerogels, nanofibers, metal organic frameworks and conducting polymers. A workshop on fundamental theory/modeling for hydrogen storage will be conducted in collaboration with the Office of Science, and closer collaborations with the basic research activity are planned.

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