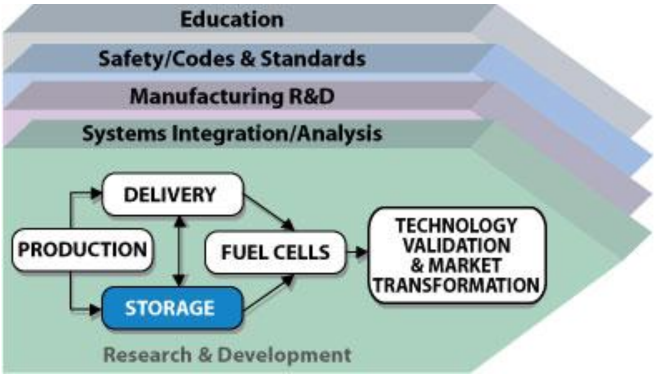
3.3 Hydrogen Storage



Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell power technologies in transportation, stationary, and portable applications. DOE's efforts had primarily been focused on the RD&D of onboard vehicular hydrogen storage systems that will allow for a driving range of greater than 300 miles or more while meeting packaging, cost, safety, and performance requirements to be competitive with current vehicles. While automakers have recently demonstrated progress with some prototype vehicles traveling more than 300 miles on a single fill, this driving range must be achievable across different vehicle models and without compromising space, performance or cost. In addition, hydrogen storage will be needed for other niche vehicular and other motive applications, for hydrogen delivery and refueling infrastructure and for non-motive and stationary applications such as back-up power, stationary power, and portable power for early fuel cell application markets. DOE is initiating efforts to address these needs as well.

3.3.1 Technical Goal and Objectives

Goal

Develop and demonstrate viable hydrogen storage technologies for transportation, stationary, and portable power applications.

Key Onboard Vehicular Application Targets

- By 2017, develop and verify onboard hydrogen storage systems achieving 1.8 kWh/kg (5.5 wt.%), 1.3 kWh/L (0.040 kg hydrogen/L).
- Ultimate full-fleet target of 2.5 kWh/kg system (7.5 wt.% hydrogen) and 2.3 kWh/L (0.070 kg hydrogen /L).
- The system cost targets for 2017 and the ultimate full fleet system target are under review by the U.S. DRIVE Partnership (Driving Research and Innovation for Vehicle efficiency and Energy sustainability).

3.3.2 Technical Approach

Onboard hydrogen storage to enable a driving range of greater than 300 miles, while meeting vehicular packaging, cost and performance requirements, is a focus of the Hydrogen Storage Program element. Research and development activities for vehicle interface technologies and off-board hydrogen storage will be coordinated with the Hydrogen Delivery Program element—emphasizing that hydrogen delivery entails delivering hydrogen from the point of production to the point of use onboard the vehicle, including storage at the fueling station (see Hydrogen Delivery section 3.2 for a complete description of off-board storage).

To lay the strategic foundation for hydrogen storage activities, a series of workshops with scientists and engineers from universities, national laboratories and industry was held to identify RD&D needs and to set priorities. For example, a "Think Tank" meeting, which included Nobel laureates and other award-winning scientists, was held to identify advanced material concepts and to develop an RD&D strategy. Interactions with the DOE Office of Science are ongoing to define and coordinate the basic research activities for hydrogen storage materials.

Fig. 3.3.1 Hydrogen storage tanks (photo courtesy of Quantum Fuel Systems Technologies Worldwide, Inc.

System-based gravimetric, volumetric and cost targets for hydrogen storage have been developed for 2017, as indicated above. In addition, the U.S. DRIVE Partnership has defined an "Ultimate Full Fleet" set of targets that is defined as virtually all vehicle platforms (e.g. makes and models) to achieve significant market penetration of hydrogen fueled vehicles. The new "Ultimate" targets are intended to make hydrogen-fueled propulsion systems competitive across the majority of vehicle classes and models (from small cars to light-duty trucks). Storage approaches currently being pursued are (1) onboard reversible hydrogen storage focused on materials-based technologies, including efforts on low cost and conformable tanks (see Figure 3.3.1) as well as compressed gas/cryogenic hybrid tanks and (2) off-board regenerable hydrogen storage, such as chemical hydrogen storage (Figure 3.3.2 is an example of a liquid carrier).

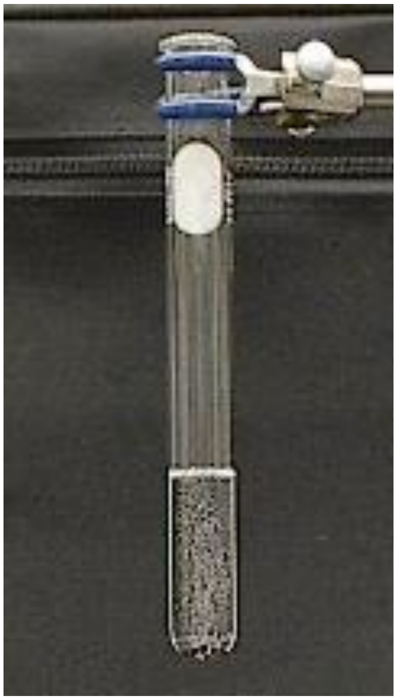


Fig. 3.3.2 Dehydrogenation of organic liquids (photo courtesy of Air Products and Chemicals, Inc.)

The primary investment focus is on storage tank cost reduction for initial vehicle market penetration, system and engineering RD&D for physical and material-based systems and applied research and development of new materials and concepts with potential to meet long-term goals.

Currently, hydrogen is stored both off-board and onboard prototype vehicles as a high-pressure compressed gas or as a cryogenic liquid. Compressed hydrogen gas tanks will likely be used in early hydrogen-powered vehicles and will need to meet cost and packaging requirements to play a role across various vehicle platforms. Furthermore, cost-effective tanks will be required for all future storage approaches (e.g., material-based approaches) and will need to conform to space limitations as well as meet performance requirements such as heat management during fueling. Hence, current efforts in tank RD&D also include novel concepts that are applicable to multiple forms of storage.

The Hydrogen Storage Program element will include on-going analysis to examine the system level performance, the lifecycle cost, energy efficiency, and environmental impact of the technologies , any changes in the system-level requirements that might alter the technical targets, and the progress of each technology development effort toward achieving the technical targets.

As technologies are down-selected with potential for onboard storage, future activities on vehicle interface technologies will be coordinated with the Delivery Program element. Vehicle refueling connection devices will need to be compatible with high-pressure and cryogenic storage in the near-term. In the long-term, as progress is made on solid-state or liquid-based material options, vehicle refueling issues such as thermal management or by-product reclamation will need to be addressed.

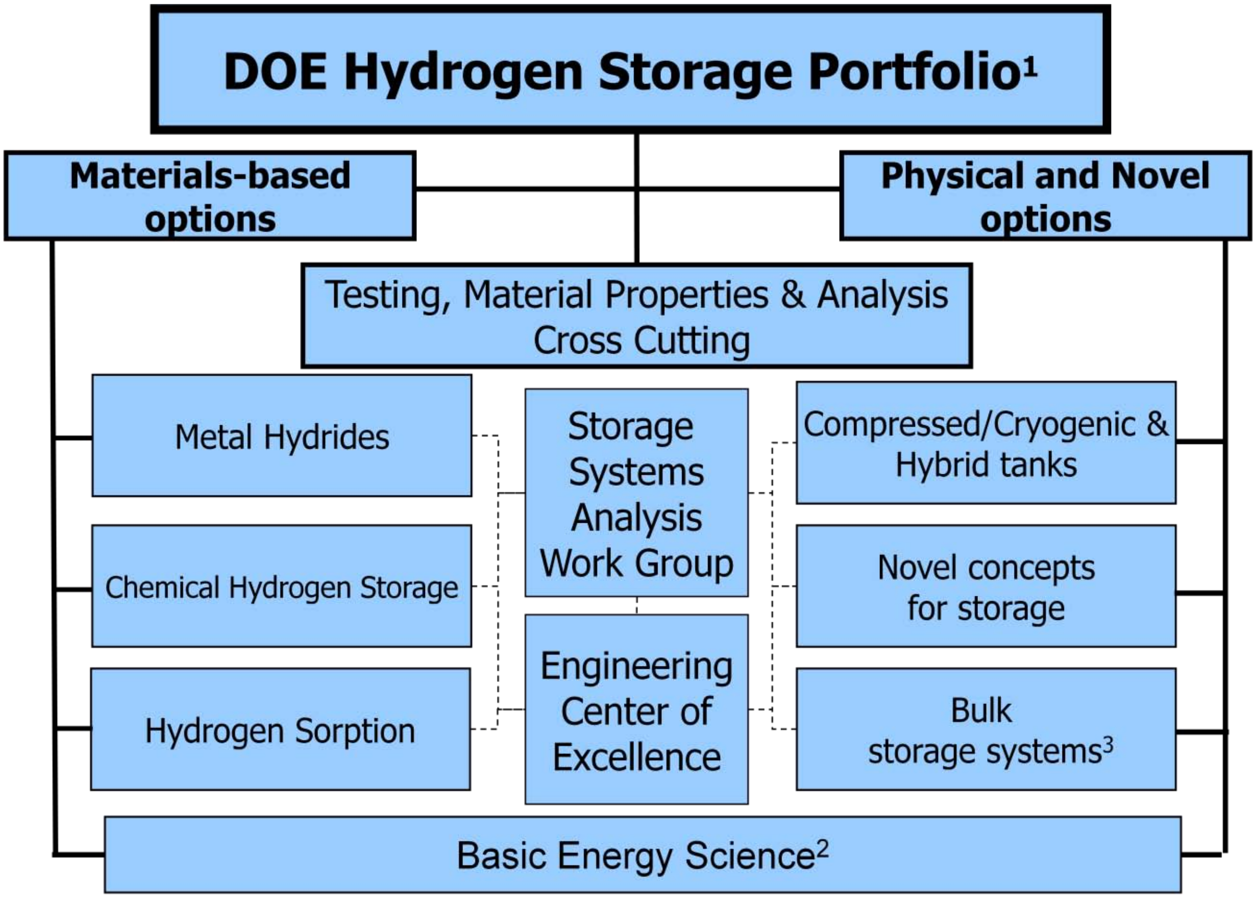
Funding for hydrogen storage RD&D will be scaled down according to measurable progress—as technical and cost targets are met or missed, funding for particular technological approaches will be adjusted. When all performance, safety and cost targets are met, hydrogen storage RD&D funding will end as appropriate. If specific performance issues remain at that time, RD&D could be extended if the risk of the continued effort is justified by the potential benefit.

3.3.3 Programmatic Status

Current Activities

In 2003, DOE launched a "Grand Challenge" to the technical community for research and development of hydrogen storage technologies to meet the targets for commercially viable systems. Since FY 2004, the hydrogen storage effort has been conducted under the framework of the National Hydrogen Storage Project. It included independent projects and Centers of Excellence (CoEs) in applied hydrogen storage RD&D funded by EERE and basic research projects for hydrogen storage funded by the DOE Office of Science. In FY 2009, the Hydrogen Storage Engineering CoE was initiated that provides a coordinated approach to the engineering RD&D of onboard materials-based systems. The Hydrogen Storage Engineering CoE is planned as a five-year effort and may produce up to three sub-scale prototype systems (based upon the most promising materials under consideration) as its final output (subject to go/no-go decision points and budget appropriations).

Crosscutting efforts on system analysis and material chemical and environmental reactivity are also included in the EERE Hydrogen Storage Portfolio. The three materials development CoEs were focused on specific hydrogen storage material classes: onboard reversible metal hydrides, hydrogen adsorbents, and chemical hydrogen storage materials (which are, in general, regenerated off the vehicle). The three materials development CoE efforts were concluded in FY2010. The Hydrogen Storage Portfolio currently consists of a total of approximately 47 universities, 15 companies and 14 federal laboratories. The organization of the Hydrogen Storage Portfolio is shown in Figure 3.3.3. Within that portfolio, activities exist that address both physical and materials-based options and cross-cutting activities of reactivity, and testing and analysis.



1. Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program element

Fig. 3.3.3 Structure of the DOE hydrogen storage activities

For compressed hydrogen, lightweight composite tanks with high-pressure ratings and conformability are being developed. High-capacity metal hydrides, including borohydrides, destabilized metal hydrides, lightweight multinary alloys, and other promising materials, are being explored to determine their potential for hydrogen storage and to improve our understanding of hydrogen storage processes. The search for new metal hydrides also includes theoretical and experimental combinatorial and high-throughput materials development and screening.
High surface area adsorbents and other nanostructured materials are being investigated for storage at lower pressures than 350 bar with comparable or superior performance to compressed gas systems. The overall goal is to develop materials that can store hydrogen at closer to ambient temperature and moderate pressure, avoiding need for cryogenic storage conditions. Two main strategies are used to meet the overall performance goals: high volumetric capacity, high surface area adsorbents and metal-sorbent hybrid materials that may store hydrogen at closer to room temperature.

Projects on chemical hydrogen storage, such as sodium borohydride, magnesium hydride slurries, ammonia borane and organic liquids, were initiated in FY 2004, with a focus on the key issue for chemical hydrogen storage—off-board regeneration of the spent fuel.

Projects on systems analysis address performance, cost and life-cycle analyses of on-board storage options. Finally, a test and evaluation capability has been established to develop standard test protocols and provide independent verification of hydrogen storage performance in onboard reversible solid-state materials.

Three DOE Centers of Excellence were initiated in FY 2005 with coordinated activities involving multiple university, industry and national laboratory partners in the key focus areas of metal hydride, adsorbent and chemical hydrogen storage materials. These efforts concluded in FY2010. New materials and concepts continue to be an emphasis in the storage portfolio. The EERE Hydrogen Storage Program Element also collaborates with the DOE Office of Science on basic science, theory and modeling related to various hydrogen storage technologies via its core research programs.

For example, Theory Focus Sessions on Hydrogen Storage Materials have been co-organized by EERE and BES (Office of Basic Energy Sciences within the Office of Science) to identify key barriers, gaps and critical areas of research in current theory/modeling approaches for hydrogen storage materials (details are available through www.hydrogen.energy.gov or directly at www1.eere.energy.gov/hydrogenandfuelcells/wkshp_theory_focus.html). The Hydrogen Program's 2010 Annual Merit Review included presentations from both EERE and BES and are available at http://www.hydrogen.energy.gov/annual_review10_proceedings.html.

Technology Status Demonstrations

In the area of onboard hydrogen storage, the state-of-the-art is 5,000- and 10,000-psi (350 and 700 bar) compressed tanks, and cryogenic liquid hydrogen tanks. Tanks have been certified worldwide according to ISO 11439 (Europe), NGV2 (U.S.), and Reijikijun Betten (Iceland) standards, and approved by TUV (Germany) and KHK (Japan). They have been demonstrated in several prototype fuel cell vehicles and are commercially available at low production volumes. All-composite 10,000-psi tanks have demonstrated a 2.35 safety factor (23,500-psi burst pressure) as required by the European Integrated Hydrogen Project specifications.

Liquid hydrogen tanks have also been demonstrated. A sodium borohydride system has been demonstrated in a concept vehicle. A lithium hydride slurry prototype has been demonstrated in a pickup truck with a hydrogen internal combustion engine.

Most recently, through DOE's Technology Validation activity (see Section 3.5), data from 155 vehicles in operation to date have demonstrated a driving range exceeding 200 miles (on road data, corrected for the EPA drive cycle). The hydrogen storage capacity based on 5,000 and 10,000 psi tanks, was demonstrated to be between 3.4 and 4.7 wt.% and 14 to 28 g/L. Such data will be periodically updated as new technologies are validated under real-world conditions. The National Renewable Energy Laboratory and Savannah River National Laboratory have validated a vehicle capable of 430 miles on a single fill.[1] Metal hydride system demonstrations have been conducted by the United Technologies Research Center (UTRC)[2] and the Sandia National Laboratory.[3]

3.3.4 Technical Challenges

For transportation applications, the overarching technical challenge for hydrogen storage is how to store the necessary amount of hydrogen required for a conventional driving range (greater than 300 miles), within the constraints of weight, volume, durability, efficiency and total cost. Clearly, many important technical challenges for hydrogen storage must be resolved to meet the ultimate performance and safety targets. Substantial improvements must be made in the weight, volume and cost of these systems, for vehicular applications.

Durability over the performance lifetime of these systems must be verified and validated, and acceptable refueling times must be achieved. Table 3.3.1 lists specific technical targets that the hydrogen storage system must achieve to meet customer-driven requirements for vehicle performance. Following a discussion of the specific technical barriers that must be overcome to achieve the performance targets, Section 3.3.5 describes the tasks that will be carried out to resolve the identified technical barriers.

Technical Targets

The technical performance targets for hydrogen storage systems are summarized in Table 3.3.1. These targets were established through the U.S. DRIVE Partnership between DOE, the U.S. Council for Automotive Research (USCAR), energy companies, and utility companies and organizations. The targets are subject to change as more is learned about system-level requirements and as fuel cell technology progresses.

Based on the lower heating value (LHV) of hydrogen and greater than 300-mile driving range, the targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. The targets are based upon requirements for the “Ultimate Full Fleet.” The fleet is defined as virtually all light-duty vehicle platforms (e.g. makes and models) to achieve significant market penetration of hydrogen fueled vehicles. The “Ultimate” targets are intended to make hydrogen-fueled propulsion systems competitive across the majority of vehicle classes and models (from small compact cars to light-duty trucks).

The “Ultimate” targets approximate current gasoline ICE vehicle systems for packaging volume across the most demanding vehicle platforms. It allows manageable increases in weight and volume over current ICE vehicle systems across the full range of vehicle platforms. A detailed explanation of each target is provided at:

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[1] Wipke, K., D. Anton, and S. Sprik (2009), “Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions (SRNS-STI-2009-00446),” available at http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf. For details of

[2] D. Mosher, et. al. (December 19, 2006), “High Density Hydrogen Storage System Demonstration Using $NaAlH_4$ Complex Compound Hydrides,” presentation by UTRC to DOE and the FreedomCAR & Fuel Partnership Hydrogen Storage Tech Team, available at http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/storage_system_prototype.pdf.

[3] T.A. Johnson and Kanouff, M.P. (April 2010), “Parameter Study of a Vehicle-scale Hydrogen Storage System (SAND2010-2140),” available at http://prod.sandia.gov/techlib/access-control.cgi/2010/102140.pdf.

www1.eere.energy.gov/hydrogenandfuelcells/storage/current_technology.html.

It should also be noted that unless otherwise indicated in Table 3.3.1, the targets are for both internal combustion engine and fuel cell power plants. In addition, hydrogen storage systems must be energy efficient in delivering hydrogen to the vehicle power plant. For onboard reversible systems, greater than 90% energy efficiency for the energy delivered to the power plant from the onboard storage system is required. For systems regenerated off-board, the overall efficiency is also important. In this case, the energy content of the hydrogen delivered to the automotive power plant should be greater than 60% of the total energy input to the process, including the input energy of hydrogen and any other fuel streams for generating process heat and electrical energy.

Current RD&D Focus is on 2017 Targets with Potential to Meet Ultimate Targets

Table 3.3.1 Technical System Targets: Onboard Hydrogen Storage for Light Duty Vehicles

Storage Parameter	Units	2017	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass) [a]	kWh/kg (kg H_2/kg system)	1.8 (0.055)	2.5 (0.075)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	1.3 (0.040)	2.3 (0.070)
Storage System Cost [b]:	$/kWh net ($/kg H_2)	TBD (TBD)	TBD (TBD)
Fuel cost [c]	$/gge at pump	2-4	2-4
Durability/Operability:			
Operating ambient temperature [d]	ºC	-40/60 (sun)	-40/60 (sun)
Min/max delivery temperature	ºC	-40/85	-40/85
Operational cycle life (1/4 tank to full) [e]	Cycles	1500	1500
Min delivery pressure from storage system; FC= fuel cell, ICE= internal combustion engine	bar (abs)	5FC/35 ICE	3 FC/35 ICE
Max delivery pressure from storage system [f]	bar (abs)	12 FC/100 ICE	12 FC/100 ICE
Onboard Efficiency	%	-	90
"Well" to Powerplant Efficiency	%	-	60
Charging / Discharging Rates:			
System fill time (5 kg)	min	3.3	2.5
Minimum full flow rate	(kg H_2/min)	(1.5)	(2.0)
Start time to full flow (20 °C) [g]	(g/s)/kW	0.02	0.02
Start time to full flow (-20 °C) [g]	s	5	5
Transient response 10%-90% and 90% - 0% [h]	s s	15 0.75	15 0.75
Fuel Purity (H_2 from storage) [i]	% H_2	SAE J2719 and ISO/PDTS 14687-2 (99.97% dry basis)	
Environmental Health & Safety:			
Permeation & leakage [j]	Scc/h	Meets or exceeds applicable standards	
Toxicity	-		
Safety	-		
Loss of useable H_2 [k]	(g/h)kg H_2 stored	0.05	0.05

* Useful constants: 0.2778kWh/MJ; 33.3kWh/kg H_2; 1 kg $H_2 \approx$ 1 gal gasoline equivalent.

Note: The above targets are based on the lower heating value of hydrogen. Targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and/or other balance-of-plant components. All capacities are defined as useable capacities that could be delivered to the power plant (i.e. fuel cell or internal combustion engine). All targets must be met at the end of service life (approximately 1500 cycles or 5000 operation hours, equivalent of 150,000 miles). Unless otherwise indicated, all targets are for both hydrogen internal combustion engine and for hydrogen fuel cell use, based on the low likelihood of power plant specific fuel being commercially viable. Commercial systems must meet manufacturing specifications for cycle life variation; see note [e] to cycle life below.

Footnotes to Target Table:

[a] Generally the 'full' mass (including hydrogen) is used; for systems that gain weight, the highest mass during discharge is used. All capacities are net useable capacity able to be delivered to the power plant. Capacities must be met at end of service life.

[b] Note: Storage system cost targets are currently under review and may be changed at a future date.

[c] 2005 US$; includes off-board costs such as liquefaction, compression, fuel regeneration, etc; Ultimate target based on H_2 production threshold cost of $2 to $4/gasoline gallon equivalent untaxed, independent of production pathway.

[d] Stated ambient temperature plus full solar load. No allowable performance degradation from –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

[e] Equivalent to 200,000; 300,000; and 300,000 miles respectively (current gasoline tank spec). Manufactured items have item-to-item variation. The variation as it affects the customer is covered by the cycle life target of number of cycles. Testing variation is addressed by testing variation metrics. It is expected that only one or two systems will be fabricated to test life of early concepts. The data generated has great uncertainty associated with it due to the low number of samples. Thus a factor is required to account for this uncertainty. The effect is to increase the required cycle life based on normal statistics using the number of samples tested. The value is given in the form XX/YY where XX is the acceptable percentage of the target life (90 means 90%), and YY is the percent confidence that the true mean will be inside the xx% of the target life (99 indicates 99% confidence or an alpha value of 0.01). For demonstration fleets this is less critical and no target is specified to functionally enable single specimen testing. Variation testing needs to be included for general sales. By the time full fleet production is reached, testing levels will also need to tighten, but availability of multiple samples will no longer be a problem. This entire sequence is standard practice in the mass production of automobiles and their components. Units are in minimum percent of the mean and a percentage confidence level. The technology readiness goals are: minimum percentage of the mean of 90% at a 99% confidence level.

[f] For delivery *to* the storage system, in the near-term, the forecourt should be capable of delivering 10,000 psi (700 bar) compressed hydrogen, liquid hydrogen, or chilled hydrogen (77K) at 5,000 psi (350 bar). In the long term, it is anticipated that delivery pressures will be reduced to between 50 and 150 bar for materials-based storage systems, based on today's knowledge of sodium alanate (Ti-catalyzed $NaAlH_4$).

[g] Flow must initiate within 25% of target time.

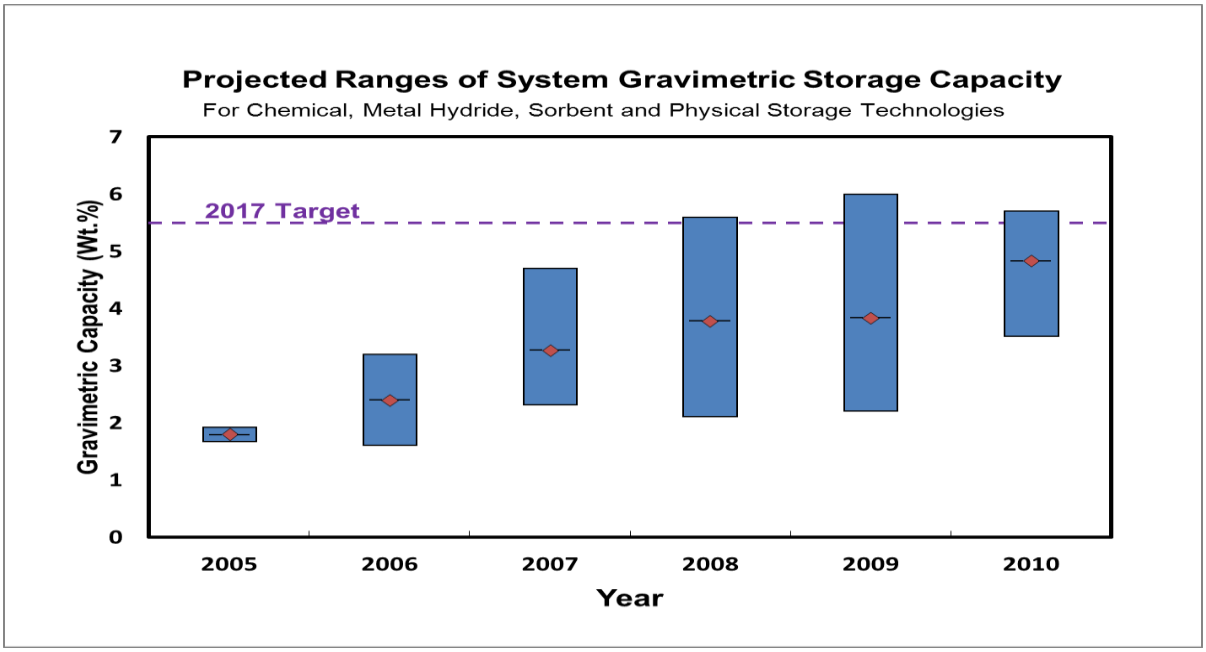
[h] At operating temperature.

[i] The storage system will not provide any purification for the incoming hydrogen, and will receive hydrogen at the purity levels required for the fuel cell. The hydrogen purity specifications are currently in both SAE J2719: Technical Information Report on the Development of a Hydrogen Quality Guideline in Fuel Cell Vehicles (harmonized with ISO/PDTS 14687-2) and ISO/PDTS 14687-2: Hydrogen Fuel — Product Specification — Part 2: PEM fuel cell applications for road vehicles. Examples include: total non-particulates, 300 ppm; H_2O, 5 ppm; total hydrocarbons (C_1 basis), 2 ppm; O_2, 5 ppm; He, 300 ppm; N_2 + Ar combined, 100 ppm; CO_2, 2 ppm; CO, 0.2 ppm; total S, 0.004 ppm; formaldehyde (HCHO), 0.01 ppm; formic acid (HCOOH), 0.2 ppm; NH_3, 0.1 ppm; total halogenates, 0.05 ppm; maximum particle size, <10 µm; and particulate concentration, <1µg/L H_2. These are subject to change. See Appendix on Hydrogen Quality in the DOE EERE Hydrogen Fuel Cells and Infrastructure Technologies Program Multiyear Research, Development and Demonstration Plan (www.eere.energy.gov/hydrogenandfuelcells/mypp/) to be updated as fuel purity analyses progress. Note that some storage technologies may produce contaminants for which effects are unknown; these will be addressed by system engineering design on a case by case basis as more information becomes available.

[j] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with CSA/HGV2 standards for vehicular tanks. This includes any coating or enclosure that incorporates the envelope of the storage system.

[k] Total hydrogen lost from the storage system, including leaked or vented hydrogen; relates to loss of range.

[l] Targets are for bulk gaseous hydrogen storage at forecourts, terminals and other off-board storage needs.



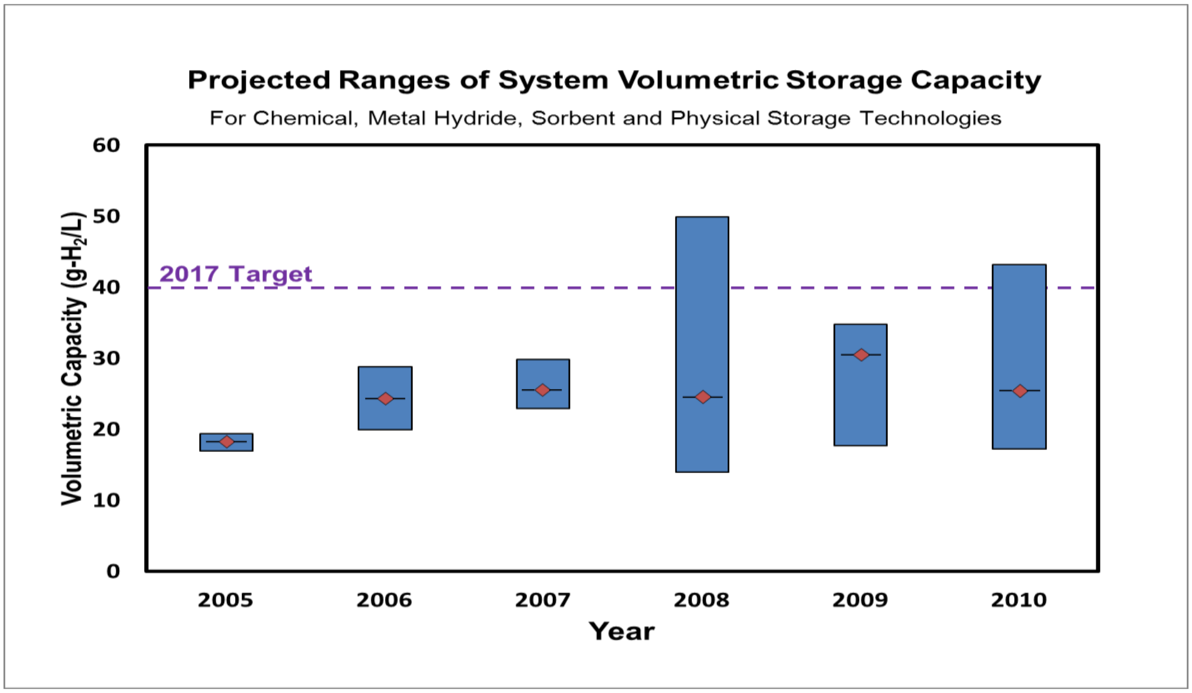


Fig. 3.3.4 (a-b) Estimates of (a) gravimetric and (b) volumetric capacities projected for onboard storage systems that can supply 5.6 kg of usable hydrogen as compared to DOE targets (based upon engineering analyses). Note that the plotted data points are the average value for all systems analyzed during 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 and volumetric targets do not necessarily meet other targets.

Figure 3.3.4 (a-b) shows the improvement in storage system capacity since 2005. The system projections were developed through analysis of data compiled from technology developers within the H_2 Storage Program. Status for any given year is reported for multiple storage technologies and represents the range of performance estimated for the range of systems analyzed in that year. Because it is challenging to estimate system-level weights and volumes when research is still at the stage of materials development, the current status data will be revisited and updated periodically. However, it is clear that none of the current systems meets the combined gravimetric, volumetric, and system cost targets for either 2015 or the Ultimate Full Fleet targets. Also note that although recent accomplishments may show materials-based capacities exceeding 5 wt.%, the targets of 5.5 wt.% and 40 g hydrogen/L by 2017 and 7.5 wt.% and 70 g hydrogen/L for the Ultimate Fleet are system-level capacities that include the material, tank and all balance-of-plant components of the storage system. The system-level data also needs to include the first charge of hydrogen as well as any preconditioning such as purification, liquefaction and regeneration of material, particularly for chemical hydrogen storage, for which the cost of regenerating spent fuel will need to be included.

Onboard Hydrogen Storage Technical Barriers

General to All Storage Approaches

A. System Weight and Volume

The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate vehicle range compared to conventional petroleum fueled vehicles. Storage media, materials of construction and balance-of-plant components are needed that allow compact, lightweight, hydrogen storage systems while enabling greater than 300-mile range in all light-duty vehicle platforms. Reducing weight and volume of thermal management components is also required.

B. System Cost

The cost of onboard hydrogen storage systems is too high, particularly in comparison with conventional storage systems for petroleum fuels. Low-cost media, materials of construction and balance-of-plant components are needed, as well as low-cost, high-volume manufacturing methods.

C. Efficiency

Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to transfer hydrogen into and out of the storage media or material is an issue for all material options. Life-cycle energy efficiency may be a challenge for chemical hydrogen storage technologies in which the spent media and by-products are typically regenerated off-board the vehicle. In addition, the energy associated with compression of and liquefaction of hydrogen must be considered for compressed and liquid hydrogen technologies. Thermal management for charging and releasing hydrogen from the storage system needs to be optimized to increase overall efficiency for all approaches.

D. Durability/Operability

Durability of hydrogen storage systems is inadequate. Storage media, materials of construction and balance-of-plant components are needed that allow hydrogen storage systems with a lifetime of at least 1500 cycles and with tolerance to hydrogen fuel contaminants. An additional durability issue for material-based approaches is the delivery of sufficient quality hydrogen for the vehicle power plant.

E. Charging/Discharging Rates

In general and especially for material-based approaches, hydrogen refueling times are too long. There is a need to develop hydrogen storage systems with refueling times of less than three minutes for a 5-kg hydrogen charge, over the lifetime of the system. Thermal management that enables quicker refueling is a critical issue that must be addressed. Also, all storage system approaches must be able to supply sufficient flow rate of hydrogen to the vehicle power plant (e.g. fuel cell or internal combustion engine) to meet the required power demand.

F. Codes and Standards

Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and assure safety and public acceptance, have not been established. Standardized hardware and operating procedures, and applicable codes and standards, are required.

G. Materials of Construction

High-pressure containment for compressed gas and other high-pressure approaches limits the choice of construction materials and fabrication techniques, within weight, volume, performance, and cost constraints. For all approaches of hydrogen storage, vessel containment that is resistant to hydrogen permeation and corrosion is required. Research into new materials of construction such as metal ceramic composites, improved resins, and engineered fibers is needed to meet cost targets without compromising performance. Materials to meet performance and cost requirements for hydrogen delivery and off-board storage are also needed (see Hydrogen Delivery section 3.2).

H. Balance of Plant (BOP) Components

Light-weight, cost-effective balance-of-plant components are needed for all approaches of hydrogen storage, especially those requiring high-pressure or extensive thermal management. These include tubing, fittings, check valves, regulators, filters, relief and shut-off valves, heat exchangers, and sensors. System design and optimal packaging of components to meet overall volumetric targets are also required.

I. Dispensing Technology

Requirements for dispensing hydrogen to and from the storage system have not been defined. This includes meeting heat rejection requirements during fueling especially for onboard reversible material-based approaches. For chemical hydrogen approaches, methods and technology to recover spent material from the fuel tank for regeneration during "refueling" are needed. Activities will be coordinated with the Delivery Program element

J. Thermal Management

For all approaches of hydrogen storage; compressed gas, cryogenic and materials-based, thermal management is a key issue. In general, the main technical challenge is heat removal upon re-filling of hydrogen for compressed gas and onboard reversible materials within fueling time requirements. Onboard reversible materials typically require heat to release hydrogen. Heat must be provided to the storage media at reasonable temperatures to meet the flow rates needed by the vehicle power plant, preferably using the waste heat of the power plant. Depending upon the chemistry, chemical hydrogen approaches often are exothermic upon release of hydrogen to the power plant, or optimally thermal neutral. By virtue of the chemistry used, chemical hydrogen approaches require significant energy to regenerate the spent material and by-products prior to re-use; this is done off the vehicle.

K. System Life-Cycle Assessments
Assessments of the full life cycle, cost, efficiency, and environmental impact for hydrogen storage systems are lacking. An understanding of infrastructure implications, particularly for chemical hydrogen storage, and approaches to reduce primary energy inputs, is lacking.

Compressed Gas Systems

L. High-pressure Conformability
Conformable high-pressure tanks will be required for compressed gas and other high-pressure approaches for hydrogen storage to meet the space constraints of light-duty vehicle applications.

M. Lack of Tank Performance Data and Understanding of Failure Mechanisms
An understanding of the fundamental mechanisms that govern composite tank operating cycle life and failure due to accident or to neglect is lacking. Research on tank performance and failure are needed to optimize tank structure for performance and cost. In addition, sensors and associated prediction correlations are needed to predict lifetime and catastrophic tank failure.

Cryogenic Liquid Systems

N. Liquefaction Energy Penalty
The energy penalty associated with hydrogen liquefaction, typically 30% of the lower heating value of hydrogen, is an issue. Methods to reduce the energy requirements for liquefaction are needed.

O. Hydrogen Boil-Off
The boil-off of liquid hydrogen requires venting, reduces driving range and presents a potential safety/environmental hazard, particularly when the vehicle is in an enclosed environment. Materials and methods to reduce boil-off in cryogenic tanks are needed.

Reversible Materials-Based Storage Systems (Reversible Onboard)

P. Lack of Understanding of Hydrogen Physisorption and Chemisorption
Fundamental understanding of hydrogen physisorption and chemisorption processes is lacking. Improved understanding and optimization of adsorption/absorption and desorption kinetics is needed to optimize hydrogen uptake and release capacity rates. An understanding of chemical reactivity and material properties, particularly with respect to exposure under different conditions (air, moisture, etc.) is also lacking.

Q. Reproducibility of Performance
Standard test protocols for evaluation of hydrogen storage materials are lacking. Reproducibility of performance both in synthesis of the material/media and measurement of key hydrogen storage performance metrics is an issue. Standard test protocols related to performance over time such as accelerated aging tests as well as protocols evaluating materials safety properties and reactivity over time are also lacking.

Chemical Hydrogen Storage Systems (Typically Regenerated Off-board)

R. Regeneration Processes

Low-cost, energy-efficient regeneration processes have not been established. Full life-cycle analyses need to be performed to understand cost, efficiency and environmental impacts.

S. By-Product/Spent Material Removal

The refueling process is potentially complicated by removal of the by-product and/or spent material. System designs must be developed to address this issue and the infrastructure requirements for off-board regeneration.

3.3.5 Technical Task Descriptions

The technical task descriptions are presented in Table 3.3.2. Issues regarding safety will be addressed within each of the tasks. The barriers associated with each task appear after the task title.

Table 3.3.2 Technical Task Descriptions

Task	Description	Barriers
1	**Advanced Compressed and Cryogenic Tank Technologies** ▪ Develop, demonstrate and verify low cost, compact 10,000-psi storage tanks. ▪ Assess the need for liner materials to reduce hydrogen gas permeation. ▪ Develop and optimize carbon fiber/epoxy over-wrap. ▪ Identify alternate designs and materials for advanced, integrated storage systems. ▪ Explore conformable tanks for compressed hydrogen. ▪ Demonstrate safety of hydrogen storage systems. ▪ Explore compressed gas/reversible storage material hybrid systems. ▪ Develop lightweight, low-cost balance of plant components for advanced compressed/cryogenic and conformable tanks. ▪ Through coordination with the Delivery element, study requirements and conceptual designs for cost-competitive off-board storage of hydrogen, including underground scenarios. ▪ Develop advanced compressed and cryogenic tank technologies to meet 2010 targets.	A-M
2	**Advanced Onboard Reversible Materials RD&D** ▪ Perform theoretical modeling to provide guidance for materials development. ▪ Improve understanding of sodium alanate system to aid development of other advanced hydride materials with higher hydrogen capacities. ▪ Investigate advanced metal hydrides with hydrogen capacities of 6 wt.% or greater with adequate charge/discharge kinetics and cycling characteristics. ▪ Investigate composite-wall containers compatible with the optimal advanced metal hydride materials. ▪ Determine the decomposition products and pathways of materials to better understand their mechanisms and kinetics. ▪ Engineer a hydride bed capable of efficiently storing and releasing hydrogen at 90°C. ▪ Determine the hydrogen storage capacity of nanostructured carbon materials; demonstrate reproducibility of synthesis and capacity measurements. ▪ Develop cost-effective fabrication processes for promising nanostructured carbon materials. ▪ Explore combinatorial approaches to rapidly identify promising hydrogen storage materials. ▪ Perform analyses to assess cost effectiveness of reversible hydrogen storage materials including scale-up to high-volume production. ▪ Explore non-thermal discharging methods, including mechanical, chemical and electrical mechanisms. ▪ Develop and verify most promising reversible storage materials to meet 2010 targets. ▪ Develop and verify most promising reversible storage materials to meet 2015 targets.	A-K, P-Q

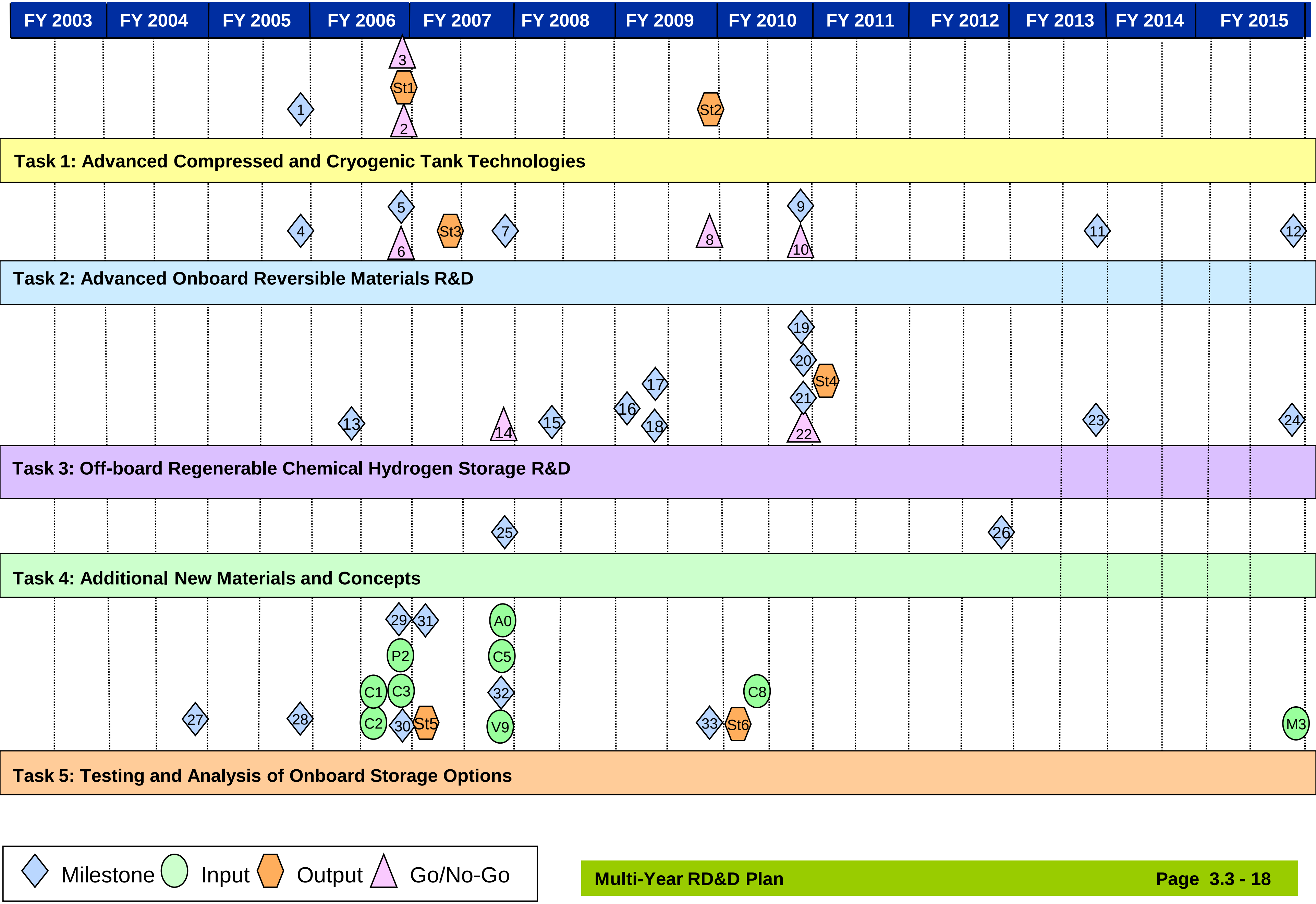
Table 3.3.2 Technical Task Descriptions (continued)

Task	Description	Barriers
3	**Off-board Regenerable Chemical Hydrogen Storage RD&D** ▪ Identify a family of chemical hydrogen storage materials capable of meeting weight and volume goals. Characterize the reaction chemistry and thermodynamics of the most promising candidates. ▪ Rank viable candidates according to hydrogen capacity based on resource availability, full fuel cycle energy efficiency and emissions, and cost of the delivered fuel. ▪ Identify and develop improved processes, chemistry, catalysts and operating conditions for the complete fuel cycle. ▪ Evaluate the safety performance of the complete system. ▪ Verify an entire closed loop, chemical hydrogen storage system, including an efficient regeneration process that meets cost and performance targets. ▪ Ensure compatibility with applicable codes and standards for on-vehicle storage and fueling interface. ▪ Assess the impact of a potentially complicated refueling process (due to spent material or by-product removal) on implementation of hydrogen storage systems that are regenerated off-board. ▪ Develop and verify most promising chemical hydrogen storage materials to meet 2010 targets. ▪ Develop and verify most promising chemical hydrogen storage materials to meet 2015 targets.	A-K, R-S
4	**Additional New Materials and Concepts** ▪ Identify and investigate new materials and storage approaches that have the potential to achieve 2010 targets of 2 kWh/kg (6wt.%) or greater, and 1.5 kWh/L or greater. ▪ Develop and characterize new materials and concepts to meet 2010 targets. ▪ Develop and characterize new materials and advanced concepts to meet 2015 targets.	A-S
5	**Testing and Analysis of Onboard Storage Options** ▪ Establish an independent test facility and standard test protocols to evaluate reversible hydrogen storage materials. ▪ Conduct analyses to examine life-cycle cost, energy efficiency, and environmental impacts of the technologies developed, changes in the system level requirements that might alter the technical targets, and progress of each technology development effort toward achieving the technical targets.	A-S

3.3.6 Milestones

The following chart shows the interrelationship of milestones, tasks, outputs and supporting inputs from other Program elements from FY 2004 through FY 2015. The input/outputs are also summarized in Appendix B.

Hydrogen Storage R&D Milestone Chart



Task 1: Advanced Compressed and Cryogenic Tank Technologies	
1	Complete preliminary feasibility study of cryogenic adsorbent tank concept (4Q, 2005)
2	Decision on compressed and cryogenic tank technologies for onboard vehicular applications (4Q, 2006)
3	Independent evaluation of gravimetric and volumetric capacities of cryo-compressed tanks (4Q, 2006)

Task 2: Advanced Onboard Reversible Materials R&D	
4	Reproducibly demonstrate 4wt% material capacity on carbon nanotubes (4Q, 2005)
5	Complete prototype metal hydride system and evaluate against 2007 targets (4Q, 2006)
6	Decision point on carbon nanotubes (4Q, 2006)
7	Down-select onboard reversible metal hydride materials (4Q, 2007)
8	Decision point on advanced carbon-based materials (4Q, 2009)
9	Complete materials-based lab-scale prototype system and evaluate against 2010 targets (4Q, 2010)
10	Decision on reversible metal hydride R&D (4Q, 2010)
11	Down-select onboard reversible hydrogen storage materials with potential to meet 2015 targets (4Q, 2013)
12	Complete lab-scale prototype system and evaluate against 2015 targets (4Q, 2015)

Task 3: Off-board Regenerable Chemical Hydrogen Storage R&D	
13	Complete preliminary estimates of efficiency for off-board regeneration (2Q, 2006)
14	Decision point on sodium borohydride (4Q, 2007)
15	Down-select chemical hydrogen storage materials and accompanying regeneration processes (2Q, 2008)
16	Demonstrate regeneration processes at laboratory-scale, and estimate efficiency (1Q, 2009)
17	Complete chemical hydrogen storage life-cycle analyses (2Q, 2009)
18	Down-select chemical hydrogen storage approaches for 2010 targets (2Q, 2009)
19	Complete lab-scale prototype chemical hydrogen storage system and evaluate against 2010 targets (4Q, 2010)
20	Demonstrate multiple cycle regeneration at laboratory-scale (4Q, 2010)
21	Identify advanced regeneration laboratory process with potential to meet 2015 targets (4Q, 2010)
22	Decision point on chemical hydrogen storage R&D (4Q, 2010)
23	Down-select chemical hydrogen storage approaches for 2015 targets (4Q, 2013)
24	Complete chemical hydrogen lab-scale prototype and evaluate against 2015 targets (4Q, 2015)

Task 4: Additional New Materials and Concepts	
25	Down select from new material concepts to meet 2010 targets (4Q, 2007)
26	Down select the most promising new material concepts with potential to meet 2015 targets (4Q, 2012)

Task 5: Testing and Analysis of Onboard Storage Options	
27	Complete construction of materials test facility (4Q, 2004)
28	Complete verification of test facility for adsorbent materials (4Q, 2005)
29	Complete verification of test capabilities for metal hydride materials (4Q, 2006)
30	Complete baseline analyses of onboard storage options for 2010 targets (4Q, 2006)
31	Establish testing capabilities for chemical hydrides (1Q, 2007)
32	Update onboard storage targets (4Q, 2007)
33	Complete analyses of onboard storage options for 2010 and 2015 targets (4Q, 2009)

Outputs

St1	Output to Technology Validation: Report on compressed/cryogenic liquid storage tanks and evaluation against 1.5 kWh/kg and 1.2 kWh/L. (4Q, 2006)
St2	Output to Technology Validation: Report on advanced compressed/cryogenic tank technologies. (4Q, 2009)
St3	Output to Fuel Cells and Technology Validation : Report on metal hydride system and evaluation against 2007 targets. (2Q, 2007)
St4	Output to Delivery, Fuel Cells and Technology Validation: Report on full-cycle chemical hydrogen system and evaluation against 2010 targets. (1Q, 2011)
St5	Output to Delivery, Systems Analysis and Systems Integration: Baseline hydrogen onboard storage system analysis results including hydrogen quality needs and interface issues (1Q, 2007)
St6	Output to Delivery, Systems Analysis, Systems Integration and Manufacturing: Final onboard hydrogen storage system analysis results of cost and performance (including pressure, temp, etc) and down-select to a primary onboard storage system candidate. (1Q, 2010)

Inputs

C1	Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical Specification. (3Q, 2006)
C2	Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks. (3Q, 2006)
C3	Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America). (4Q, 2006)
C5	Input from Codes & Standards: Materials compatibility technical reference. (4Q, 2007)
C8	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard. (2Q, 2010)
V9	Input from Technology Validation: Final report on safety and O&M of three refueling stations. (4Q, 2007)
A0	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system. (4Q, 2007)
M3	Input from Manufacturing: Report on fabrication and assembly processes for high-pressure H_2 storage technologies that can achieve a cost of $2/kWh. (4Q, 2015)
P2	Input from Production: Assessment of fuel contaminant composition. (4Q, 2006)