FreedomCAR & Fuel Partnership

HYDROGEN STORAGE TECHNOLOGIES ROADMAP

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FreedomCAR & Fuel Partnership
Hydrogen Storage Technologies Roadmap

1. Mission:

Drive the development and demonstration of commercially viable hydrogen storage technologies that meet FreedomCAR and Fuel Partnership goals.

2. Objectives:

- By 2010, develop and validate onboard hydrogen storage systems achieving 2 kWh/kg (6 wt%), 1.5 kWh/L, and $4/kWh.
- By 2015, develop and validate onboard hydrogen storage systems achieving 3 kWh/kg (9 wt%), 2.7 kWh/L, and $2/kWh.
- In collaboration with the Hydrogen Delivery Technical Team, develop and validate vehicle interface technologies for fueling onboard hydrogen storage systems.

3. Technical Targets

Table 1 shows the technical targets for onboard hydrogen storage systems. These targets were originally established through the FreedomCAR Partnership between DOE and the U.S. Council for Automotive Research (USCAR). The FreedomCAR Partnership was expanded in 2003 to include five major energy companies and is now called the FreedomCAR and Fuel Partnership. The targets are subject to change as more is learned about system level requirements and as progress in fuel cell technology is made. In addition, limited tradeoffs between targets are being explored. The basis for each target is explained in further detail below.

Table 1 Technical Targets: On-Board Hydrogen Storage Systems

Storage Parameter	Units	2007	2010	2015
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass)[a]	kWh/kg (kg H_2/kg system)	1.5 (0.045)	2 (0.06)	3 (0.09)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	1.2 (0.036)	1.5 (0.045)	2.7 (0.081)
Storage system cost [b] (& fuel cost)[c]	$/kWh net ($/kg H_2) $/gge at pump	6 (200) ---	4 (133) 2-3	2 (67) 2-3

Durability/Operability				
- Operating ambient temperature [d]	ºC	-20/50 (sun)	-30/50 (sun)	-40/60 (sun)
- Min/max delivery temperature	ºC	-30/85	-40/85	-40/85
- Cycle life (1/4 tank to full) [e]	Cycles	500	1000	1500
- Cycle life variation [f]	% of mean (min) at % confidence	N/A	90/90	99/90
- Min delivery pressure from tank; FC= fuel cell, I=ICE	Atm (abs)	8FC / 10ICE	4FC / 35ICE	3FC / 35ICE
- Max delivery pressure from tank[g]	Atm (abs)	100	100	100
Charging/discharging Rates				
- System fill time (for 5 kg)	min	10	3	2.5
- Minimum full flow rate	(g/s)/kW	0.02	0.02	0.02
- Start time to full flow (20 ºC) [h]	s	15	5	5
- Start time to full flow (- 20 ºC) [h]	s	30	15	15
- Transient response 10%-90% and 90% -0%[i]	s	1.75	0.75	0.75
Fuel Purity (H_2 from storage)[j]	% H_2	99.99 (dry basis)		
Environmental Health & Safety				
- Permeation & leakage [k]	Scc/h	Meets or exceeds applicable standards		
- Toxicity	-			
- Safety	-			
- Loss of useable H_2 [l]	(g/h)/kg H_2 stored	**1**	**0.1**	**0.05**

Useful constants: 0.2778kWh/MJ, ~33.3kWh/gal gasoline equivalent.

Note: Above targets are based on the lower heating value of hydrogen and greater than 300-mile vehicle range; 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. Unless otherwise indicated, all targets are for both internal combustion engine and for fuel cell use, based on the low likelihood of power-plant specific fuel being commercially viable. Also note that while efficiency is not a specified target, systems must be energy efficient. For reversible systems, greater than 90% energy efficiency for the energy delivered to the power plant from the on-board storage system is required. For systems generated off-board, 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.

Footnotes to Table 1

[a] Generally the ‘full’ mass (including hydrogen) is used, for systems that gain weight, the highest mass during discharge is used.

[b] 2003 US$; total cost includes any component replacement if needed over 15 years or 150,000 mile life.

[c] 2001 US$; includes off-board costs such as liquefaction, compression, regeneration, etc; 2015 target based on H_2 production cost of $2 to $3/gasoline gallon equivalent untaxed, independent of production pathway.

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

[e] Equivalent to 100,000; 200,000; and 300,000 miles respectively (current gasoline tank spec).

[f] All targets must be achieved at end of life.

[g] In the near term, the forecourt should be capable of delivering 10,000 psi compressed hydrogen, liquid hydrogen, or chilled hydrogen (77 K) at 5,000 psi. In the long term, it is anticipated that delivery pressures will be reduced to between 50 and 150 atm for solid state storage systems, based on today’s knowledge of sodium alanates.

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

[i] At operating temperature.

[j] The storage system will not provide any purification, but will receive incoming hydrogen at the purity levels required for the fuel cell. For fuel cell systems, purity meets SAE J2719, Information Report on the Development of a Hydrogen Quality Guideline in Fuel Cell Vehicles. Examples include: total non-particulates, 100 ppm; H_2O, 5 ppm; total hydrocarbons (C_1 basis), 2 ppm; O_2, 5 ppm; He, N_2, Ar combined, 100 ppm; CO_2, 1 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, particulate concentration, <1µg/L H_2. These are subject to change. See Appendix F of DOE 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 as more information becomes available.

[k] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with CSA/NGV2 standards for vehicular tanks. This includes any coating or enclosure that incorporates the envelope of the storage system.

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

4. Basis for Targets:

Background

Early materials-based targets for onboard hydrogen storage systems were well designed to promote scientific research in the critical area of hydrogen storage. Promising new technologies were nurtured under these targets, and meaningful improvements in existing technologies were achieved. The focus now swings from demonstrating possibilities to making commercially viable components and products. Logically there is a concomitant change from discovery-oriented targets to engineering-oriented targets, and target levels are increasingly driven by system needs and customer expectations. In addition, the storage system must strive to serve both ICE and fuel cell vehicles. These system targets are aggressive (e.g. 9 wt%). They are not meant to extend what is known by another incremental step, rather they are a challenge to the industrial and scientific communities to reach in terms of innovative, even radical, new ways to achieve what the consumer expects: a hydrogen vehicle that does everything current vehicles do, at a similar cost, but with the societal advantages of hydrogen. The targets are based on the U.S. weighted average corporate vehicle (WACV) that includes minivans, light trucks, economy cars, and SUV/crossover vehicles in proportion to their sales. Depending on progress in other areas related to hydrogen vehicle development, these targets may have to be altered and will be periodically revisited.

System Gravimetric Capacity: Usable specific energy from hydrogen, net:

This is a measure of the specific energy from the standpoint of the total onboard storage system, not just the storage medium. The term specific energy is used interchangeably with the term gravimetric capacity. The storage system includes interfaces with the refueling infrastructure, safety features, the storage vessel itself, all storage medium, 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. Obviously, it cannot be so heavy as to preclude use on a vehicle. Further, the fuel efficiency of any vehicle is inversely related to the vehicle’s mass. If the intent is to create an efficient, and thus lightweight vehicle, and to have it meet all customer expectations in terms of performance, convenience, safety, and comfort, then the total percentage of the vehicle weight devoted to the hydrogen storage system must be limited. These targets lead to the ultimate goal of greater than 300 mile range in such a vehicle by the year 2015, and are suitably discounted in earlier years based on the assumptions of the expected vehicle usage and customers for those initial vehicles.

The targets are based on customer expectations, rather than on the capabilities of the current candidates for hydrogen storage. For reference, the total fuel system in the WACV with a weight of about 1740 kg with a fuel capacity of 19.8 gallons and a resultant range (@ 18.7 mpg) of 370 miles, has a mass of about 74 kg (including 55.4 kg of fuel). (The above fuel economy includes the EPA adjustment factor.) The energy in that fuel totals (33.3 kW-h/gal x 19.8 gallons =) 659 kWh, and the resultant specific energy is (659/74) = 8.9 kWh/kg. For fuel economy gains of 2.5 and 3.0X, the corresponding specific energy for the WACV are approximately 3.5 and 3 kWh/kg, respectively. Obviously, these targets include an expectation that vehicle and powertrain efficiency improvements will be forthcoming. The target is in units of net useful energy in kWh per maximum system mass in kg. “Net useful energy” is used to account both for unusable energy (i.e. hydrogen left in a tank below minimum powertrain system pressure requirement) and for hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g. fuel used to heat a hydride to initiate or sustain hydrogen release). “Maximum system mass” implies that all of the equipment enumerated above plus the maximum charge of hydrogen are included in the calculation. Reactive systems increase in mass as they discharge; in such systems the discharged mass is used. Light duty vehicles with current fuel cell efficiencies of ~50% were used to estimate the targets below.

Usable, specific-energy from H_2 (H_2 mass/max system mass)	kWh/kg net	1.5	2	3

System Volumetric Capacity: Usable volumetric energy density from hydrogen, net:

This is also a measure of energy density from a system standpoint, rather than from a storage medium standpoint. The term energy density is used interchangeably with the term volumetric capacity. As above, the on-board hydrogen storage system includes every component required to safely accept hydrogen from the delivery infrastructure, store it on board, and release conditioned hydrogen to the powerplant. Again, given vehicle constraints and customer requirements (i.e. aerodynamics for fuel economy, luggage capacity for people), the system cannot take up too much volume, and the “shape factor” that the volume occupies becomes important. Also, as before, any unusable fuel must be taken into account. The targets assume both increased vehicle efficiency and the ability to store hydrogen in volumes that are currently dedicated to systems that may not be required in a hydrogen-fueled vehicle (i.e. a catalytic converter or muffler). For reference, the WACV described above (with a roughly 20-gallon tank) has a total fuel system volume of about 107 liters (including tank with vapor space, filler tube, pump, filter, fuel lines, vapor canister, valves, and mounting straps), stored energy of about 659 kWh, and a resultant usable energy density of about (659/107 =) 6.15 kWh/L net. For fuel economy gains of 2.5 and 3.0X, the energy density is approximately 2.5 kWh/L and 2 kWh/L, respectively. Today’s gasoline tanks are considered conformable. Conformability requires a tank to take irregular shapes, and to “hug” the space available in the vehicle, but right angle bends and inch wide protuberances are not required. For conformable fuel tanks the required volumetric energy density may be reduced up to 20% because space not allocated for fuel storage may be used without a penalty. Because early hydrogen storage systems may not be completely conformable, an additional 20% is added to these targets to give approximately 3 kWh/L and 2.5 kWh/L for fuel economy gains of 2.5 and 3.0X respectively. The target is set at 2.7 kWh/L. By contrast liquid hydrogen by itself has a density of 2.35 kWh/L. The targets are in units of net usable energy in kWh per system volume in liters. Light duty vehicles with current fuel cell efficiencies of ~50% and non-conformable fuel tanks (e.g., spherical or cylindrical storage tanks) were used to estimate the targets below.

Usable energy density from H_2	kWh/L net	1.2	1.5	2.7

Specific storage system cost:

This target refers to the total projected cost of the entire on-board hydrogen storage system, including all hardware and storage media, plus an amortized estimate for any components or media that would have to be replaced for the system to demonstrate a useful life of 150,000 miles in a vehicle. It is understood that the onboard fuel storage system for a hydrogen fueled vehicle may never reach the low cost of a fuel system in a current production vehicle, but it is expected that the societal benefits of hydrogen vehicles, combined with potential cost offsets and improved vehicle and powertrain efficiencies, will justify these targets. The target is in units of (2003 US) dollars per kW-h of usable energy capacity (“usable energy” has been previously defined). The use of constant dollars is to facilitate direct comparisons. For reference, the example WACV would have a system cost of about $269 and a usable capacity of 659 kWh, for a resultant specific storage system cost of $0.41/kWh. Accounting for 2.5 and 3.0X fuel economy gains, the cost becomes $1.03-$1.23/kWh. Note that the cost of the *first* charge (and any additional costs associated with the first charge such as preconditioning cost), is included in the specific storage system cost, regardless of storage method (e.g. high pressure tanks, chemical storage, metal hydrides, etc.). For example, if the first charge is 8 kg of hydrogen at a cost of $2.50/kg (within the cost target of $2 to $3 per kg hydrogen) the specific storage system cost is approximately $1.30/kWh, assuming a 3.0X fuel economy gain. Targeting for cost competitiveness in 2015, the cost target has been set at $2/kWh.

Specific storage system cost	$/kW·h net (2003 US$)	6	4	2

Fuel cost:

This target is meant to provide guidance for chemical storage systems that are regenerated off-board. It also includes costs for compression, liquefaction, delivery, chemical recovery, etc. as required. The cost of regenerating by-products must be considered in terms of the fuel cost targets. This target reflects hydrogen cost independent of production pathway. Although fuel cost targets prior to 2015 are not pathway independent and thus not specified for all potential pathways (e.g., natural gas reforming, biomass, electrolysis, photobiological, etc.), an approximate hydrogen cost of $4 to $5/kg can be used for estimating storage system cost in the near term. The unit of $/gallon gasoline equivalent (gge) is equivalent to $/kg of hydrogen.

Fuel cost	2001 US$/ gallon gasoline equivalent (pump price)	- ----	2 to 3	2 to 3

Durability/Operability:

Operating temperature (/solar load): The storage system must dependably store and deliver hydrogen at all expected ambient conditions. The operation range expands with time. This reflects the expectation that the limited demo fleets will experience a less severe subset of ambient conditions. As commercial sales begin the vehicles can be expected to experience the full range of conditions, and eventually will be expected by consumers to operate perfectly in any weather encountered. The units are degrees C. The notation (sun) indicates that the upper temperature is a hot soak condition in full direct sun, including radiant heat from the pavement.

Operating ambient temperature	°C	-20/50 (sun)	-30/50 (sun)	-40/60 (sun)

Minimum/maximum delivery temperature of H_2 from tank: Fuel cells currently operate at approximately 80 C. If the temperature exceeds 100°C operation is unacceptable. In addition, if hydrogen enters above the cell temperature, this adds to the already significant water management and heat rejection problem. Thus, an upper limit on temperature is desirable. The value of 85 C is selected based on today's PEMFC technology. Over time, a higher value such as 100 C may be substituted because fuel cells are likely to operate at increasingly higher temperatures, and as the fleet size is increased, it will also become increasingly important that the storage system comply more closely with the fuel cell preferred operating range. The lower limits reflect both wider acceptance of fuel cells in varying climates and fuel cell improvements for lower temperature operation. The units are degrees C.

Delivery temperature of H_2 from tank	°C	-30/85	-40/85	-40/85

Cycle life: Customers expect the fuel system to last the life of the vehicle, typically 150,000 miles. Assuming a 300mile range, that amounts to 500 full fill cycles. Many customers fill at partial capacity rather than at empty, requiring more fill cycles which implies more exposure to refill conditions and more time at the maximum fill level. Demo fleets may not require the customer expected durability, so 500 cycles is acceptable. Once wider sales start, 150000-mile life will be expected so an engineering factor is applied to ensure product reliability. At full fleet capability the risk increases and the engineering factor is raised to near that expected of gasoline. The units here are simply the number of cycles that must be demonstrated as a mean value. The cycle is defined as going from quarter full to full.

Cycle life (1/4 tank to full)[i]	Cycles	500	1000	1500

Cycle life variation: Manufactured items have item-to-item variation. The variation as it affects the customer is covered by the cycle life target; the variation as it affects testing is covered in this target. 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 (95 indicates 95% confidence or an alpha value of 0.05). 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.

Cycle life variation	% of mean (min) @ % confidence	N/A	90/90	99/90

Delivery Pressure from hydrogen storage system (minimum acceptable): This target acknowledges that the onboard hydrogen storage system is responsible for delivering hydrogen in a condition that the powerplant can use. Since there can be no flow without a pressure differential, a minimum supply pressure is required just to move the hydrogen from the bulk storage to the powerplant. If the hydrogen were merely available at the entrance to a fuel cell, for instance, any pumps necessary to push or draw that fuel through the stack would be considered part of the fuel storage system. This is the only target that is different for fuel cells and for internal combustion engines. This is because the IC technology relies on pressurized fuel injection, and is envisioned to advance from low-pressure central or port injection to high-pressure in-cylinder direct injection by 2010. The units are in kilopascals and bar (roughly, standard atmospheres) absolute pressure.

Delivery pressure (minimum acceptable at full flow) FC=fuel cell, ICE = internal combustion engine	Atm (abs)	FC: 8 ICE: 10	FC: 4 ICE: 35	FC: 3 ICE: 35

Delivery Pressure from hydrogen storage system (maximum acceptable): This target is for the pressure delivered from the on-board hydrogen storage system to the automotive power plant. This target ensures that the on-board hydrogen storage system should not be designed such that extraordinary measures for pressure regulation are required before fuel is supplied to the fuel cell system.

Delivery pressure (maximum)	Atm (abs)	100	100	100

Charging/Discharging Rates:

System fill time (5-kg H_2 system): Consumers expect to refuel a vehicle quickly and conveniently, especially on extended trips. The filling target is designed to parallel current customer experience.

Currently, gasoline vehicles are filled in about 2-5 minutes, with small vehicles taking less time and large ones more time. Based on the expected efficiency of fuel cell vehicles, 5 to 13 kg of hydrogen will be needed for light duty vehicles. The target applies to systems with 5 kg H_2 *or less*, with larger systems requiring proportionally more fill time. The long-term goal is to achieve near parity with current gasoline filling times. Demo fleets could operate with longer fill times. The units are minutes.

Important note for scale models with less than 5kg of hydrogen: For scale models of solid-phase storage systems, one should keep the fill time constant - realizing that fill time involves not only delivery of the hydrogen, but also heat transfer and kinetic factors (in solid phase storage options) - and instead scale the mass flow rate to the scale model's size. For example, a laboratory scale system with 200 mg of metal hydride should achieve complete adsorption during recharging within 3 minutes to be consistent with 2010 targets.

System fill time (5 kg)	min	10	3	2.5

Minimum full-flow rate: This target is a measure of the maximum flow rate of hydrogen required by the powertrain to achieve the desired vehicle performance. It is based on an average 3000 lb. current production vehicle, which typically has a powerplant of about 150kW, but modified to account for a FreedomCAR goal of 45% efficiency for a hydrogen-powered internal combustion engine. It is based on actual measured maximum gasoline fuel flow. This should not be considered only a transient phenomenon (though a vehicle would not accelerate through an entire tank of fuel, it might be called upon to tow a large, heavy trailer up an 18-mile grade, such as is found on Interstate 5 near Baker California). However, because fuel cell efficiency is poorest at full load, while ICEs are at or near their highest efficiency at full load, fuel cell vehicles will require the 2005 target level. Fuel cells are not likely to require the increase in this requirement with time. Several comments are in order here. These targets will ensure that, whatever the motive technology, the storage systems will be capable of meeting its requirements. Further, it protects for the possibility that IC engines powered by hydrogen may actually precede FC vehicles to market (and thus help to create a need for a hydrogen infrastructure). Second, this target is still quite limited, as it neglects the requirements of the ICE powered SUV/minivan/light truck segment, which currently makes up 50% of the market. Finally, this target is intended to indicate the potential for scalability for the hydrogen storage technology. This target is in units of mass/time normalized to powerplant size.

Minimum full flow	(g/sec)/kW	.02	.02	.02

Start time to full-flow at 20°C:

The vehicle may be able to start based on hydrogen in the lines, but to maintain adequate function without the need for a second energy storage medium (batteries), full flow must be available almost instantly. Customers are currently accustomed to sub second start times. And full power available on demand any time after the key is released. The units for this target are seconds after start. Early demo fleets may not require starting times that rival current ICE technology, so a longer time is allowed. However, once large-scale production is started a value near that of an ICE is given. This need not mean the entire storage system must start in 5 seconds- only that it is capable of delivering fuel at maximum flow if requested. A small, moderate pressure buffer could serve to lengthen the true start up time. The mass and volume of the buffer would be charged against the system mass and volume. The target start time to achieve 50% rated power for the complete fuel cell system is 30 seconds (for 2005) and 5 seconds (for 2010 and 2015). The storage system targets for start time to full-flow are set to meet the overall powerplant needs. In addition, the storage system must provide some flow to the powerplant within 25% of the time target for full-flow.

Start time to full flow at 20°C	Sec	15	5	5

Start time to full-flow at minimum ambient (-20 C):
See Start time at 20°C. The longer times reflect current customer expectation that in cold weather starting is more difficult. It is important to note that batteries are at their worst power capabilities at very low temperature. If a battery assist were contemplated, the battery system would likely have to be sized based on this starting condition, and thus would be rather large. This is why it is desirable to avoid batteries if possible. The target start time to achieve 50% rated power for the complete fuel cell system at –20 C is 60 seconds (for 2005) and 30 seconds (for 2010 and 2015). Consistent with the above target, some flow will be required to the powerplant within 25% of the full-flow target time. Given the possibility that some hydrogen may be used to assist with cold start of the powerplant, the storage system is set to achieve full-flow within 50% of the start time for the powerplant. Units are in seconds.

Start time to full flow at min ambient	Sec	30	15	15

Transient response 10% to 90% and 90% to 0%: Transient response is one of the greatest challenges a vehicle powertrain faces. The storage system must track the needs of the fuel cell closely to provide adequate power and a suitable driving experience and must meet the fuel cell system requirement of 2 seconds (2005 target) and 1 second (2010 and 2015 targets). The transient response is not symmetric. The 10 to 90% transient target is to meet the demand of the fuel cell or ICE during acceleration. The 90 to 0% transient reflects the fact the fuel cell can stop using hydrogen almost instantly and the fuel supply must stop quickly enough to avoid over-pressuring any part of the system. This parameter impacts performance, fuel cell durability, and vehicle control. The units are seconds to change between 10% flow and 90% flow, or 90% flow and no flow.

Transient response 10% to 90% and 90% to 0%	Sec	1.75	0.75	0.75

Purity:

Hydrogen must be relatively pure going to the fuel cell or system efficiency will be degraded; ICEs are much more forgiving, though an exhaust after-treatment system may not be. Units are in volume % on a dry basis. Even inert impurities can degrade performance by progressively diluting the hydrogen at the anode, and necessitating venting of the anode, including some of the stored hydrogen. See target table footnote for specific impurity levels. It is also assumed that impurities from the hydrogen source do not degrade storage system performance. In other words, the hydrogen output from the storage system should be able to meet fuel cell purity targets without contaminating the 99.99% hydrogen input to the storage system. The fuel purity requirements are set to meet ISO specification ISO/PDTS 14687-2. The specification is an interim document and, as additional operational experience is gained with the existing fleet of fuel cell vehicles, it will likely be modified. See Appendix F of DOE Multiyear Research, Development and Demonstration Plan (www.eere.energy.gov/hydrogenandfuelcells/mypp/), to be updated as fuel purity analyses progress.

Purity of H_2 from tank	% (dry)	99.99	99.99	99.99

Environmental, Health & Safety:

Permeation/leakage, toxicity and safety: These targets are of great importance because they deal with protecting the health and well being of the owner. These types of concerns are generally regulated by the government. Only the permeation and leakage target has a clear set of units, standard cc of hydrogen per hour. Permeation and leakage is differentiated from hydrogen loss in that hydrogen that leaves the storage system but is first transformed into another species (e.g. water, via catalytic oxidation in a vent line) is not included in permeation and leakage but would be included in hydrogen loss. Permeation and leakage thus pertains to the possibility of generating a combustible hydrogen-air mixture outside the storage tank. Toxicity covers the possibility of consumer exposure to the storage material in normal, or abnormal conditions, plus worker exposure during manufacture and assembly. Safety covers all the typical safety statutes including certification and operation of vehicles, manufacture, transport, dispensing of fuel, and end of life issues. In each of these categories, compliance with federal standards, and potentially state and local standards will be required.

Permeation and leakage	Scc/h	Meets or exceeds applicable standards
Toxicity		Meets or exceeds applicable standards
Safety		Meets or exceeds applicable standards

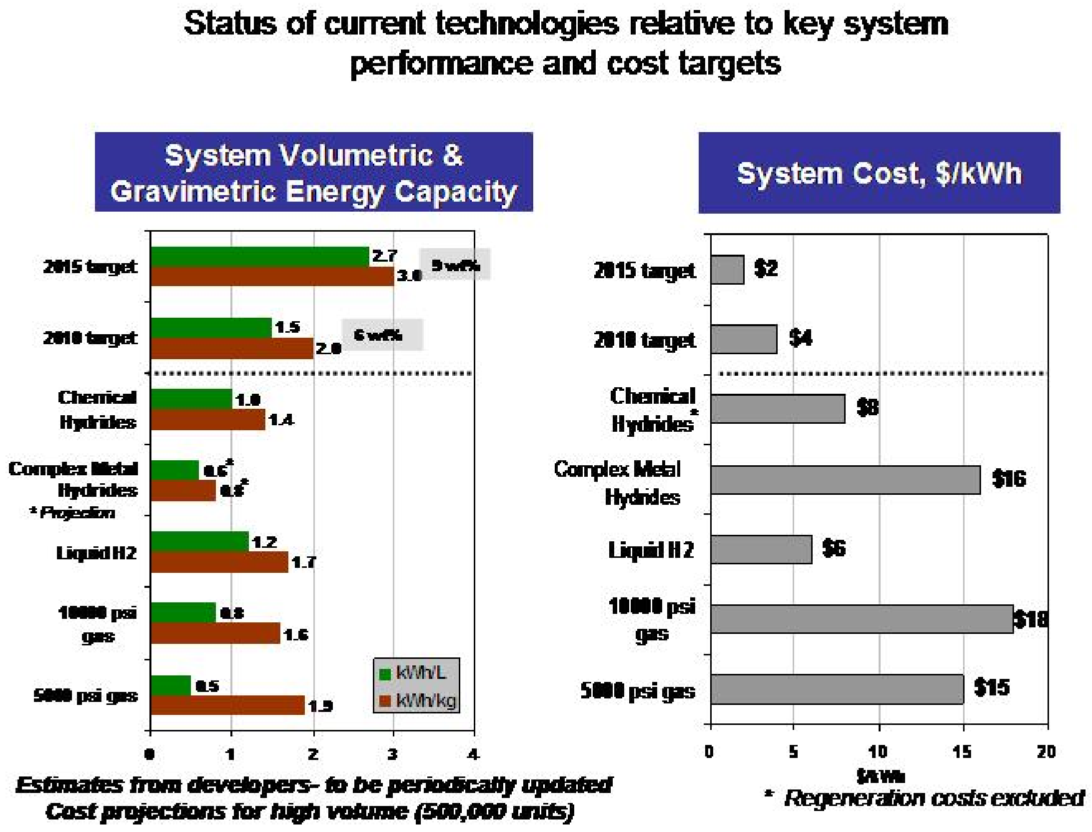
Hydrogen loss: This target protects against loss of range after extended periods of rest, for example parking during a vacation. Demonstration fleets are not expected to operate extensively in the normal consumer cycle, and the owners are better prepared to deal with low fuel situations, thus a lower standard is required. Vehicles purchased by consumers will be expected to have minimal perceptible loss of range after a week or two of parking, similar to gasoline vehicles today. Because the targets are normalized to mass of hydrogen stored, this target protects all tank sizes equally. At a value of 0.1, a full tank will require more than a year to empty. The units are g/h of hydrogen lost via all routes, per kg of hydrogen stored.

Loss of useable hydrogen	(g/h)/kg H_2 stored	1	0.1	0.05

5. Gap Analysis

Figure 1 shows the status of current technologies relative to the key technical targets of volumetric (kWh/L) and gravimetric (kWh/kg) energy densities, and cost.

Figure 1 Current Technology Status vs. Targets



Estimates from developers- to be periodically updated
Cost projections for high volume (500,000 units)

* *Regeneration costs excluded*

The current status data are estimates provided by technology developers and the R&D community. 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 2010 or 2015. Also note that although recent accomplishments may show materials-based capacities of over 6 wt.%, the targets of 6 wt.% by 2010 and 9 wt.% by 2015 are *system-level* capacities which 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. For chemical hydrogen storage, the cost for regenerating spent fuel will need to be addressed.

The following "red, yellow, green" gap analysis indicates the status of current hydrogen storage technologies relative to the most critical 2015 technical targets of specific energy, energy density, and cost. Red indicates a large gap between status and target, and suggests that the current performance is a potential showstopper to the success of that technology and that a breakthrough may be needed. Typically, red categories will require the most work and the greatest amount of resources. Yellow indicates that the performance may not be a showstopper; but a substantial amount of work needs to be done to achieve the target. An example could be an engineering solution to achieve the energy density. Green indicates that minimal work is needed to achieve the target. Note that there are no "green" categories in the hydrogen storage gap analysis.

Figure 2 Comparison of Storage Options: Gap Analysis

	Compressed Hydrogen	**Liquid Hydrogen**	**Advanced Metal Hydrides**	**Chemical Hydrogen Storage**	**Carbon or Sorbents**	**Advanced Concepts**
Specific Energy	Yellow	Yellow	Red	Yellow	Red	Red
Energy Density	Red	Red	Red	Yellow	Red	Red
Cost	Red	Red	Red	Red	Red	Red

6. Technical Barriers/Strategy

A variety of hydrogen storage approaches are under consideration:

- Advanced compressed/cryogenic tanks, including conformable and hybrid approaches
- Advanced metal hydride-based hydrogen storage
- Chemical hydrogen storage (including off-board regeneration)
- Carbon-based and high surface area materials
- Advanced Concepts

A standard testing and certification program specifically aimed at assessing the performance, safety, and cycle life of reversible solid-state hydrogen storage materials is being developed. A set of performance and safety evaluation standards based on input from industry and government is also planned. Systems analyses activities are also a key part of the hydrogen storage portfolio. Such analyses are critical, to evaluate the approaches comparatively and to make down-select decisions. Current analysis activities include storage systems analyses to optimize the trade-offs among weight, volume and cost, as well as life-cycle cost, energy efficiency, and environmental impact analyses.

6.1 ON-BOARD HYDROGEN STORAGE TECHNICAL BARRIERS

General Barriers Applicable 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 on-board 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 on-board 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 Technical Team.

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 on-board reversible materials within fueling time requirements. On-board reversible materials typically require heat to release hydrogen on board the vehicle. 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 On Board)

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.

6.2 Technical Task Descriptions

The technical task descriptions are presented in Table 2. Issues regarding safety will be addressed within each of the tasks. The barriers associated with each task appear after the task title.

Table 2. Technical Task Descriptions

Task	Description	Barriers

1	Compressed and Cryogenic Tanks to Meet 2007 Targets • 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.	A-O
2	Advanced Compressed and Cryogenic Tank Technologies • Develop advanced compressed and cryogenic tank technologies to meet 2010 targets.	A-O
3	On-Board Reversible Materials R&D for 2007 Targets • 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. •	A-K, P-Q
4	On-Board Reversible Materials R&D for 2010 Targets • Develop and verify most promising reversible storage materials to meet 2010 targets.	A-K, P-Q
5	On-Board Reversible Materials R&D for 2015 Targets • Develop and verify most promising reversible storage materials to meet 2015 targets.	A-K, P-Q

6	Off-Board Regenerable Chemical Hydrogen Storage R&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.	A-K, R-S
7	R&D of Advanced Off-Board Regenerable Chemical Hydrogen Storage for 2010 Targets • Develop and verify most promising chemical hydrogen storage materials to meet 2010 targets.	A-K, R-S
8	R&D of Advanced Off-Board Regenerable Chemical Hydrogen Storage for 2015 Targets • Develop and verify most promising chemical hydrogen storage materials to meet 2015 targets.	A-K, R-S
9	New Materials and Concepts Feasibility • 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.	A-S
10	New Materials and Concepts R&D to meet 2010 Targets • Develop and characterize new materials and concepts to meet 2010 targets.	A-S
11	New Materials and Advanced Concepts R&D to meet 2015 Targets • Develop and characterize new materials and advanced concepts to meet 2015 targets.	A-S
12	Testing and Analysis of On-board 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

6.2 Timeline/Milestones

The timeline, specific milestones, go/no go decision points and inputs/outputs across program areas are shown in Figure 2. Table 3 provides a brief description for each of the key milestones, decision points and inputs/outputs across other activities.

Figure 3 Hydrogen Storage RD&D Plan

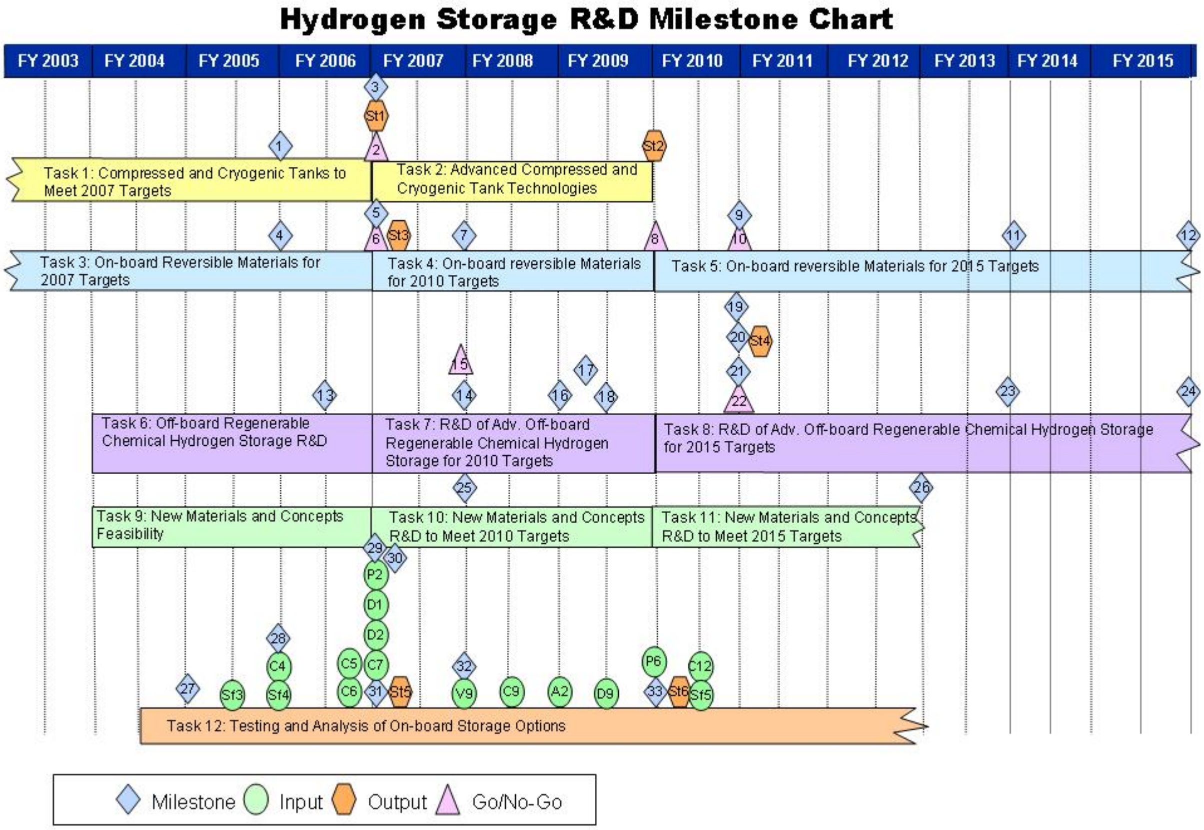


Table 3 Key milestones, go/no go decision points and inputs/outputs for hydrogen storage activities

Milestone	Description	Due Date
1	Complete feasibility study of hybrid tank concepts	4Q 2005
2	Go/No-Go: Decision on compressed and cryogenic tank technologies for on-board vehicular applications	4Q 2006
3	Independent evaluation of gravimetric and volumetric capacities of cryo-compressed tanks	4Q 2006
4	Reproducibly demonstrate 4 wt% material capacity on carbon nanotubes	4Q 2005
5	Complete prototype metal hydride system and evaluate against 2007 targets	4Q 2006
6	Go/No-Go: Decision point on carbon nanotubes	4Q 2006
7	Down-select on-board reversible metal hydride materials	4Q 2007
8	Go/No-Go: Decision point on advanced carbon-based materials	4Q 2009
9	Complete materials-based prototype system and evaluate against 2010 targets	4Q 2010
10	Go/No-Go: Decision on continuation of on-board reversible metal hydride R&D	4Q 2010
11	Down-select on-board reversible hydrogen storage materials with potential to meet 2015 targets	4Q 2013
12	Complete prototype system and evaluate against 2015 targets	4Q 2015
13	Complete preliminary estimates of efficiency for off-board regeneration	2Q 2006
14	Down-select from chemical hydrogen regeneration processes	4Q 2007
15	Go/no-go decision on sodium borohydride	4Q 2007
16	Demonstrate chemical hydrogen regeneration laboratory-scale process and determine efficiency	4Q 2008
17	Complete chemical hydrogen storage life-cycle analyses	1Q 2009
18	Down-select from chemical hydrogen storage approaches for 2010 targets	2Q 2009
19	Complete prototype chemical hydrogen storage system and evaluate against 2010 targets	4Q 2010
20	Demonstrate multiple cycle chemical hydrogen regeneration at laboratory-scale	4Q 2010
21	Identify advanced chemical hydrogen regeneration laboratory process with potential to meet 2015 targets	4Q 2010
22	Go/No-Go: Decision point on chemical storage R&D for 2015 targets	4Q 2010
23	Down-select from chemical hydrogen storage approaches for 2015 targets	4Q 2013

24	Complete chemical hydrogen prototype and evaluate against 2015 targets	4Q 2015
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
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	Establish testing capabilities for chemical hydrides	1Q 2007
31	Complete baseline analyses of on-board storage options for 2010 targets	4Q 2006
32	Update onboard storage targets	4Q 2007
33	Complete analyses of on-board storage options for 2010 and 2015 targets	4Q 2009

Inputs

Sf3	Input from Safety: Safety requirements and protocols for refueling.	2Q 2005
C4	Input from Codes and Standards: Standards for compressed gaseous on-board storage.	4Q 2005
Sf4	Input from Safety: Safety requirements for on-board storage.	4Q 2005
C5	Input from Codes and Standards: Hydrogen fuel quality standard as ISO Technical specification.	3Q 2006
C6	Input from Codes and Standards: Technical assessment of standards requirements for metallic and composite bulk storage tanks.	3Q 2006
P2	Input from Production: Assessment of fuel contaminant composition.	4Q 2006
D1	Input from Delivery: Assessment of cost and performance requirements for off board storage systems.	4Q 2006
D2	Input from Delivery: Hydrogen contaminant composition and issues.	4Q 2006
C7	Input from Codes and Standards: Final standards (balloting) for fuel dispensing systems (CSA America).	4Q 2006
V9	Input from Technology Validation: Final report on safety and O&M of three refueling stations.	4Q 2007
C9	Input from Codes and Standards: Materials compatibility technical reference.	2Q 2008
A2	Input from Systems Analysis: Initial recommended hydrogen quality at each point in the system.	4Q 2008
D9	Input from Delivery: Off-board storage technology.	2Q 2009
P6	Input from Production: Assessment of fuel contaminant composition.	4Q 2009
C12	Input from Codes and Standards: Final hydrogen fuel quality standard as ISO Standard.	2Q 2010
Sf5	Input from Safety: Safety requirements and protocols for refueling.	2Q 2010

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 on-board storage system analysis results including hydrogen quality needs and interface issues	1Q 2007
St6	Output to Delivery, Systems Analysis and Systems Integration: Final on-board hydrogen storage system analysis results of cost and performance (including pressure, temp, etc) and down-select to a primary on-board storage system candidate	1Q 2010

Note: All years listed are Fiscal Years

7. Programmatic Strategy

The Hydrogen Storage activity will focus primarily on the research and development of on-board vehicular hydrogen storage systems that will allow for a driving range of 300 miles or more. There are specific technical targets, including gravimetric, volumetric, and cost targets for 2010, and 2015, as indicated in the Objectives. Storage approaches that will be pursued to achieve these goals are compressed gas and liquid hydrogen tanks for near-term vehicles, and reversible solid-state hydrogen storage materials, chemical hydrogen storage, and advanced concepts for the longer-term vehicle applications (2010-2015 targets).

To help lay the strategic foundation for the hydrogen storage activities, DOE held a series of workshops with scientists and engineers from universities, national laboratories, and industry to identify key issues and R&D priorities. A "Think Tank" meeting, which included Nobel laureates and other award-winning scientists, was held to identify advanced material concepts and to develop an R&D strategy. Interactions between the DOE Office of Hydrogen, Fuel Cells and Infrastructure Technologies (Office of Energy Efficiency and Renewable Energy) and the DOE Office of Basic Energy Sciences (Office of Science) are ongoing to define and coordinate the basic research activities for hydrogen storage materials.

As promising approaches are down-selected, future efforts will include activities on vehicle refueling/interface issues in collaboration with the Delivery and Codes & Standards Technical Teams. Key aspects to include will be safety, reliability, refueling time, and minimum complexity for the operator.

Hydrogen storage R&D will wind down as technical performance and cost targets are met and as technologies are implemented and commercialized. If specific performance issues remain at that time, R&D could be extended if the risk of the continued effort is justified by the potential benefit.

In 2003, the DOE issued a solicitation, the “Grand Challenge” for research and development of hydrogen storage technology. Full and open competition for the “Grand Challenge” included universities, industry and national laboratories eligible for awards. For the first time, national laboratories competed for hydrogen storage awards through a separate category in the solicitation for R&D on Metal Hydrides, Carbon-based Materials and Chemical Hydrogen Storage. This ensured that the most viable approaches and best teams capable of solving the critical challenge of hydrogen storage were selected. University and industry participants were eligible to submit proposals as team members under the focused, collaborative projects, or as leads under a separate category, or both. In addition, independent industry and university projects were solicited on new materials and concepts, as well as on off-board hydrogen storage and systems analyses.

In 2004, the awards from the Grand Challenge were announced with projects at 30 universities, 10 companies and 10 federal laboratories. The selections included focused collaborative R&D on Metal Hydrides, Chemical Hydrogen Storage, and Carbon-Based Materials, with multiple university, industry and national laboratory partners. Independent awards to universities and industry were also announced on systems analyses, new concepts, and off-board storage. The Grand Challenge projects were initiated in FY 2005. DOE also plans to implement an annual solicitation process as a complementary mechanism to continuously solicit and evaluate promising concepts for on-board storage (subject to congressional appropriations).

A major thrust of future efforts will be on innovative chemistries and novel materials approaches- areas of higher technical risk but greater potential impact in terms of meeting storage capacity targets. Future efforts will also include greater collaboration with the DOE Office of Science - through projects aimed at fundamental understanding of hydrogen storage materials and mechanisms. Additional projects through the DOE Office of Science through their 2004 solicitation on basic research for hydrogen storage were initiated in FY2005.

8. Technology Status

In the area of on-board hydrogen storage, the state-of-the-art is 5000- and 10,000-psi 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 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 pick up truck with a hydrogen internal combustion engine. Off-board storage has been demonstrated at several hydrogen refueling stations.

In addition to the status of demonstrations described above, the following projects are currently funded by the DOE Hydrogen Program.

Table 4. Current Hydrogen Storage Projects (FY 2005)

Approach	Organizations	Project Focus
Compressed, Cryo-compressed and Conformal Hydrogen Tanks	Quantum Fuel Systems Technologies Worldwide, Inc.	10,000 psi Composite Tanks, Cost Reduction
	Lawrence Livermore National Laboratory	Cryo-compressed and conformal Tanks; Advanced Concepts
Advanced Metal Hydrides	United Technologies Research Center (2 projects)	Materials discovery of new high-capacity advanced metal hydride compositions; study of system prototype using sodium alanate
	United Oil Products (UOP)	Discovery of novel complex/advanced hydrides using combinatorial testing and molecular modeling screening methods
	Center of Excellence on Metal Hydrides (Sandia National Laboratory-Livermore, Brookhaven National Laboratory, California Institute of Technology, General Electric, HRL Laboratories, Intematix Corporation, Jet Propulsion Laboratory, NIST, Oak Ridge National Laboratory, Savannah River National Laboratory, Stanford University, University of Hawaii, University of Illinois-Urbana-Champaign, University of Nevada-Reno, University of Pittsburgh/Carnegie Mellon University, University of Utah)	Light-weight complex hydrides, destabilized binary hydrides, intermetallic hydrides, modified lithium amides, and other advanced on-board reversible hydrides

Table 4. Current Hydrogen Storage Projects (FY 2005)

Approach	Organizations	Project Focus
	University of Connecticut	Mechanically activated, nanoscale lithium nitride materials
Carbon-based Materials and other High Surface Area Sorbents	Center of Excellence on Carbon-based Materials (National Renewable Energy Laboratory, Air Products & Chemicals, Inc., California Institute of Technology, Duke University, Lawrence Livermore National Laboratory, NIST, Oak Ridge National Laboratory, Pennsylvania State University, Rice University, University of Michigan, University of North Carolina, University of Pennsylvania)	Carbon-based materials and high surface area sorbents including metal doped single walled nanotubes, metal organic frameworks, nanohorns and fibers, conducting polymers; modeling and mechanistic understanding
	Gas Technology Institute	Electron-Charged Enhanced Hydrogen Storage on Graphitic Materials
	State University of New York at Syracuse (SUNY)	Nanostructured Activated Carbon
	University of Pennsylvania and Drexel University	Carbide-Derived Materials with “Tunable Porosity”
Chemical Hydrogen Storage (Including Chemical Hydrides)	Millennium Cell	Sodium borate regeneration
	Air Products & Chemicals, Inc.	Liquid chemical hydride
	Safe Hydrogen LLC	Magnesium hydride slurry
	Center of Excellence on Chemical Hydrogen Storage (Los Alamos National Laboratory, Pacific Northwest National Laboratory, Intematix Corporation, Millennium Cell, Northern Arizona University, Pennsylvania State University, Rohm and Haas, Inc., University of Alabama, University of California-Davis, UCLA, University of Pennsylvania, University of Washington, US Borax)	New chemical hydrogen storage and regeneration processes
	Research Triangle Institute	Synthesis and Hydrogen Extraction Processes for Aminoborane (Boron Nitrogen Hydrides)
New Materials and Concepts	Cleveland State University	Complex metal nanostructured grids

Table 4. Current Hydrogen Storage Projects (FY 2005)

Approach	Organizations	Project Focus
	Alfred University	Hollow glass microspheres and electromagnetic radiation
	Carnegie Institute of Washington	Clathrates
	Michigan Technological University	Metal perhydrides
	TOFTEC, Inc.	Synthesis of carbon and boron nitride materials by gamma irradiation
	University of California-Berkeley and Lawrence Berkeley National Laboratory	Nanoporous polymers, nanoporous coordination solids, destabilized high-density hydrides, nanostructured boron nitride and magnesium and metal alloy nanocrystals
	University of California-Santa Barbara	Nanoporous nickel phosphates, inorganic and organic framework materials and metal hydrogen complexes
	University of Michigan	Metal-organic frameworks
	University of Missouri	Organic clathrates
Testing and Evaluation	Southwest Research Institute	Standard Test Protocols, Independent Test Facility
Analysis	TIAX LCC	Analysis of performance and life cycle costs of on-board storage options
	Argonne National Laboratory	Analysis of hybrid concepts, performance and life cycle impacts of storage systems.