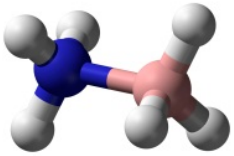
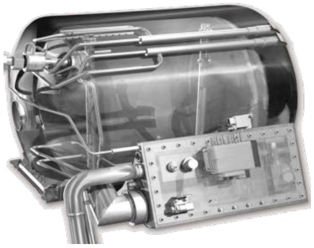
USDRIVE

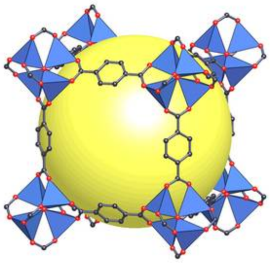
DRIVING RESEARCH AND INNOVATION FOR
VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

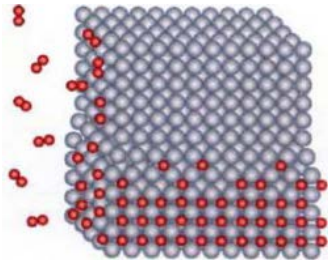
Hydrogen Storage Technical Team Roadmap

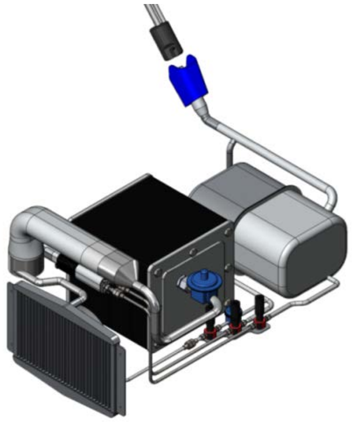
June 2013

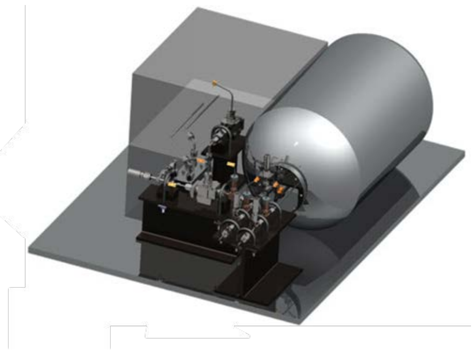


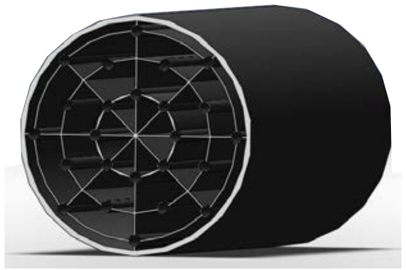


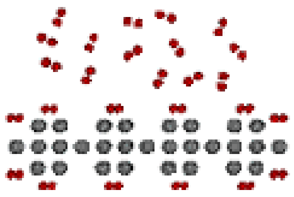












This roadmap is a document of the U.S. DRIVE Partnership. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) is a voluntary, non-binding, and nonlegal partnership among the U.S. Department of Energy; USCAR, representing Chrysler Group LLC, Ford Motor Company, and General Motors; Tesla Motors; five energy companies —BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US; two utilities — Southern California Edison and DTE Energy; and the Electric Power Research Institute (EPRI).

The Hydrogen Storage Technical Team is one of 12 U.S. DRIVE technical teams ("tech teams") whose mission is to accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure.

For more information about U.S. DRIVE, please see the U.S. DRIVE Partnership Plan, www.vehicles.energy.gov/about/partnerships/usdrive.html or www.uscar.org.

Table of Contents

List of Figures

List of Tables

1. Mission and Scope

Mission: Accelerate research and innovation that will lead to commercially viable hydrogen-storage technologies that meet the U.S. DRIVE Partnership goals.

Scope: Review and evaluate the potential, and limitations, of novel approaches, materials, and systems for hydrogen storage onboard light-duty fuel cell vehicles and provide feedback to the U.S. Department of Energy (DOE) and Partnership stakeholders. Generate system goals and performance targets, and establish test methods for hydrogen storage systems onboard vehicles. Collaborate with other technical teams and assist the Partnership in matters relating to hydrogen storage.

2. Key Issues and Challenges

Hydrogen storage is a key enabling technology for the advancement of hydrogen vehicles in the automotive industry. Storing enough hydrogen (4-10 kg) onboard a vehicle to achieve a driving range greater than 300 miles is a significant challenge. On a weight basis, hydrogen has nearly three times the energy content of gasoline when comparing lower heating values (33 kWh/kg for H_2 compared to 12 kWh/kg for gasoline). However, on a volume basis, the situation is reversed (approximately 1kWh/L for 700 bar H_2 at 15°C compared to 9 kWh/L for gasoline). In addition to energy density, hydrogen storage systems face challenges related to cost, durability/operability, charge/discharge rates, fuel quality, efficiency, and safety, which may limit widespread commercialization of hydrogen vehicles. Although hydrogen storage systems have shown continuous improvement since 2005 and many targets have been met in isolation, further advancements are needed to meet all of the performance targets simultaneously.

Hydrogen storage activities within the U.S. DRIVE Partnership, in conjunction with the DOE's Fuel Cell Technologies Office in the Office of Energy Efficiency and Renewable Energy,[1] are focused on applied research and development (R&D) of technologies that can achieve a driving range greater than 300 miles (500 km) for the full span of light-duty vehicles, while meeting packaging, cost, safety, and performance requirements. Such technologies, incorporated within a fuel cell vehicle, would be competitive with incumbent vehicle technologies. From conventional vehicle data, the driving range of 300 miles has been identified as the minimum entry point for the market. In comparison, hydrogen vehicles in DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project had an Environmental Protection Agency (EPA) adjusted driving range from 100 miles (Generation 1 observed minimum) to 250 miles (Generation 2 observed maximum).[2] However, there have been examples of fuel cell demonstration vehicles that have approached or exceeded the driving range target of 300 miles, even though significant effort regarding cost and packaging is still required to achieve commercial viability across various vehicle classes. Thus, it is clear that hydrogen storage systems must be improved in order to provide the customer with the expected driving range across all vehicle platforms.

2.1 Hydrogen Storage Technical Barriers

2.1.1 System Weight and Volume

The weight and volume of hydrogen storage systems are presently too high, resulting in inadequate driving range on a single fill compared to incumbent technologies. Storage media, containment vessels, and balance-of-plant components are needed that allow compact, lightweight, hydrogen storage systems while enabling a driving range greater than 300 miles.

2.1.2 System Cost

The cost of hydrogen storage systems is significantly higher than fuel systems on gasoline-powered vehicles. This implies the need for low-cost hydrogen storage system designs, materials, and high-volume manufacturing methods.

2.1.3 Fuel Cost as Related to the Storage System

Each considered hydrogen storage technology has a unique and significant impact on the delivered cost of hydrogen. These costs must be taken into account in assessing storage system performance relative to program goals. Compression and the cascade storage system currently comprise over half the expense for a station delivering high pressure (700 bar) hydrogen gas, adding over $1.00/kg to the cost of delivered hydrogen.[3] A low pressure, room temperature storage technology would lower costs at the forecourt and minimize capital investment required for compression and heat transfer. Sorbent systems currently under development will increase fuel costs due to the need to cool hydrogen to liquid nitrogen temperatures. At present, most chemical storage systems incur unacceptable fuel costs due to the complexity of rehydrogenation of the hydrogen carrier materials.

2.1.4 Efficiency

Energy efficiency is a challenge for all advanced hydrogen storage approaches. In particular, the energy associated with absorption/adsorption and desorption of hydrogen in the storage media is an issue for all options other than compressed gas and chemical storage systems. Life-cycle energy efficiency may be a challenge for chemical hydrogen storage technologies in which the spent media and by-products are regenerated off-board. Likewise, the energy associated with the compression and liquefaction of hydrogen must be considered for hydrogen technologies, which use these approaches. In addition, thermal management for charging and releasing hydrogen from the storage system needs to be optimized to increase overall efficiency for all hydrogen storage approaches.

2.1.5 Durability/Operability

Durability of hydrogen storage systems needs improvement and verification. Storage media, containment vessels, and balance-of-plant components are needed that enable hydrogen storage systems with acceptable lifetimes and consistent performance over the expected operating cycles and temperatures.

2.1.6 Charging/Discharging Rates

In general, and especially for material-based approaches, hydrogen refueling times tend to be longer than those for conventional fuels (at least several minutes to refuel 5 kg of H_2). Thermal management that enables rapid refueling is a critical issue that must be addressed. Also, the storage system must be able to supply a sufficient flow rate of hydrogen to the power plant to meet the required power demand at acceptable pressures and temperatures under all driving conditions.

2.1.7 Fuel Quality

The storage system must reliably provide hydrogen at applicable fuel quality standards, within the power plant's inlet specifications of temperature, pressure, and flow rate. For material-based storage approaches, the storage system must be able to be charged with and deliver contaminant-free hydrogen that also meets the applicable fuel quality standards.

2.1.8 Environmental, Health & Safety

Applicable codes and standards for hydrogen storage systems and interface technologies, which will facilitate implementation/commercialization and assure safety and public acceptance, are being established for automotive applications. Standardized certification and regulation test methods are required for all hydrogen storage technologies.

3. Technical Targets and Current Status

3.1 Technical Targets

Table 1 shows the 2017 and "Ultimate Full Fleet" technical targets for onboard hydrogen storage systems. The "Ultimate Full Fleet" or ultimate set of targets are intended to make hydrogen-fueled vehicle platforms competitive across the majority of the vehicle classes (from small cars to light-duty trucks) and achieve significant market penetration.

The majority of these targets were originally established in 2003 through the FreedomCAR Partnership between DOE and the U.S. Council for Automotive Research (USCAR). Since then, they have been periodically reviewed and updated based on technology assessments to ensure continued alignment with market driven requirements. In 2012, an additional Partnership-level research target of $10/kWh by the year 2020 was established as the hydrogen storage system cost target.

All of the targets are subject to change as more is learned about system level requirements, as tradeoffs between targets are explored, and as fuel cell and hydrogen storage technologies progress. The basis for each target is explained in further detail in the DOE document, *Targets for Onboard Hydrogen Storage Systems for Light-Duty Vehicles*.[4]

Table 1. Technical System Targets: Onboard Hydrogen Storage for Light-Duty Fuel Cell Vehicles[a]

Storage Parameter	Units	2017	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass) [b]	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) [b]	kWh/L (kg H_2/L system)	1.3 (0.040)	2.3 (0.070)
Storage System Cost:	$/kWh net ($/kg H_2)	12 400	8 266
- 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)	Cycles	1,500	1,500
- Min delivery pressure from storage system	bar (abs)	5	3
- Max delivery pressure from storage system	bar (abs)	12	12
- Onboard efficiency [e]	%	90	90
- "Well" to powerplant efficiency [e]	%	60	60
Charging/Discharging Rates:			
- System fill time (5 kg)	min (kg H_2/min)	3.3 (1.5)	2.5 (2.0)
- Minimum full flow rate	(g/s)/kW	0.02	0.02
- Start time to full flow (20°C)	s	5	5
- Start time to full flow (-20°C)	s	15	15
- Transient response at operating temperature 10-90% and 90-0%	s	0.75	0.75
Fuel Quality (H_2 from storage): [f]	% H_2	SAE J2719 and ISO/PDTS 14687-2 (99.97% dry basis)	

Table 1. (Cont.)

Storage Parameter	Units	2017	Ultimate
Environmental Health & Safety: • Permeation & leakage [g] • Toxicity • Safety	 - - -	Meets or exceeds applicable standards	
Loss of Useable H_2: [h]	(g/h)/kg H_2 stored	0.05	0.05

Note: Useful constants: 0.2778 kWh/MJ; lower heating value for H_2 is 33.3 kWh/kg H_2; 1 kg H_2 ≈ 1 gal gasoline equivalent (gge).

Footnotes to Target Table:

[a] Targets are based on the lower heating value of hydrogen, 33.3 kWh/kg H_2. Targets are for a complete system, including tank, material, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and all other balance-of-plant components. All capacities are defined as useable capacities that could be delivered to the fuel cell power plant. All targets must be met at the end of service life (approximately 1,500 cycles or 5,000 operation hours, equivalent of 150,000 miles).

[b] Capacities are defined as the useable quantity of hydrogen deliverable to the powerplant divided by the total mass/volume of the complete storage system, including all stored hydrogen, media, reactants (e.g., water for hydrolysis-based systems), and system components. Capacities must be met at end of service life. Tank designs that are conformable and have the ability to be efficiently package onboard vehicles may be beneficial even if they do not meet the full volumetric capacity targets.

[c] Hydrogen threshold fuel cost is independent of pathway and is defined as the untaxed cost of hydrogen produced, delivered, and dispensed to the vehicle [http://hydrogen.energy.gov/pdfs/11007_h2_threshold_costs.pdf]. For material-based storage technologies, the impact of the technology on the hydrogen threshold fuel cost (e.g., off-board cooling, off-board regeneration of chemical hydrogen storage materials, etc.) must be taken into account.

[d] Stated ambient temperature plus full solar load (i.e., full exposure to direct sunlight). No allowable performance degradation from -20°C to 40°C. Allowable degradation outside these limits is to be determined.

[e] Onboard efficiency is the energy efficiency for delivering hydrogen from the storage system to the fuel cell powerplant, i.e., accounting for any energy required operating pumps, blowers, compressors, heating, etc. required for hydrogen release. Well-to-powerplant efficiency includes onboard efficiency plus off-board efficiency, i.e., accounting for the energy efficiency of hydrogen production, delivery, liquefaction, compression, dispensing, regeneration of chemical hydrogen storage materials, etc. as appropriate. H2A and HDSAM analyses should be used for projecting off-board efficiencies.

[f] Hydrogen storage systems must be able to deliver hydrogen meeting acceptable hydrogen quality standards for fuel cell vehicles (see SAE J2719 and ISO/PDTS 14687-2). Note that some storage technologies may produce contaminants for which effects are unknown and not addressed by the published standards; these will be addressed by system engineering design on a case-by-case basis as more information becomes available.

[g] Total hydrogen lost into the environment as H_2; relates to hydrogen accumulation in enclosed spaces. Storage system must comply with applicable standards for vehicular tanks including but not limited to SAE J2579 and the United Nations Global Technical Regulation. This includes any coating or enclosure that incorporates the envelope of the storage system.

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

3.2 Current Status

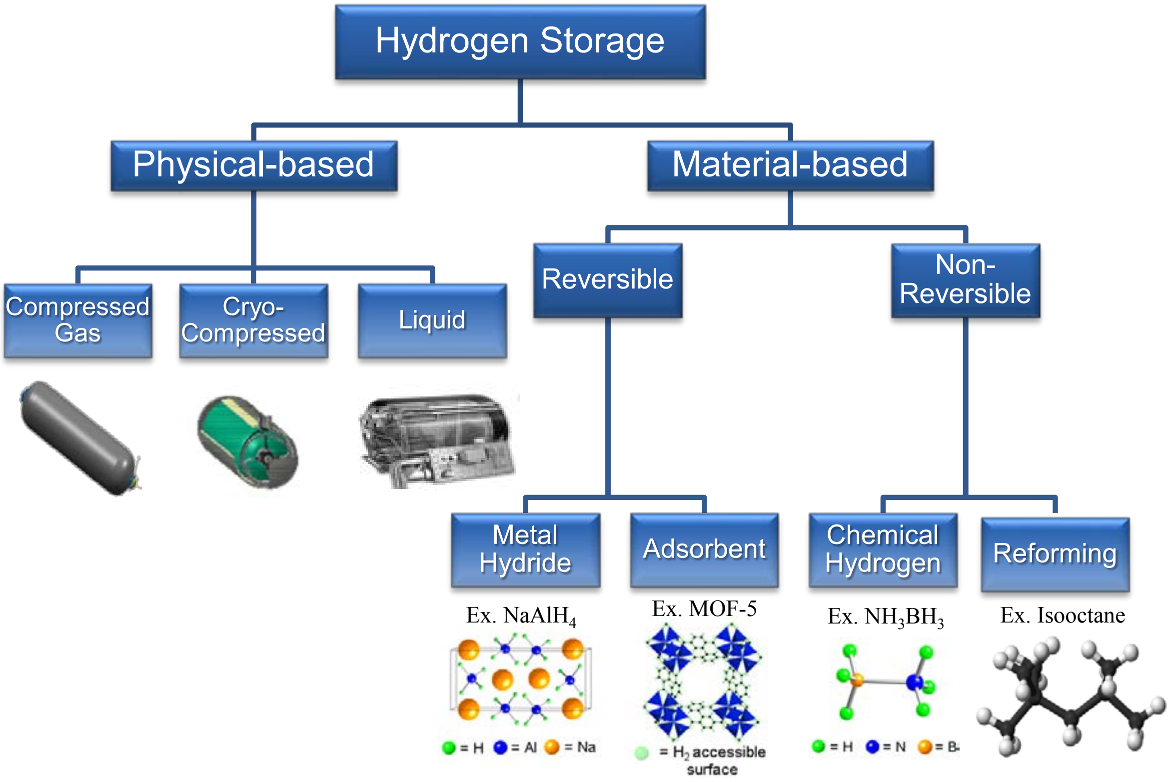


Figure 1. Potential Hydrogen Storage Technologies

3.2.1 Physical-Based Storage

The current near-term technology for onboard automotive hydrogen storage is 350 and 700 bar (5,000 and 10,000 psi, respectively) nominal working-pressure compressed vessels (i.e., “tanks”). Compressed gas storage systems have been demonstrated in hundreds of prototype fuel cell vehicles and are commercially available at low production volumes. The tanks within these systems have been certified worldwide according to ISO 11439 (Europe), ANSI/AGA NGV2 (U.S.), and Reijikijun Betten (Iceland) standards, and approved by TUV (Germany) and KHK (Japan). The United Nations is in the process of releasing a Global Technical Regulation that will unify the regulation requirements of these systems based on the guidance from SAE J2579 hydrogen system standard.

While compressed hydrogen storage is typically at ambient temperatures, cold (i.e., sub-ambient but greater than 150 K: cold-compressed) and cryogenic (i.e., 150 K and below: cryo-compressed) compressed hydrogen storage is also being investigated due to the higher hydrogen densities achievable. Finally, another physical-based hydrogen storage approach is the cryogenic liquid hydrogen system that has also been demonstrated on vehicles in lower numbers. While these systems exhibit higher hydrogen densities, their overall system densities are reduced due to the need for insulation and the boil-off and venting that occurs from extended dormancy.

3.2.2 Material-Based Storage

Currently, material-based storage technologies include metal hydrides, sorbent-based materials, and chemical hydrogen storage materials. Complex and conventional metal hydrides store hydrogen in solid form where hydrogen atoms are chemically bonded to other metal or semimetal atoms through ionic, covalent, or metallic-type bonds. All sorbents, such as micro-porous activated carbons or metal-organic frameworks (MOF), generally share a common mechanism of utilizing the weak van der Waals bonding between molecular hydrogen and the sorbent (on the order of 1 to 10 kJ/mol H_2 for most sorbents), which results in the need for storage temperatures at or near that of liquid nitrogen (77 K). A third class of hydrogen storage materials are chemical hydrogen storage materials, which have the potential to contain large quantities of hydrogen by mass and volume on a material basis and can be prepared in either a solid or liquid form. These materials can be heated directly, passed through a catalyst-containing reactor, or combined with water (i.e., hydrolysis) or other reactants to produce hydrogen.

In 2005, the DOE's Fuel Cell Technologies Office initiated three Centers of Excellence[5,6,7] that focused on developing advanced hydrogen storage materials capable of meeting the DOE hydrogen storage system-level performance targets. While significant progress was made across each material-based technology, none currently satisfy all of the stringent performance requirements for light-duty vehicles.

DOE has also identified several material-based approaches that were deemed unlikely to achieve the performance targets, including onboard reforming,[8] hydrogen storage via hydrolysis of sodium borohydride,[9] hydrolysis of aluminum metal and alloys,[10] and adsorption by undoped single-wall carbon nanotubes.[11] Further research in these areas was suspended or not initiated. The technical assessments of these technologies as made by DOE are publicly available via the sources noted above.

3.2.3 Projected Systems

The projected performance and cost status of hydrogen storage systems currently in development are shown in Table 2. Although the gravimetric and volumetric capacities, along with cost, are used to demonstrate the performance status, there are 21 specific onboard storage targets (see Table 1 for specific list of targets) that must be met simultaneously in order to make hydrogen storage systems competitive with incumbent technologies. The current projected performance estimates were provided by technology developers and the R&D community, and they assume a storage capacity of 5.6 kg of usable hydrogen. Because it is challenging to estimate system-level weights and volumes when research is still at the material development stage, the current status for each type of system will be revisited and updated periodically.

A recently published analysis[12] documents that neither the 350 bar nor 700 bar compressed gas tanks can meet both the 2017 gravimetric and volumetric capacity targets. Only cryo-compressed storage is predicted to meet the gravimetric and volumetric targets for 2017, yet this technology still cannot meet all 21 targets, such as the loss of useable hydrogen and the "well" to powerplant efficiency targets. In addition, no physical storage systems are currently projected to meet the cost targets presented in Table 1. Overall, there are significant gaps between the performance of current systems and the Ultimate gravimetric, volumetric, and system cost targets. For instance, while progress has been made developing and demonstrating materials with gravimetric capacities exceeding 5.5 wt.%, the 2017 and Ultimate targets are system-level targets that include the material, tank, and all balance-of-plant components of the storage system. As a result, analyses and engineering efforts have shown that in order to meet the system-level targets, the gravimetric capacity of the material may need to be about twice that of the system-level target.[13] It should also be noted that the system-level data includes the contributions of hydrogen or hydrogen media in both the cost and mass projections.

Table 2. Projected Performance of Hydrogen Storage Systems [a]

Hydrogen Storage System	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Cost ($/kWh; projected to 500,000 units/yr)
700 bar compressed (Type IV) [b]	1.7	0.9	19
350 bar compressed (Type IV) [b]	1.8	0.6	16
Cryo-compressed (276 bar) [b]	1.9	1.4	12
Metal hydride ($NaAlH_4$) [c]	0.4	0.4	TBD
Sorbent (AX-21 carbon, 200 bar) [c]	1.3	0.8	TBD
Chemical hydrogen storage (AB-liquid) [c]	1.3	1.1	TBD
2017 Target Values	1.8	1.3	12
Ultimate Target Values	2.5	2.3	8

Footnotes to Status Table:

[a] Assumes a storage capacity of 5.6 kg of usable H_2.

[b] Based on Argonne National Laboratory performance and TIAX cost projections.[14]

[c] Based on Hydrogen Storage Engineering Center of Excellence performance projections.[15]

The onboard hydrogen storage system can also have implications off-board the vehicle that are not typically reflected in the onboard cost and performance analyses. For instance, in order for a 700 bar compressed onboard hydrogen storage to achieve the 2017 target refill time of 3.3 minutes, precooling of the hydrogen down to a range of -20 to -40 °C at the forecourt will be required.[16] In the case of reversible metal hydrides and sorbent systems, hydrogen refueling involves an exothermic bonding of hydrogen to the solid phase material. The generated heat will have to be removed, typically involving off-board cooling equipment. In the case of chemical hydrogen storage materials, the spent dehydrogenated material will need to be removed from the vehicle and likely stored at the forecourt for transport to a facility for regeneration back to hydrogenated fuel. When assessing onboard storage technologies, delivery and forecourt implications, including associated costs and technical challenges, will need to be addressed as well.

The projected performance of the materials-based storage systems in Table 2 was determined from detailed storage system models developed by the Hydrogen Storage Engineering Center of Excellence (HSECoE).[17] The DOE established the HSECoE in 2009 to advance the development of material-based hydrogen storage systems for hydrogen-fueled light-duty vehicles. The focus of the HSECoE is to develop complete, integrated system concepts that utilize condensed-phase materials as the primary hydrogen storage media (i.e., reversible metal hydrides, chemical hydrogen storage materials, and sorbents) and advanced engineering concepts and designs that can simultaneously meet or exceed all the DOE targets.

3.2.4 Demonstrated Systems

Several material-based hydrogen storage systems have also been demonstrated in the laboratory or on prototype vehicles. Examples of these systems that have been published within the past decade are given in Table 3. The quantity of hydrogen stored in laboratory tests was usually less than required for most light-duty passenger vehicles and not all operational parameters were evaluated.

Table 3. Summary of Demonstrations of Materials-based Hydrogen Storage Systems

Research Organization	Mass of H_2 (kg)	Storage Technology	Demonstration Platform	Country	Year Reported	Reference
Ovonic	3.00	Metal hydride (AB_2) & 100 bar H_2 gas	Laboratory & prototype passenger cars	USA	2004	18
Millennium Cell & Chrysler	10.60	Hydrolysis ($NaBH_4$)	Passenger car	USA	2002	19
Ergenics	14.00	Metal hydride (AB_2) & 15 bar H_2 gas	Laboratory & mine loader	USA	2006	20
Toyota	1.25	Metal hydride (bcc-AB) & 350 bar H_2 gas	Laboratory	Japan	2010	21
CNRS	0.10	Metal hydride (MgH_2)	Laboratory	France	2011	22
United Technologies Research Center	0.45	Metal hydride ($NaAlH_4$)	Laboratory	USA	2007	23
HZG	0.30	Metal hydride ($NaAlH_4$)	Laboratory	Germany	2012	24
Sandia National Lab & General Motors	3.00	Metal hydride ($NaAlH_4$)	Laboratory	USA	2011	25
U. Birmingham & EMPA	4.00	Metal hydride (AB_2)	Canal boat	England & Switzerland	2011	26
TU Munchen & UTR	0.70	Cryo-adsorption activated carbon	Laboratory	Germany / Canada	2010	27

Through DOE's Technology Validation activities, 183 hydrogen fuel cell vehicles were demonstrated. Of those 183 vehicles, the 51 vehicles using 700 bar tanks for hydrogen storage approached an average driving range of 250 miles (on-road data, corrected for the EPA drive cycle). The 350 and 700 bar tank technologies used in these vehicles demonstrated hydrogen storage densities between 2.8 and 4.4 wt.% and 17 to 25 g/L.[28] Table 4 lists several makes and models of fuel cell vehicles, along with select associated hydrogen storage system metrics, that have been developed for either limited public use or as a concept demonstration vehicles. The table was filtered based on three criteria including functioning vehicles (not concepts), relevance (post-2005), and those vehicles with viable references directly through an original equipment manufacturer (OEM) source. Table 4 highlights the hydrogen storage and range challenge as the chassis type reduces in size from a SUV to a subcompact car. Such data is periodically updated as vehicles are publically disclosed and certified by OEMs. Although the power plants of the vehicles are different, it should be noted that vehicle fuel economy is expected to increase with advancements in fuel cell performance, battery technology, and vehicle architecture including mass reduction.

Table 4. Examples of Onboard Hydrogen Storage Systems

Fuel Cell Vehicle	Storage Technology	Chassis Style	Curb Weight (kg)	Useable [a] Mass of H_2 Stored (kg)	Fuel Economy in miles/ kg H_2 (city/ hwy) [b]	Driving Range (miles)	Latest Reference Year	Vehicle & Storage Reference	FE/ Driving Range Reference
Design Level: Publically Operated (multiple vehicles built and certified unites provided to customers)									
Mercedes-Benz F-Cell	700 bar	Subcompact car	1,809	3.7	52/53	190	2012	OEM [29]	EPA
Ford Focus	350 bar	Compact car	1,600	4.0	48/53	200	2006	OEM [30]	EPA
Honda Clarity	350 bar	Mid-size car	1,625	3.9	60/60	240	2012	OEM [31]	EPA
Hyundai Tucson-ix35	700 bar	Compact SUV	1,830	5.4	65	351	2013	OEM [32]	Est./OEM[32]
Chevrolet Equinox	700 bar	Compact SUV	2,010	4.2	47 [c]	199	2007	OEM [33]	Est./OEM[33]
Nissan X-trail	350 bar	Compact SUV	1,790	No ref.	No ref.	229	2006	OEM [34]	OEM[3434]
Kia Borrego	700 bar	Full-size SUV	2,300	7.8	60 [c]	470	2010	OEM[32]	Est./OEM[32]
Toyota Highlander FCHV-adv	700 bar	Full-size SUV	1,880	6.0	58 [c]	350	2011	OEM [35]	Est./OEM[35]
Design Level: Concept Demonstration (at least a single functional vehicle representative of a future product)									
Honda FCX V4	350 bar	Subcompact car	1,680	3.5	62/51	190	2005	OEM [36]	EPA
Ford Focus	700 bar	Compact car	1,600	5.0	48/53	250	2010	OEM[30]	EPA
VW Tiguan HyMotion	700 bar	Compact SUV	1,870	3.2	44 [c]	142	2007	OEM [37]	OEM
Chevrolet Sequel	700 bar	Full-size SUV	2,170	7.7	39 [c]	300	2007	OEM[33] [33]	Est./OEM[33]
Ford Explorer	700 bar	Full-size SUV	2,560	9.5	40	380 [d]	2011	OEM [38]	OEM[38] /Est.

Footnotes to Status Table:

SUV = sport utility vehicle, FE = Fuel Economy.

[a] Useable capacity was calculated if the total volume or capacity was indicated.

[b] Fuel economy can vary based on test method and real-world conditions.

[c] Fuel economy was estimated based on range reference and useable capacity.

[d] Driving range was estimated based on fuel economy reference and useable capacity.

4. Gaps and Technical Barriers

4.1 Physical Hydrogen Storage Systems (Including Compressed, Cold /Cryo-compressed, and Liquid)

Hydrogen storage systems based on the physical containment of hydrogen as a compressed gas or as a liquid have been demonstrated that can meet many of the 2017 targets, such as the operating temperature range, cycle life, delivery pressure, and refill rates. However, neither liquid based nor compressed systems (including cold/cryo-compressed tanks) currently meet the system cost targets, which is a crucial gap for the automotive industry. In addition, most of these systems do not meet the system level gravimetric and volumetric hydrogen capacity targets. These gaps are small, but they are still a significant challenge since further reductions in mass or volume will not be easily attained. For cryogenic systems, the loss of usable hydrogen during dormancy is also a key challenge. Finally, liquefying or compressing hydrogen requires a significant amount of energy, resulting in a gap to meeting the energy efficiency targets.[39]

4.2 Metal Hydride Hydrogen Storage Systems

For many metal hydrides, the system mass and volume are excessive. Hydrogen containment and release are typically accompanied by heat effects due to the enthalpy changes associated with the hydrogenation/dehydrogenation reactions. Since hydrides are often electrical and thermal insulators, a heat transfer system, material modification, or both are required to achieve sufficient hydrogen uptake resulting in an increase in the system's cost, mass, and volume. Additionally, hydrides can also undergo a significant reduction in particle size, resulting in densely packed powders in the discharged state and in turn, causing excessive force on walls as the hydride is re-formed during charging. These systems undergo chemical reactions and/or phase transitions during hydride formation, so the rate of hydrogen uptake will be slower relative to filling a compressed gas tank. Finally, if the enthalpy of dehydrogenation is high, then not only will the system operating temperature be high, but a significant amount of hydrogen will have to be burned to provide heat necessary to release hydrogen. Likewise, materials having large enthalpies of hydrogen absorption will liberate large quantities of heat during refueling. The removal of this extraneous heat will require connecting the vehicle's storage system to external, high-capacity heat exchangers at the refueling station to complete a hydrogen refill within the desired fueling time.

4.3 Sorbent-Based Hydrogen Storage Systems

As a result of the low binding energy and the need to operate near cyrogenic temperatures, most sorbent-based systems are configured in a similar manner as cryo-compressed systems, although typically at lower operating pressures. Generally, the sorbent material is contained within a pressurized tank surrounded by a multi-layer vacuum insulation. The hydrogen is typically released by reducing pressure and applying heat for the endothermic desorption. High surface area materials that have been studied for onboard hydrogen storage have shown favorable results for hydrogen uptake at moderate pressures, kinetics, purity, and reversibility at 77 K. Despite these promising characteristics, sorbent-based hydrogen storage has barriers similar to cryo-compressed tanks, such as system cost and loss of useable hydrogen during dormancy. Compression and cooling requirements will also lead to efficiency losses and higher hydrogen costs.

4.4 Chemical Hydrogen Storage Systems

Unlike the other hydrogen storage methods, chemical hydrogen storage systems must be regenerated off-board the vehicle. In liquid form, these systems can be designed to operate like a conventional gasoline fuel system using low pressure liquid tanks and pumps. The challenge for these systems is the additional complexity of managing the dehydrogenation reactors (i.e., exothermic or endothermic materials), removing impurities from the hydrogen supply, and the transport of material (i.e., viscosity and flocculation) throughout the system. In addition, the off-board regeneration of the hydrogen carrier material leads to efficiency losses and higher hydrogen costs.

Table 5 shows the major barriers for each type of storage system currently envisioned and additional details regarding each barrier follows. In addition, Appendix A contains examples of strategies that will be pursued to overcome each of the barriers outlined below.

Table 5. Existing Barriers for Potential Hydrogen Storage Systems

	Physical-Based Storage Systems			Material-Based Storage Systems		
Barrier	**Compressed**	**Cold / Cryo-Compressed**	**Liquid**	**Metal Hydride Storage Systems**	**Sorbent-Based Storage Systems**	**Chemical Hydrogen Storage Systems**
A) Materials of Construction	•	•	•	•	•	•
B) Balance-of-Plant Cost	•	•	•	•	•	•
C) Thermal Management		•	•	•	•	•
D) Tank Cost	•	•	•	•	•	
E) Tank Mass	•	•		•	•	
F) Off-board Energy Efficiency		•	•		•	•
G) Heat Transfer Systems				•	•	•
H) Material Gravimetric Capacity				•	•	•
I) Material Volumetric Capacity				•	•	•
J) Reaction Thermodynamics				•	•	•
K) Cryogenic Tank Operation		•	•		•	
L) High Temperature Tank Operation				•		•
M) Carbon Fiber Cost	•	•				
N) Material Thermal Conductivity				•	•	
O) Fuel Purity				•		•
P) Kinetics				•		•
Q) Reactor Design						•
R) Material Handling						•

In more detail, the barriers for all types of hydrogen storage systems are:

a) Materials of Construction: The weight, volume, performance, operating temperature, and cost constraints limit the choice of construction materials and fabrication techniques for high-pressure containment of compressed hydrogen and other hydrogen storage approaches. In addition, the materials of construction must be resistant to hydrogen embrittlement, permeation, and corrosion for all approaches. Research into new materials such as improved resins, engineered carbon fibers, and metallic, ceramic, and/or polymer composites are needed to meet cost targets without compromising performance. These materials also should be compatible with joining and sealing processing without impacting either manufacturing cost or system reliability.

b) Balance-of-Plant Cost: The balance-of-plant cost is often underestimated. The cost for valves, piping, and safety equipment is often a significant contributor to the system cost, even at high volumes, due to the specialized materials needed to manage moderate or high pressures of hydrogen. Hydrogen embrittlement is a concern for many metals, and those metals that are less susceptible (e.g., high alloy steel) are typically more expensive. The sheer part count in the balance-of-plant also adds to the assembly cost and raises reliability and durability issues.

c) Thermal Management: For many hydrogen storage options, including cryogenic and materials-based systems, thermal management is a key issue. In general, the main technical challenge for compressed gas and onboard reversible material systems is efficient heat removal during refueling to allow a complete hydrogen refill within the desired fueling time. Onboard reversible material systems also typically require heat to release hydrogen. In this case, heat (preferably using waste heat from the fuel cell) must be provided to the storage media at reasonable temperatures to meet the flow rates needed by the power plant. Finally, chemical hydrogen storage systems, depending upon the chemistry, are often exothermic upon release of hydrogen, or optimally thermoneutral. Thus, exothermic systems will also require heat rejection during operation.

d) Tank Cost: The manufacturing cost of high pressure tanks is significant. The cost is typically driven by high material costs (e.g., carbon fiber for Type II, III and IV tanks), complex manufacturing processes with specialized equipment, low volume techniques, and regulatory compliance.

e) Tank Mass: For current designs, the mass of the tank required to withstand the pressure and temperature of normal operation, fueling, and environmental stresses is too high to allow the total system to meet the gravimetric capacity target.

f) Off-board Energy Efficiency: The energy efficiency of the entire system is often strongly influenced by the energy required to produce and deliver the hydrogen. For example, precooling and compression of hydrogen is 10%–15% of the total energy in compressed hydrogen.[3,36] Energy for liquefaction of hydrogen can require 25% of the energy in the liquefied hydrogen itself. [36,40] Off-board regeneration of certain chemical hydrogen storage materials may require significant energy in both heat and electricity.

g) Heat Transfer Systems: Heat transfer systems needed to add or remove heat from storage systems add cost due to materials and manufacturing complexity. The heat transfer systems must be efficient and meet the strict onboard energy efficiency targets for the storage system. For example, sorbents and metal hydride materials typically have low thermal conductivity, so these systems require effective approaches to manage the heat of adsorption/absorption during fueling and desorption.

h) Material Gravimetric Capacity: The gravimetric capacity of hydrogen storage material is critical. The material capacity must exceed the gravimetric system targets in order to meet the total material-based hydrogen storage system target. If the target is not met, additional vehicle reinforcements could be required, further increasing the overall weight of the vehicle.

i) Material Volumetric Capacity: Due to low material densities, sorbent-based materials generally have lower hydrogen volumetric capacities. While the volumetric capacity can be improved through compaction of the sorbent material, compaction can lead to increases in manufacturing costs, and reductions in the surface area and gravimetric capacity of the material. Although the hydrogen volumetric densities can be high for metal hydrides,[41] practical issues related to volume expansion/compression can reduce effective densities up to 40-60% of theoretical values. Using chemical hydrogen storage materials as solutions or slurries will reduce volumetric densities in a similar fashion.

j) Reaction Thermodynamics: The enthalpy of reaction is the change in energy between the initial and final states. It therefore relates to the amount of heat that needs to be added or removed during hydrogen release or charging of a material. The release of hydrogen from most sorbents and reversible metal hydrides is endothermic (i.e., requires an input of energy), while for chemical hydrogen storage materials, hydrogen release might be endothermic (e.g., alane) or exothermic (e.g., ammonia borane). High reaction enthalpies for materials with endothermic hydrogen release are deleterious since they require greater heat rejection during charging and may require consumption of some of the stored hydrogen to provide the energy for release. This reduces the onboard efficiency and also requires more effective thermal management structures within the system. For current hydrogen sorbents, the reaction enthalpy (commonly referred to as binding energy or heat of adsorption), is too low, thus requiring cryogenic temperatures to achieve significant adsorbed capacities. Sorbent materials with higher heat of hydrogen adsorption are required to avoid cryogenic operation.

k) Cryogenic Tank Operation: Cryogenic tanks must withstand extremely cold temperatures, allow only trivial heat transfer, and tolerate occasional large temperature swings from relatively warm to extreme cold. These tanks must maintain these properties for the life of the tank, which can be a challenge for tanks insulated with vacuum jackets. In addition, these systems typically require instrumentation and other potential sources of heat conduction that penetrate the layers of the tank. To achieve low heat transfer, the system designs must have few penetrations and still perform all required functions.

l) High-Temperature Tank Operation: Tanks must be able to tolerate moderate to high temperatures based on the reaction temperature needed to release the hydrogen from a given hydrogen storage material. The tank components and materials must be inert to hydrogen at elevated operating temperatures and pressure.

m) Carbon Fiber Cost: High strength carbon fiber is expensive. Recent calculations show that carbon fiber is the most expensive component in high pressure compressed gas systems, accounting for up to 75% of the cost at high manufacturing volumes.[3,6] New feedstock and processing techniques are needed to reduce the cost of the carbon precursors by minimizing the capital cost and reducing the required processing energy.

Reductions in the cost of carbon fiber may also benefit metal hydride and sorbent based material systems depending upon their system pressure.

n) Material Thermal Conductivity: The need for heat transfer within the tanks of metal hydride or sorbent based systems can require the addition of material with high thermal conductivity or other heat transfer enhancement, such as metal fins. This adds mass, volume, and cost to the system, but can result in increased hydrogen uptake and refilling rates. These tradeoffs must be examined and balanced to find the optimal system.

o) Fuel Purity: For chemical hydrogen storage materials and some metal hydrides (e.g., amides and borohydrides), the presence of constituents that poison the fuel cell (e.g., ammonia or diborane) will require additional purification elements within the system if released with the hydrogen.

p) Kinetics: The rate at which hydrogen is stored or released can be determined by kinetics for absorption and desorption. The reactions in metal hydride materials are complex solid phase transformations, which may not be inherently fast and can be difficult to catalyze.

q) Reactor Design: Chemical hydrogen storage systems require reactor designs that control the temperature to avoid run away conditions (i.e., exothermic material) or to optimize the hydrogen release (i.e., endothermic material).

r) Material Handling: The handling of the bulk chemical hydrogen storage material within the system is important to achieve the required fueling rates and ensure the continuous transport of hydrogen storage material throughout the system at temperature extremes. Material handling issues include segmentation, flocculation, and stability for both the hydrogenated and dehydrogenated material.

5. R&D Strategy to Overcome Barriers and Achieve Technical Targets

Future hydrogen storage efforts will focus primarily on the research and development of onboard vehicular hydrogen storage systems that will allow for a commercially viable system that provides a driving range of 300 miles or more. There are specific 2017 and Ultimate Full-Fleet technical targets for a commercially viable system including: gravimetric, volumetric, and cost targets as indicated in Table 1. Storage approaches that will be pursued to achieve commercial viability with a driving range of at least 300 miles include ambient, cold, and cryogenic compressed gas tanks for near- to mid-term vehicles, and material-based storage and other advanced concepts for longer term vehicle applications (2020 and beyond). The near-, mid-, and long-term strategies are explain in greater detail below; in addition, Appendix A contains examples of specific strategies that will be pursued to overcome each of the barriers outlined in Section 4.

5.1 Near-Term Strategy

Ambient temperature compressed gas storage is currently the most mature storage technology for use onboard vehicles. At ambient temperatures, the density of hydrogen gas itself at 700 bar is approximately 40 g/L. Therefore, after factoring in the additional volume of the system, a 700 bar compressed ambient storage system is unable to meet either the 2017 or Ultimate system level storage targets of 40 g/L or 70 g/L, respectively. However, the technology has been used on most of the hydrogen fuel cell vehicles demonstrated to date, including 179 (51 at 700 bar and 128 at 350 bar) of the 183 vehicles that participated in DOE's Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project. In June of 2009, DOE confirmed an average driving range of up to 430 miles for two Toyota Fuel Cell Hybrid Vehicles (FCHV-adv) equipped with 700 bar pressure vessels.[42] This driving range was confirmed under "real-world" operating conditions; however, it should be noted that this vehicle may not necessarily be a commercially viable vehicle in terms of cost and packaging for all vehicle classes. Since this technology has the potential to achieve the driving range target, it is considered a promising near-term commercialization pathway.

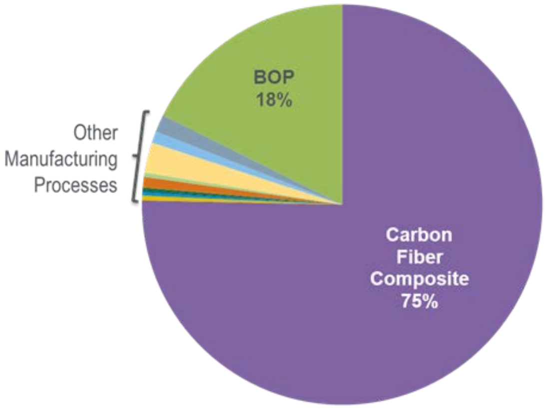


Figure 2. Percent Cost Breakdown of a 700-bar Type IV Hydrogen Storage System (Strategic Analysis 2012)

While limited improvements in these systems can be expected by reducing the weight and volume of balance-of-system components, the main strategy to advance this technology is to reduce the cost of high-pressure compressed gas vessels. TIAX LLC has estimated that the costs for current designs of complete 700 bar carbon fiber composite pressure vessel-based hydrogen storage systems, with a 5.6 kg useable capacity range, to be from $36 to $19/kWh for low (10,000 units per year) to high (500,000 units per year) volume manufacturing projections,[43] which corresponds to fuel systems costs of about $6,700 to $3,500 per vehicle, respectively. Analyses show that the cost of carbon fiber composite used in the high-pressure tanks dominates the total system cost (up to 75%). Therefore, the program will emphasize efforts to address the major costs elements of compressed gas systems. These efforts may include development of low-cost precursors for the production of high-strength carbon fiber, lower cost carbon fiber production processes, carbon fiber/resin modifications to increase overall composite strength, and identification of alternatives to carbon fiber. Research and analyses on improved and alternative tank designs will be pursued to reduce the amount of carbon fiber composite required to meet performance specifications. Additional cost reductions are expected to be achieved through advancements in tank liners, end bosses, and balance-of-plant components. An example of a potential strategy for reducing 700 bar compressed hydrogen system costs to achieve U.S. DRIVE metrics is illustrated in Figure 3.

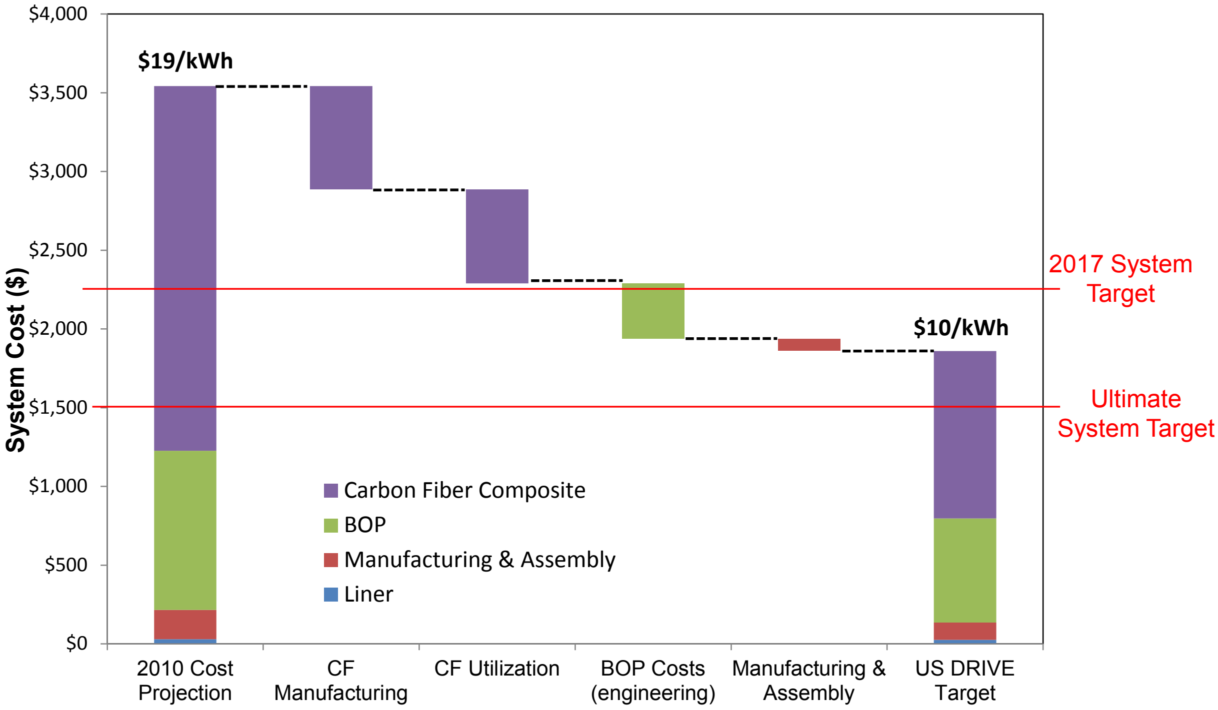


Figure 3. Potential Cost Reduction Strategy for Compressed Vessels to Meet the 2020 U.S. DRIVE Cost Target

5.2 Mid-Term Strategy

When the storage temperature of hydrogen is lowered, higher gas densities can be obtained. Therefore the concept of storing hydrogen at sub-ambient temperatures will be explored as a mid-term strategy to better meet DOE onboard storage targets. Work at Lawrence Livermore National Laboratory, with further analyses by Argonne National Laboratory and TIAX LLC, have indicated that cryo-compressed hydrogen storage systems have potential to meet the 2017 gravimetric and volumetric storage targets.[3,44] Cold-compressed hydrogen gas storage systems operating at temperatures that are sub-ambient, but not as low as cryogenic, e.g., -40 to -100°C, may also provide advantages over ambient temperature compressed gas storage without requiring either liquid hydrogen delivery or vacuum jacketed insulated vessels. Therefore, the potential of sub-ambient gas storage will be investigated over a range of storage temperatures, along with consideration of the impact that the storage temperature will have on the infrastructure requirements.

5.3 Long-Term Strategy

Advanced materials-based hydrogen storage technologies with potential to meet all DOE onboard vehicle hydrogen storage targets will be pursued for longer term application. From 2005 through 2010, the DOE funded three Centers of Excellence (CoE) to develop advanced materials — one center for each of reversible metal hydrides, hydrogen sorbents, and off-board regenerable chemical hydrogen storage materials.

Over the five-year life of the three CoEs,[4,5,6] millions of distinct material compositions and structures were investigated computationally with hundreds of new materials being experimentally synthesized and their hydrogen storage properties characterized. These efforts significantly increased the knowledge base of potential hydrogen storage materials. One identified need was to better understand the correlation between prospective material properties and complete system performance.

In 2009 a fourth CoE, the Hydrogen Storage Engineering Center of Excellence (HSECoE was established to carry out engineering-focused research and development of complete materials-based hydrogen storage systems for onboard automotive applications. Results from the HSECoE will be used to identify both materials and system engineering gaps between the state-of-the-art technology and the onboard storage targets. These efforts will allow determination of material-level properties required for a system to meet the performance targets, which will be used to guide material development efforts. Identified gaps, and potential failure modes of these systems and balance of plant components, will be used to guide the needed engineering efforts to progress these material-based approaches. In Phase I of the HSECoE, comprehensive system engineering analyses and assessments were made of the three classes of storage media to give direct comparisons against the DOE performance targets for light-duty vehicles as reported in Table 2. Phase II efforts are bench-level testing and evaluation of system configurations, including material packaging and balance-of-plant components, along with conceptual design validation. By the end of Phase II, detailed designs and component specifications for each subscale prototype of the integrated storage systems will be provided. Phase III will include fabrication and testing of the selected prototype storage system(s) for model validation and performance evaluation against DOE targets.

R&D strategies to advance longer term materials-based technologies to overcome the technical barriers and meet DOE onboard vehicle performance targets will also be pursued. Current projections[12] for reversible metal hydrides indicate that a material with an enthalpy sufficiently low to allow use of PEM fuel cell waste heat to provide the energy of desorption (i.e., approximately 25-30 kJ/mole of H_2) will need to have a gravimetric capacity of about 11 wt.% and much faster kinetics below 100°C than existing materials. Therefore, reversible metal hydride efforts will focus on identifying high capacity materials with low enthalpy and improving the sorption and desorption kinetics within relevant temperature ranges. Current cryogenic sorption materials cannot meet volumetric targets; therefore, efforts will be focused on improving the hydrogen volumetric storage density of these materials. Also, increasing their operational temperature closer to ambient would improve overall system performance. Chemical hydrogen storage materials that require off-board regeneration need to be maintained in a liquid phase throughout the hydrogenation/dehydrogenation cycle over the complete operating and ambient temperature range. Therefore, efforts on these materials will include focus on liquid-phase materials (i.e., liquids, solutions and slurries) with high hydrogen densities. Also, the regeneration costs and efficiencies need to be significantly improved over current state-of-the-art materials and processes.

5.4 Leveraging U.S. DRIVE Efforts

Whenever possible, the program will coordinate with other programs such as DOE's Vehicles Technologies Office, Advanced Manufacturing Office, Office of Science, and Advance Research Project Agency – Energy (ARPA-E); the Defense Advanced Research Project Agency (DARPA); and the National Aeronautics and Space Administration (NASA), to identify and leverage related activities. In addition, research and development activities are being carried out on hydrogen storage technologies for light-duty vehicles around the world. These efforts will continue to be leveraged to advance the U.S. DRIVE partnership efforts. Principal Investigators of key relevant R&D projects are encouraged to actively participate as "Technical Experts" in the International Energy Agency — Hydrogen Implementing Agreement (IEA-HIA) and International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) tasks. Participation in these organizations' events allow for regular exchange of information and formation of international collaborations relevant to U.S. DRIVE objectives. Participation at key conferences and establishment of formal and informal collaborations that are expected to benefit the U.S. DRIVE efforts are also encouraged. Finally, within the U.S. DRIVE Partnership, the Hydrogen Storage Technical Team interacts with several other technical teams where hydrogen storage targets and technology pathways are impacted by their analyses. These technical teams include Fuel Cells, Fuel Pathway Integration, Hydrogen Delivery, Hydrogen Production, Materials, and Hydrogen Codes and Standards Technical Teams.

Appendix A: Example Strategies to Overcome Existing Barriers

(Barriers Provided in Table 4)

Table 6a. Example Strategies to Overcome Existing Barriers for Physical Hydrogen Storage Systems

Barrier	Compressed	Cold & Cryo-Compressed
A) Materials of Construction	1) Metallic embrittlement qualification 2) Polymer permeation standardization 3) Advancement in sealing robustness 4) Compatible joining technology	1) Metallic embrittlement qualification 2) Qualification methods for cold or cyrogenic high pressure hydrogen 3) Advancement in sealing robustness 4) Compatible joining technology
B) Balance-of-Plant Cost	1) Low-cost metallic options 2) Polymer replacement of metals 3) Component reduction/integration 4) Standardization of components	1) Low-cost metallic options 2) Polymer replacement of metals 3) Component reduction/integration 4) Standardization of components
C) Thermal Management		1) Tank/BOP insulation 2) Heat exchanger 3) Tank conditioning during refuel
D) Tank Cost	1) Optimize carbon fiber/resin utilization 2) Alternative fibers 3) Enhance filament winding process 4) Liner alternatives 5) Boss design/interface considerations 6) Regulatory compliance screening/ optimization	1) Type III optimization of metal liner/carbon fiber/resin utilization 2) Insulation 3) Enhance filament winding process 4) Liner alternatives/manufacturing
E) Tank Mass	1) Optimize carbon fiber/resin utilization 2) Polymer replacement of metals 3) Liner alternatives 4) Boss design/interface considerations	1) Type III optimization of metal liner, carbon fiber, & resin utilization 2) Insulation 3) Liner alternatives
F) Off-board Energy Efficiency		1) Liquefaction/compression energy optimization
G) Heat Transfer Systems		
H) Material Gravimetric Capacity		
I) Material Volumetric Capacity		
J) Reaction Thermodynamics		
K) Cryogenic Tank Operation		1) Tank / BOP Insulation (vacuum jacketed tank) 2) Metal liner/carbon fiber thermal expansion cycling
L) High Temperature Tank Operation		

Table 6a. (Cont.)

Barrier	Compressed	Cold & Cryo-Compressed
M) Carbon Fiber Cost	1) New precursor feedstock 2) Revise precursor material/processing 3) Decrease carbon fiber capital cost 4) Optimize carbon fiber processing energy 5) Evaluate alternative fiber qualification methods	1) New precursor feedstock 2) Revise precursor material/processing 3) Decrease carbon fiber capital cost 4) Optimize carbon fiber processing energy 5) Evaluate alternative fiber qualification methods
N) Material Thermal Conductivity		
O) Fuel Purity		
P) Kinetics		
Q) Reactor Design		
R) Material Handling		

Table 6b. Example Strategies to Overcome Existing Barriers for Material-Based Hydrogen Storage Systems

Barrier	Metal Hydride Storage Systems	Sorbent-based Storage Systems	Chemical Hydrogen Storage Systems
A) Materials of Construction	1) Metallic embrittlement qualification 2) Compatible joining technology 3) Advancement in sealing robustness 4) Compatible joining technology	1) Metallic embrittlement qualification 2) Qualification methods for cold or cyrogenic high pressure hydrogen 3) Advancement in sealing robustness 4) Compatible joining technology	1) Corrosion resistant liners 2) Dual liquid containers with bladder isolation between source and spent fuel 3) Robustness to slurry residual
B) Balance-of-Plant Cost	1) Low-cost metallic options 2) Polymer replacement of metals 3) Component reduction / integration 4) Standardization of components	1) Low-cost metallic options 2) Polymer replacement of metals 3) Component reduction / integration 4) Standardization of components	1) Low-cost metallic options 2) Polymer replacement of metals 3) Component reduction / integration 4) Standardization of components
C) Thermal Management	1) Heat rejection during refueling 2) Fuel cell waste heat utilization 3) Internal cooling / heat tubes	1) Heat rejection during refueling 2) Fuel cell waste heat utilization 3) Internal cooling/heating tubes	1) Heat rejection during operation 2) Fuel cell waste heat utilization
D) Tank Cost	1) Optimize carbon fiber/resin utilization 2) Alternative fibers 3) Enhance filament winding process 4) Liner alternatives 5) Boss design/interface considerations 6) H_2 gravimetric density improvement	1) Move to lower pressure Type I tanks 2) H_2 volumetric density improvement	

Table 6b. (Cont.)			
Barrier	**Metal Hydride Storage Systems**	**Sorbent-based Storage Systems**	**Chemical Hydrogen Storage Systems**
E) Tank Mass	1) Type I to Type IV migration	1) Optimize carbon fiber / resin utilization 2) Polymer replacement of metals 3) Liner alternatives 4) Boss design/interface considerations 5) H_2 storage density improvement	
F) Off-board Energy Efficiency		1) Lower pressure operation to reduce compression requirements 2) Increase material / system operating temperature	1) Single step fuel regeneration of spent fuel
G) Heat Transfer Systems	1) Internal integrated heat exchanger	1) Internal integrated heat exchanger	1) Internal integrated heat exchanger
H) Material Gravimetric Capacity	1) Lighter Z metal hydride alloy development	1) High specific surface area adsorbents	1) Increase the solids loading of the carrier liquid
I) Material Volumetric Capacity	1) Optimize packing density of powders while accommodating volumetric changes between absorption /desorption without restricting H_2 gas permeation in beds	1) Increase in adsorbent packing density without restricting H_2 gas permeation in beds 2) Optimize micropore volume	1) Increase the solids loading of the carrier liquid
J) Reaction Thermodynamics	1) Reduce enthalpy to reduce operating temperature	1) Metal addition to increase isosteric enthalpy	1) Safety mechanisms to prevent thermal run-away for exothermic materials 2) Burning H_2 for endothermic materials

Table 6b. (Cont.)

Barrier	Metal Hydride Storage Systems	Sorbent-based Storage Systems	Chemical Hydrogen Storage Systems
K) Cryogenic Tank Operation		1) Electron backdonation to insure constant isosteric enthalpy 2) Efficient cooling to low temperature during refueling 3) Tank/BOP Insulation (vacuum jacketed tank)	
L) High Temperature Tank Operation	1) Elevated temperature inert tank component evaluation		1) Maintaining fuel & reaction products in liquid/ slurry phases using higher temp
M) Carbon Fiber Cost			
N) Material Thermal Conductivity	1) Novel heat exchangers 2) Heat transfer fluid	1) Exfoliated graphite additives 2) High conductivity metal foam /tube encasement	
O) Fuel Purity	1) Regenerable impurity (ammonia / borane) filters 2) Containment of volatile liquid organic compounds or solvents 3) Filters to prevent migration of particulates		1) Regenerable impurity (ammonia/borane) filters 2) Containment of volatile liquid organic compounds or solvents 3) Gas liquid separator
P) Kinetics	1) Catalyst additions 2) Shorten diffusion path		1) Catalyst additions 2) Integration of ballast tank in system
Q) Reactor Design			1) Design to accommodate pumping viscous slurries 2) Improved catalyst lifetimes

Table 6b. (Cont.)

Barrier	Metal Hydride Storage Systems	Sorbent-based Storage Systems	Chemical Hydrogen Storage Systems
R) Material Handling			1) Develop stable slurries / ionic liquids 2) Robust low temperature operation and freeze start performance

References

[1] Office of Energy Efficiency and Renewable Energy, "Fuel Cell Technologies Office," U.S. Department of Energy, http://www1.eere.energy.gov/hydrogenandfuelcells/.

[2] National Renewable Energy Laboratory, "Innovation for Our Energy Future," http://www.nrel.gov/hydrogen/docs/cdp/cdp_2.ppt.

[3] T.Q. Hua, R.K. Ahluwalia, J.-K. Peng, M. Kromer, S. Lasher, K. McKenney, K. Law, J. Sinha, "Technical assessment of compressed hydrogen storage tank systems for automotive applications," *Int. J. Hydrogen Energy* 36 (2011): 3037–3049.

[4] Office of Energy Efficiency and Renewable Energy, *Targets for Onboard Hydrogen Storage Systems for Light-Duty Vehicles*, U.S. Department of Energy, http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage_explanation.pdf.

[5] Lennie Klebanoff and Jay Keller, *Final Report for the DOE Metal Hydride Center of Excellence*, Sandia National Laboratory, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/metal_hydride_coe_final_report.pdf.

[6] Kevin Ott, *Final Report for the DOE Chemical Hydrogen Storage Center of Excellence*, Los Alamos National Laboratory, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/chemical_hydrogen_storage_coe_final_report.pdf.

[7] Lin Simpson, *Final Report for Hydrogen Sorption Center*, U.S. Department of Energy, prepared by Sandia National Laboratory (Golden, CO: Sandia National Laboratory, 2010), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/hydrogen_sorption_coe_final_report.pdf.

[8] Office of Energy Efficiency and Renewable Energy, *On-board Fuel Processing Go/No-go Decision*, U.S. Department of Energy, (Washington, DC: U.S. Department of Energy, 2004), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/committee_report.pdf.

[9] U.S. Departmen of Energy Hydrogen Program, *Go/No-Go Recommendation for Sodium Borohydride for Onboard Vehicular Hydrogen Storage*, prepared by Sandia National Laboratory (Golden, CO: Sandia National Laboratory, 2007), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/42220.pdf.

[10] J. Petrovic and G. Thomas, *Reaction of Aluminum with Water to Produce Hydrogen*, U.S. Department of Energy (Washington, DC: U.S. Department of Energy, 2010), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/aluminum_water_hydrogen.pdf.

[11] United States Department of Energy Hydrogen Program, *Go/No-Go Decision: Pure, Undoped Single Wall Carbon Nanotubes for Vehicular Hydrogen Storage* (Washington, DC: U.S. Department of Energy, 2006), http://www.hydrogen.energy.gov/pdfs/go_no_go_nanotubes.pdf.

[12] M.D. Paster, R.K. Ahluwalia, G. Berry, A. Elgowainy, S. Lasher, K. McKenney, M. Gardiner, "Hydrogen storage technology options for fuel cell vehicles: Well-to-wheel costs, energy efficiencies, and greenhouse gas emissions,"*Int. J. Hydrogen Energy* 36 (2011): 14534–14551.

[13] J.M. Pasini, C. Corgnale, B.A. van Hassel, T. Motyka, S. Kumar, K.L. Simmons, **“**Metal hydride material requirements for automotive hydrogen storage systems,” *Int. J. Hydrogen Energy* (Accepted).

[14] R.C. Bowman, Jr. and N.T. Stetson, “Onboard hydrogen storage systems: projected performance and cost parameters,” *DOE Hydrogen and Fuel Cells Program Record* (Washington, DC: U.S. Department of Energy, 2010), http://hydrogen.energy.gov/pdfs/9017_storage_performance.pdf.

[15] D.L. Anton, T. Motyka, B. Hardy, D. Tamburello, *Hydrogen Storage Engineering Center of Excellence (HSECoE),* U.S. Department of Energy, prepared by Savannah River National Laboratory (Aiken, SC: Savannah River National Laboratory, 2012), http://www.hydrogen.energy.gov/pdfs/progress12/iv_d_1_anton_2012.pdf.

[16] Jessie Schneider, *SAE J2601 - Worldwide Hydrogen Fueling Protocol: Status, Standardization & Implementation* (presentation, California Energy Commission workshop, Diamond Bar, California, July 10, 2012), http://www.energy.ca.gov/contracts/notices/2012-07-10_workshop/presentations/SAE_Jesse_Schneider_Fueling_Protocol.pdf.

[17] U.S. Department of Energy, “Hydrogen Storage Engineering Center of Excellence,” http://hsecoe.srs.gov/.

[18] B.S. Chao, R.C.Young, V. Myasnikov, Y. Li, B. Huang, F. Gingl, P.D. Ferro, V. Sobolev, S.R. Ovshinsky, “Recent Advances in Solid Hydrogen Storage Systems,” *Mat. Res. Soc. Symp. Proc.* 801 (2004): BB1.4.1.

[19] Ying Wu, “Development of Advanced Chemical Hydrogen Storage and Generation System” (presentation, Annual Merit Review Proceedings, May 23–25, 2004), http://www.hydrogen.energy.gov/pdfs/review05/stp_10_wu.pdf.

[20] A.R. Miller, D.H. DaCosta, M. Golben, “Reversible Metal-hydride Storage for a Fuel Cell Mine Loader” (presentation, Intertech’s Hydrogen Production & Storage Forum, Vancouver, Canada, September 11–13, 2006).

[21] K. Komiya, et al., “High-Pressure Hydrogen-Absorbing Alloy Tank for Fuel Cell Vehicles,” SAE International Publication 2010-01-0851, 2010, doi:10.4271/2010-01-0851.

[22] S. Garrier, A. Chaise, P. de Rango, P. Marty, B. Delhomme, D. Fruchart, S. Miragli, “MgH_2 intermediate scale tank tests under various experimental conditions,” *Int. J. Hydrogen Energy*, 36 (2011): 9719.

[23] D.A. Mosher, S. Arsenault, X. Tang, D.L. Anton, “Design, fabrication and testing of $NaAlH_4$ based hydrogen storage systems,” *J. Alloys Compounds* 446–447 (2007): 707.

[24] J.M. Bellosta von Colbe, et al., “Behavior of scaled-up sodium alanate hydrogen storage tanks during sorption,” *Int. J. Hydrogen Energy* 37 (2012): 2807.

[25] T. Johnson, S. Jorgensen, D. Dedrick, “Performance of a Full-Scale Hydrogen-Storage Tank Based on Complex Hydrides,” *Faraday Discuss.* 151 (2011): 327–352.

[26] A.I. Bevan, A. Zuettel, D. Book, I.R. Harris, “Performance of a metal hydride store on the ‘Ross Barlow’ hydrogen powered canal boat,” *Faraday Discuss.* 151 (2011): 353–367.

[27] R. Paggiaro, F. Michl, P. Benard, W. Polifke, "Cryo-adsorptive hydrogen storage on activated carbon. II: Investigation of the thermal effects during filling at cryogenic temperatures," *Int. J. Hydrogen Energy* 35 (2010): 648–659.

[28] K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, and G. Saur, *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*, NREL/TP-5600-54860, prepared by National Renewable Energy Laboratory (Golden, CO: National Renewable Energy Laboratory, 2012), http://www.nrel.gov/hydrogen/pdfs/54860.pdf.

[29] Mercedes-Benz USA LLC, "The B-Class with Fuel Cell Electric Drive Technology," http://www.mbusa.com/vcm/MB/DigitalAssets/pdfmb/green/f-cell.pdf.

[30] Mike Veenstra, "Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project" (presentation, Ford Motor Company, June 10, 2010), http://www.hydrogen.energy.gov/pdfs/review10/tv003_veenstra_2010_o_web.pdf.

[31] American Honda Motor Co., Inc., "FCX Clarity Specifications," http://automobiles.honda.com/fcx-clarity/specifications.aspx.

[32] Hyundai Motor America, "Press Release: Hyundai ix35 Fuel Cell," http://www.hyundainews.com/us/en-us/Media/PressRelease.aspx?mediaid=38232.

[33] U. Eberle and R. von Helmolt, "Sustainable transportation based on electric vehicle concepts: a brief overview," *Energy Environ. Sci.* 3 (2010): 689–699.

[34] Nissan Motor Co., Ltd., "Fuel Cell Vehicle X-TRAIL FCV," http://www.nissan-global.com/EN/DOCUMENT/PDF/ENVIRONMENT/TECHNOLOGY/en_xtail_fcv.pdf.

[35] Toyota Motor Corporation, "News Release: TOYOTA FCHV Makes Osaka-Tokyo Trip without Refueling," September 28, 2007, http://www.toyota.co.jp/en/news/07/0928.html.

[36] American Honda Motor Co., Inc., "The History of the Honda FCX Clarity, Fuel Cell Electric Vehicle FCEV," http://corporate.honda.com/environment/fuel_cells.aspx?id=fuel_cells_fcx.

[37] Volkswagen, "Hy-Motion-Touran/Tiguan," http://www.volkswagenag.com/content/vwcorp/content/en/innovation/research_vehicles/HyMotion.html.

[38] M. Veenstra, and B. Hobein, "On-Board Physical Based 70 MPa Hydrogen Storage Systems," *SAE Int. J. Engines* 4, no. 1 (2011):1862–1871, doi:10.4271/2011-01-1343.

[39] M. Gardiner, "Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs," *DOE Hydrogen and Fuel Cells Program Record*, U.S. Department of Energy (Washington, DC: U.S. department of Energy,2009), http://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf.

[40] R.K. Ahluwalia, T.Q. Hua, J.-K. Peng, S. Lasher, K. McKenney, J. Sinha, M. Gardiner, "Technical assessment of cryo-compressed hydrogen storage tank systems for automotive applications," *Int. J. Hydrogen Energy* 35 (2010): 4171–4184.

[41] D.P. Broom, *Hydrogen Storage Materials The Characterisation of Their Storage Properties* (Springer, London UK, 2011), 48–49.

[42] K. Wipke, et al., *Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions*, SRNS-STI-2009-00446, National Renewable Energy Laboratory and Savannah River National Laboratory, 2009, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/toyota_fchv-adv_range_verification.pdf.

[43] Jeffrey Rosenfeld, "Cost Analyses of Hydrogen Storage Materials and On-Board Systems" (presentation, DOE Annual Merit Review, May 11, 2011), http://www.hydrogen.energy.gov/pdfs/review11/st002_law_2011_o.pdf.

[44] U.S. Department of Energy Hydrogen Program, *Technical Assessment: Cryo-Compressed Hydrogen Storage for Vehicular Applications* (Washington, DC: U.S. Department of Energy, revised 2008), http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/cryocomp_report.pdf.