Targets for Onboard Hydrogen Storage Systems for Light-Duty Vehicles

US Department of Energy
Office of Energy Efficiency and Renewable Energy and
The FreedomCAR and Fuel Partnership

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Background

Onboard hydrogen storage for transportation applications continues to be one of the most technically challenging barriers to the widespread commercialization of hydrogen-fueled light-duty vehicles. The DOE Office of Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies (FCT) Program's hydrogen storage activity focuses primarily on the applied research and development (R&D) of low-pressure, materials-based technologies to allow for a driving range of greater than 300 miles (500 km) while meeting packaging, cost, safety, and performance requirements to be competitive with comparable vehicles in the market place. While automakers have demonstrated progress with some prototype vehicles traveling greater than 300 miles on a single fill, this driving range must be achievable across different vehicle makes and models and without compromising customer expectations of space, performance, safety, or cost. The DOE Hydrogen Program website and the FCT Program's Multi-Year Research, Development, and Demonstration Plan contain further information on the Program and its objectives.[1]

Hydrogen storage system performance targets for light-duty vehicles were developed through the FreedomCAR and Fuel Partnership,[2] a collaboration among DOE, the U.S. Council for Automotive Research (USCAR), the major energy companies, and utility partners. The targets apply to system-level properties and are customer and application driven. As scheduled in the FreedomCAR and Fuel Partnership plan, the hydrogen storage system targets are reviewed every five years to assess technology improvements and to ensure continued alignment with market driven requirements.

The original 2015 targets were set to enable greater than 300-mile range on most light-duty vehicles without making significant changes to the vehicle and being available at similar cost. In the six years since 2003, the market and technology landscapes have changed. Most notably, significant progress has been made on the development of hydrogen fueled vehicles. The automotive original equipment manufacturers (OEMs) have introduced many fuel cell and hydrogen internal combustion engine (ICE) vehicles to a wide range of prospective customers since the original targets were formulated. Valuable information has been and continues to be gathered with regard to vehicle performance and customer requirements and expectations. Additionally, in that time frame, several new vehicle technologies such as hybrid vehicles, from mild to plug-in, have gained traction as the next generation of vehicle technologies based on electrification. The original DOE system targets were formulated by comparing the performance of a fuel cell vehicle (FCV) to an advanced gasoline ICE vehicle as the baseline. With the advances of hybrid technologies, it is likely that the new baseline comparison vehicle will be, in part, hybridized. At the same time it should be recognized that hydrogen FCVs could easily be hybrids, being inherently electric vehicles already. Finally, today's consumers in the North American market are demanding more efficient vehicles than the models available; this is not expected to change appreciably in the future.

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[1] http://www.hydrogen.energy.gov/ and http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/storage.pdf

[2] The FreedomCAR and Fuel Partnership includes USDOE*, United States Council for Automotive Research (USCAR includes Ford Motor Company*, Chrysler LLC* and General Motors*), Shell*, BP, ConocoPhillips*, Chevron*, ExxonMobil, California Edison and DTE Energy. The asterisked organizations participate on the Partnership Hydrogen Storage Technical Team. The Hydrogen Storage Technical Team also has participation from Argonne National Laboratory and Sandia National Laboratory (retired).

As a result of these new developments, the Partnership has revised the assumptions underlying the existing DOE hydrogen storage system targets, and in so doing have established a set of new targets. This document describes the basis for the technical targets for onboard hydrogen storage for light-duty vehicles in the FCT Program's Multiyear Research, Development and Demonstration Plan. A detailed explanation of each target is given in the following pages.

Basis for Target Change

Significant progress has been made on the development of hydrogen fueled vehicles during the years since the targets were initially established in 2003:

1. The automotive OEMs have introduced many fuel cell and hydrogen ICE vehicles since the original targets were created. "Real-world" driving and testing experience has been accumulated through internal OEM programs and public participation in the DOE Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, also referred to as the DOE "National Hydrogen Learning Demonstration."[3] Valuable experience and data have been gathered with regards to understanding fuel cell vehicle system design limitations, vehicle performance, and customer requirements & expectations.[4] One goal of the DOE Demonstration and Validation project has been to understand what compromises of performance needs versus technology capability are possible without compromising customer expectations.
2. The new targets are derived from current fuel cell vehicle fleet baseline performance. These early fleets represent a more accurate approximation of how future systems will perform compared to the baseline gasoline ICE vehicles (whereas a single *estimated* fuel economy improvement factor was used to formulate the original targets). The Partnership has established new performance targets based upon the packaging and design experience of these early fleet vehicles. This baseline is used to project future system target performance needs. The Partnership targets represent consensus values among USCAR members based on their internal system requirements. Each OEM has proprietary goals and assumptions to which their individual products are designed.
3. Experience with most of the fuel cell fleet has demonstrated the OEMs' ability to design and modify vehicle architecture around hydrogen systems. Varying degrees of additional mass and volume have been demonstrated in these vehicles to accommodate the hydrogen storage, fuel cell and other hydrogen subsystems onboard the vehicle. The assumption that the vehicle architecture will not change for fuel cell-based systems is no longer valid. Thus, in the new targets, the corollary assumption that hydrogen storage systems must fit within current packaging requirements for ICE vehicles is no longer assumed.
4. The OEMs acknowledge that hydrogen storage systems will likely require more complex and thus more costly designs and materials as compared to current gasoline storage systems. Likewise, most complementary fuel economy improvement approaches (e.g. hybrid powertrains) will likely be at an increased cost over conventional vehicle powertrains (e.g.

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[3] http://www1.eere.energy.gov/hydrogenandfuelcells/tech_validation/fleet_demonstration.html

[4] http://www.nrel.gov/hydrogen/proj_learning_demo.html

ICE). Going forward, the cost of advanced ICE or hybrid vehicles, which will be necessary to meet recent Corporate Average Fuel Economy (CAFE) requirements, will change the future baseline costs and help reduce the stringent cost targets for fuel cell vehicles. **[NOTE: the hydrogen storage system cost target will be revised at a later date to allow for coordination with other Partnership vehicle target changes such as the fuel cell cost target.]**

Assumptions

As a result of the new developments in advanced vehicle technologies mentioned above, the Partnership has revised its assumptions underlying the existing DOE hydrogen storage system targets, and in so doing have established a set of new targets. New assumptions include the following: (1) vehicle architectures will likely change (be designed) to accommodate more space for hydrogen storage system; (2) the fuel economy predictions are now based upon current fleet data and projected improvements. See below for complete listing of changed assumptions.

The unchanged assumptions are that the system targets are based upon complete system and application requirements (not on what state-of-the-art technology can achieve), all targets must be met simultaneously, and the targets should enable greater than 300-mile range across the majority of the current light-duty vehicle fleet (i.e. many makes and models). See below for complete listing of unchanged assumptions.

The revised DOE targets include a new category, the "Ultimate Full Fleet” target. The “Ultimate Full Fleet” target is meant to capture virtually all light-duty vehicle platforms (“significant market penetration”). The new “Ultimate Full Fleet” target is intended to facilitate the introduction of hydrogen-fueled propulsion systems across the majority of vehicle classes and models. The “Ultimate Full Fleet” target values are set at 70 g H_2/L and 7.5 percent H_2 by weight. The “Ultimate Full Fleet” targets have a similar meaning to the previous 2015 target of 81 g/L and 9 percent H_2 by weight in that both sets of targets were designed to enable greater than 300 mile range for most light-duty vehicle platforms.

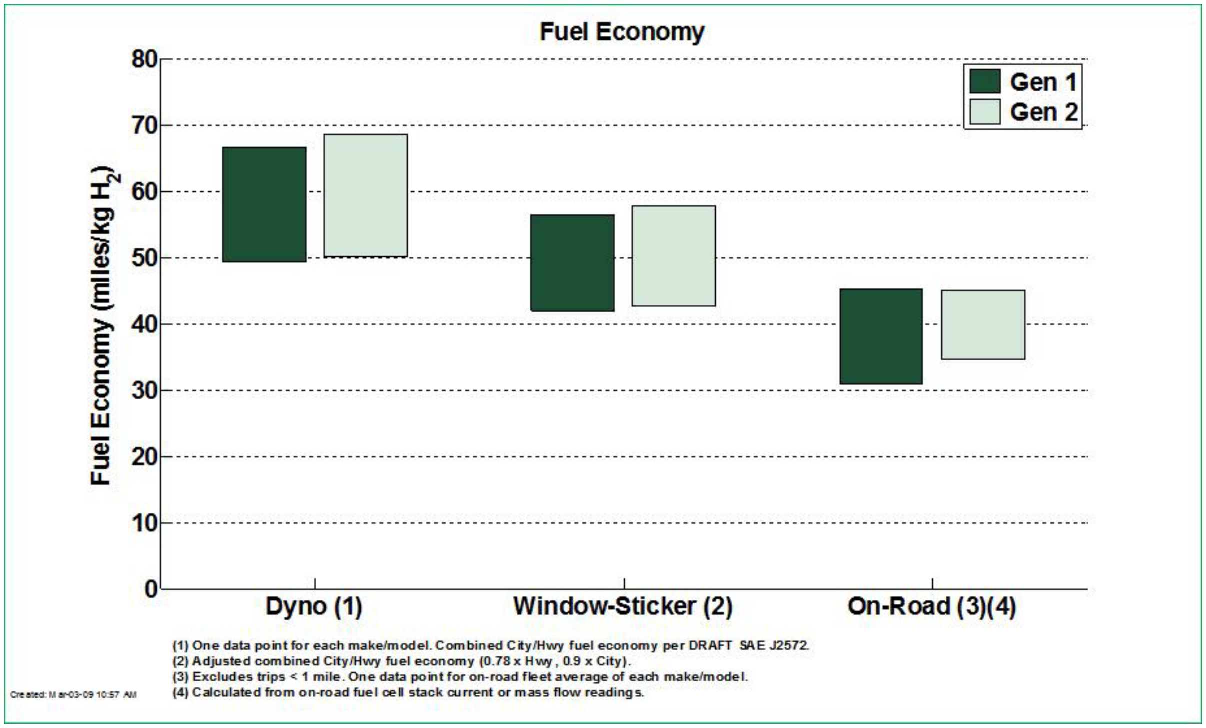
<u>Unchanged Assumptions</u>

1. All targets must be met simultaneously on a total SYSTEM level. The performance targets apply to a complete storage system, including the tank, storage media, safety system, valves, regulators, piping, mounting brackets, insulation, added cooling capacity, and any other balance-of-plant components.
2. Targets are based on what is required to meet the application requirements and customer expectations; not on what the state-of-the-art technology can achieve.
3. A wide variety of vehicle types from small subcompact cars to light-duty trucks were considered in the target calculations; the fuel storage requirement varied between approximately 5 to 13 kg hydrogen, based on the corresponding vehicle type (class) and expected driving range.
4. Some volumetric allowance (up to 20 percent extra) can be adopted in the targets for fully-conformable (geometrically speaking) storage systems.

New Assumptions

1. Due to experience gained with fuel cell vehicle (FCV) fleets and the continued development of hybrid technology, the previous assumption of applying a constant fuel economy gain of 2.5 to 3 times over traditional gasoline ICE vehicles is no longer valid. Fuel economy varies significantly based on degree of hybridization. Furthermore, almost all fuel cell vehicles demonstrated to date have also employed some degree of hybridization from mild to plug-in. The new assumptions of vehicle fuel economy are derived from the actual vehicle data obtained from the current fuel cell vehicle fleet; these early fleets represent a more accurate approximation of how future systems will perform than the previously set fuel economy assumptions.[5] Example fuel economy data obtained for Generation 1 and 2 vehicles from the DOE "Learning Demonstration Program" are shown below in Figure 1.

Figure 1. Fuel Economy Data from the DOE Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project [6]



(1) One data point for each make/model. Combined City/Hwy fuel economy per DRAFT SAE J2572.
(2) Adjusted combined City/Hwy fuel economy (0.78 x Hwy, 0.9 x City).
(3) Excludes trips < 1 mile. One data point for on-road fleet average of each make/model.
(4) Calculated from on-road fuel cell stack current or mass flow readings.

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2. The OEMs utilized the packaging and design space allotted for hydrogen storage in these fleet vehicles in calculating the new targets. That is, the majority of vehicles in the fleet have demonstrated the OEMs' abilities to design and modify vehicle architecture around the hydrogen systems. Two examples of such modifications include redesign of floor pan to accommodate larger hydrogen storage systems and alterations in vehicle architecture to

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[5] The National Research Council's and the National Academy of Engineering's report, Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs used the following fuel economy ratios: Ratio of FCV fuel economy to evolved gasoline ICE of 2.40 and ratio of FCV fuel economy to gasoline hybrid of 1.66.

[6] Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Spring 2009 Composite Data Products, March 2009, K. Wipke, S. Sprik, J. Kurtz, and T. Ramsden, National Renewable Energy Laboratory. http://www.nrel.gov/hydrogen/docs/cdp/cdp_6.jpg

accommodate fuel cell/electronic systems components. Varying degrees of increased mass and volume acceptance (due to the fuel cell and H_2 storage systems) have been demonstrated in these vehicles. Experience has shown that it is generally easier to accommodate extra weight; however accommodating additional packaging volume remains difficult. Importantly, all vehicle modifications must be performed without making compromises to customer expectations for cargo/passenger space, performance, or safety.

3. Speculation on the effects of heavily hybridized vehicles (e.g. plug-ins, range extended etc.) was minimized. If included in the target calculation assessments, significant hybridization can both positively and negatively impact the suggested hydrogen storage system requirements and performance. For example, a 50-mile all electric range extended vehicle would reduce the hydrogen storage system range requirement by approximately 10 percent and potentially relax start-up time and system response, however it would also compete for packaging volume, weight, and cost.

Revised Targets

Table 1. New High Level Storage System Targets for Light-Duty Vehicles

Target	***2010 (new)***	***2010 (old)***	***2015 (new)***	***2015 (old)***	***Ultimate Full Fleet***
System Gravimetric Density (% wt)	4.5 (1.5 kWh/kg)	6 (2.0 kWh/kg)	5.5 (1.8 kWh/kg)	9 (3 kWh/kg)	7.5 (2.5 kWh/kg)
System Volumetric Density (g/L)	28 (0.9 kWh/L)	45 (1.5 kWh/L)	40 (1.3 kWh/L)	81 (2.7 kWh/L)	70 (2.3 kWh/L)
System Fill Time for 5-kg fill, min (Fueling Rate, kg/min)	4.2 min (1.2 kg/min)	3 min (1.67 kg/min)	3.3 min (1.5 kg/min)	2.5 min (2.0 kg/min)	2.5 min (2.0 kg/min)
Storage System Cost (\$/kg H_2): To be determined in conjunction with other Partnership cost target changes	TBD	133 (\$4/kWh)	TBD	67 (\$2/kWh)	TBD

The new “Ultimate Full Fleet” targets are similar in philosophy to the previous 2015 targets in that they represent the hydrogen storage system performance that is required for full vehicle penetration into the light-duty market across a broad range of makes and models. The “Ultimate Full Fleet” targets also approximate current gasoline ICE vehicle systems for packaging volume across the most demanding vehicle platforms. While the “Ultimate Full Fleet” targets allow increases in weight and volume compared to current vehicle fuel tank systems, these increases are manageable across the range of light-duty vehicle platforms. Storage systems that can meet the “Ultimate Full Fleet” targets would therefore have driving ranges that are competitive with most of the current ICE vehicle fleet shown in Figure 2. This plot encompasses vehicle types ranging from subcompact cars and compact hybrid vehicles to full SUVs and extended range light-duty pickup trucks.

Figure 2. Example of Vehicle Sales versus Driving Range for 2007 US Market[7]

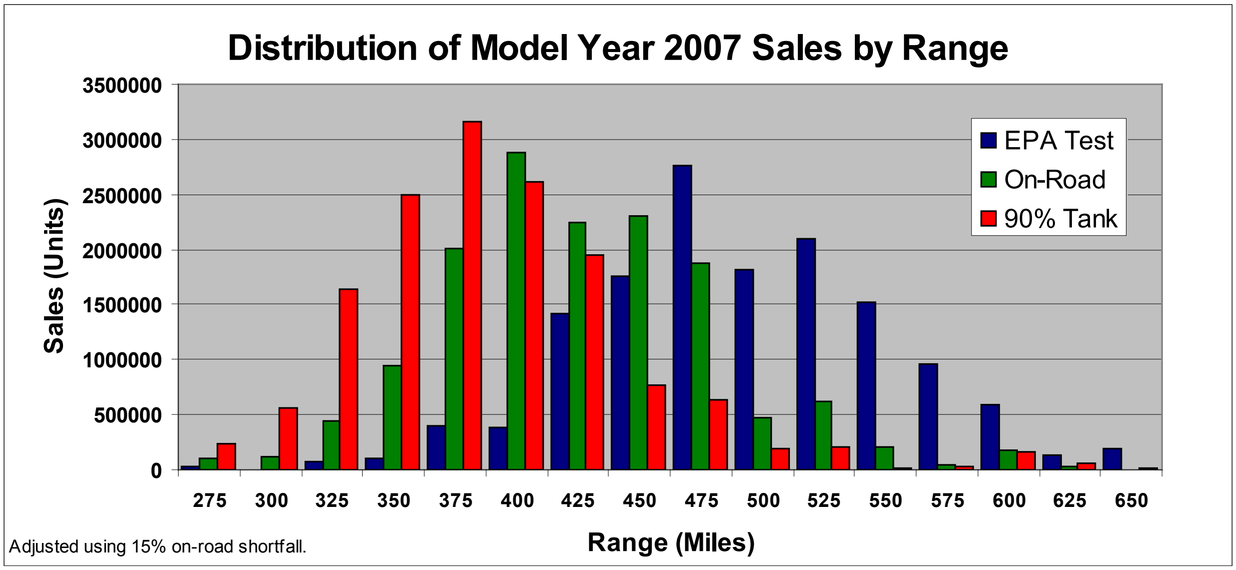

Figure 2 depicts a histogram of the number of ICE vehicles sold in the U.S. with a given driving range. The data are based on the 2005 EPA combined cycle data for all model year 2007 vehicles. (This includes all brands – not just Chrysler, Ford and GM). The graph represents a logical basis for estimating system performance requirements based on current expectations of vehicle owners. It is understood that the values in the graph may change with time; however the Partnership has endeavored to minimize speculation on how these ranges will vary.

Table 2 lists all the revised DOE hydrogen storage system performance targets for light-duty vehicles. A detailed explanation of each target follows the table.

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[7] Oak Ridge National Laboratory, D. Greene

DOE Targets for Onboard Hydrogen Storage Systems for Light-Duty Vehicles

Table 2 Technical Targets: Onboard Hydrogen Storage Systems

Storage Parameter	Units	2010	2017	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass)[a]	kWh/kg (kg H_2/kg system)	1.5 (0.045)	1.8 (0.055)	2.5 (0.075)
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	0.9 (0.028)	1.3 (0.040)	2.3 (0.070)
Storage System Cost[b]:	\$/kWh net (\$/kg H_2)	TBD (TBD)	TBD (TBD)	TBD (TBD)
- Fuel cost[c]	\$/gge at pump	3-7	2-4	2-4
Durability/Operability:				
- Operating ambient temperature[d]	ºC	-30/50 (sun)	-40/60 (sun)	-40/60 (sun)
- Min/max delivery temperature	ºC	-40/85	-40/85	-40/85
- Operational cycle life (1/4 tank to full)[e]	Cycles	1000	1500	1500
- Min delivery pressure from storage system; FC= fuel cell, ICE= internal combustion engine	bar (abs)	5 FC/35 ICE	5 FC/35 ICE	3 FC/35 ICE
- Max delivery pressure from storage system[f]	bar (abs)	12 FC/100 ICE	12 FC/100 ICE	12 FC/100 ICE
- Onboard Efficiency	%	90	90	90
- "Well" to Powerplant Efficiency	%	60	60	60
Charging / Discharging Rates:				
- System fill time (5 kg)	min (kg H_2/min)	4.2 (1.2)	3.3 (1.5)	2.5 (2.0)
- Minimum full flow rate	(g/s)/kW	0.02	0.02	0.02
- Start time to full flow (20°C)[g]	s	5	5	5
- Start time to full flow (-20°C)[g]	s	15	15	15
- Transient response 10%-90% and 90% - 0%[h]	s	0.75	0.75	0.75
Fuel Purity (H_2 from storage)[i]:	% H_2	SAE J2719 and ISO/PDTS 14687-2 (99.97% dry basis)		
Environmental Health & Safety:				
- Permeation & leakage[j]	Scc/h	Meets or exceeds applicable standards		
- Toxicity	-			
- Safety	-			
- Loss of useable H_2[k]	(g/h)kg H_2 stored	0.1	0.05	0.05

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

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

Footnotes to Table 2

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

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

[c] 2005 US$; includes off-board costs such as liquefaction, compression, fuel regeneration, etc; ultimate target based on H_2 production 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 –20 °C to 40 °C. Allowable degradation outside these limits is to be determined.

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

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

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

[h] At operating temperature.

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

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

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

The "Ultimate Full Fleet" targets were developed by projecting performance demonstrated by the OEMs in packaging hydrogen storage systems into fuel cell vehicles. Experience derived from both internal development activities and public participation in DOE programs was leveraged. The "Ultimate Full Fleet" is defined as virtually all vehicle platforms (e.g. makes and models) to achieve significant market penetration of hydrogen fueled vehicles. The "Ultimate Full Fleet" target is intended to facilitate the introduction of hydrogen-fueled propulsion systems across the majority of vehicle classes and models (from subcompact cars to light-duty trucks).

The targets are based on providing a sufficient amount of ***net available*** hydrogen onboard the vehicle to capture an increasing number of segments of the North American light-duty vehicle market. It is also important to emphasize that these targets must be achieved at the end of the service life. All targets must be met simultaneously. Depending on progress in other areas related to hydrogen vehicle development, these targets may have to be altered and will be periodically revisited.

System Capacity: Usable specific energy from hydrogen, net

To determine the "Ultimate Full Fleet" capacity targets, data from a range of fuel cell fleet vehicles from the DOE "National Hydrogen Learning Demonstration" were used, including small, compact, mid-size and crossover light-duty vehicles. The vehicles had a varied degree of hybridization. All participating OEMs in the DOE "National Hydrogen Learning Demonstration" project have demonstrated that more weight and volume for hydrogen systems can be packaged on vehicles without compromising most of the customers' expectations. However, it is generally accepted that most of these prototype vehicles fall short of expected driving range for the North American market. Estimates were made to determine the increased hydrogen system performance required to allow the newly designed fuel cell vehicles to capture a significant portion of the light-duty vehicle market (e.g. many makes and models). Figure 2, shown previously, is one example of a performance attribute, in this case driving range, which customers in the North American light-duty vehicle market expect.

The "Ultimate Full Fleet" targets will allow packaging of hydrogen storage systems so that various hydrogen-fueled fuel cell vehicle platform configurations can match the performance of the current vehicle market. For example, as shown in Figure 2, approximately 90 percent of the vehicles have a 300 to 500 mile on-road driving range. Data from the DOE "National Hydrogen Learning Demonstration" project was used to estimate capacity requirements to match the performance requirements of most makes and models of the current vehicle fleet. Table 3, below, lists data obtained from 2nd generation fuel cell vehicles as part of the DOE "National Hydrogen Learning Demonstration" project. The data was obtained from vehicles with predominately compressed hydrogen storage systems (350 and 700 bar).

Table 3: Second Generation Vehicle Data from the DOE "National Hydrogen Learning Demonstration" Project[8]

"Gen 2" FCV Data	Units	Range of Values	
		Lower	Upper
Fuel Economy	mi/kg·H_2	43	58
Range	mi	196	254
H_2 Capacity	kg·H_2	4.6	4.4
Gravimetric density	wt%·H_2	2.5	4.4
Volumetric density	kg·H_2/L	0.018	0.025
Storage System Mass	kg	182	100
Storage System Volume	L	253	175

DOE used the second generation data from the DOE "National Hydrogen Learning Demonstration" project in Table 3 to estimate the capacities required to meet the requirements of most of the light-duty vehicle makes and models illustrated in Figure 2. Using the configurations of the second generation vehicles, DOE used a range of 500 mile as an example to illustrate the Ultimate Full Fleet needs. These are shown in Table 4 below.

Table 4: Estimated Gravimetric and Volumetric Capacities for Ultimate Full Fleet Usage

Storage Parameters	Units	Range of Required Values	
		Lower	Upper
Amount of stored H_2	kg·H_2	11.6	8.6
Gravimetric Capacity	wt%·H_2	6.4	8.7
Volumetric Capacity	kg·H_2/L	0.057	0.062
Target – Gravimetric Capacity	wt%·H_2	**7.5**	
Target – Volumetric Capacity	kg·H_2/L	**0.070**	

The "Ultimate Full Fleet" gravimetric capacity target is set to 7.5 percent by weight in line with the range estimated from the Gen 2 data of 6.4 to 8.7 percent by weight.

For the volumetric "Ultimate Full Fleet" capacity target, a correction factor of 15 percent above the average required volumetric capacity was used. The 15 percent volume adjustment is motivated by two factors. First, as the volumes quoted in Table 3 refer to exact or water volumes, they represent the minimum volume required by the storage vessel. The effective/box

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[8] Fuel cell vehicle data gathered by NREL as part of the DOE "National Learning Demonstration" Project. Data are for second generation ("Gen 2") fuel cell vehicles: Ford HySeries Edge, Chevy Equinox, Daimler F-Cell, Hyundai Tucson (Kia Sportage). "Upper" and "Lower" refer to the limiting values measured across these vehicles. Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, Spring 2009 Composite Data Products, March 2009, K. Wipke, S. Sprik, J. Kurtz, and T. Ramsden, National Renewable Energy Laboratory. Data website is the following: http://www.nrel.gov/hydrogen/proj_learning_demo.html

volume available onboard the vehicle is typically less. Within the spacing available, designers must allow for system serviceability, impact requirements, etc. The correction factor to estimate the packaging inefficiency may vary significantly based on the type of system and internal design requirements of each OEM. For example single versus multiple tank configurations will have different correction factors; plumbing routes for fill lines also impact volume. In practice, the realistic "engineering volume" consumed by a hydrogen storage system will always exceed its water volume. Second, three of the four vehicles in the NREL dataset are crossover or small-SUV-type. Packaging of hydrogen storage in these larger vehicles will generally be easier than in smaller ones. Taking these two factors into account, a target value slightly higher than the NREL average was adopted.

The new 2010 and 2015 milestones were derived based on an extrapolation using the ultimate fleet targets against current state of the art technology (based on publicly available documents such as TIAX and Argonne systems analyses).[9] The 2010 milestone value represents performance that would allow early market penetration into low volume niche vehicles and fleets. The values are deliberately challenging (but not exclusive) for compressed hydrogen gas technologies. A breakthrough in compressed tanks would be required for some vehicle platforms.

The revised 2015 milestone represents what is required for the approximate mean of the vehicle fleet and captures most compact, midsize and crossover vehicle segments. This performance level allows significant market penetration of vehicle platforms such as most compact, mid-size and crossover vehicles (the exception is that small sports cars and large trucks are excluded). The new 2015 targets do not represent performance required for significant market penetration; the "Ultimate Full Fleet" targets do this. **The new 2015 target levels remain as before, a key milestone to enable OEM decisions on commercialization of hydrogen fuel cell vehicles.**

Table 5: Estimated Gravimetric and Volumetric Capacities Targets for Interim 2010 and 2015 Milestones

Required FCV Data	**Units**	**2010 Targets**		**2015 Targets**	
		Fuel Economy		**Fuel Economy**	
		Lower	**Upper**	**Lower**	**Upper**
Required H_2	$kg \cdot H_2$	7.0	5.2	9.3	6.9
Required Gravimetric Capacity	$wt\% \cdot H_2$	3.8	5.2	5.1	6.9
Required Volumetric Capacity	$kg \cdot H_2/L$	0.034	0.037	0.046	0.049
Target – Gravimetric Capacity	$wt\% \cdot H_2$	**4.5**		**5.5**	
Target – Volumetric Capacity	$kg \cdot H_2/L$	**0.028**		**0.040**	

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[9] See the DOE Hydrogen Program Annual Progress Reports. 2008: http://www.hydrogen.energy.gov/annual_progress08_storage.html#e; 2007: http://www.hydrogen.energy.gov/annual_progress07_storage.html#f and 2006: http://www.hydrogen.energy.gov/annual_progress06_storage.html#f

The differences between the new "Ultimate Full Fleet" system gravimetric and volumetric targets and the previous 2015 targets are minimal, as indicated by the calculations shown below based on **5 kg useable H_2**.

System Gravimetric Density (7.5%) versus former target for full light-duty vehicle penetration (9.0%)

- Mass difference: (Ultimate Full Fleet target – former 2015 Target) = ~11 kg (or 24 lbs)
- In other words, for the new Ultimate Full Fleet system, accommodation has been made for an additional ~11 kg of storage system mass onboard the vehicle, on average.

Volumetric density requirements (70 g H_2/L) versus former target for full light-duty vehicle penetration (81 g H_2/L)

- Volume difference: (Ultimate Full Fleet target – former 2015 Target) = ~9.7 L
- In other words, for the new Ultimate Full Fleet system, an average of additional ~10 L of storage system packaging volume onboard the vehicle has been accommodated.

The Ultimate Full Fleet fueling rate target is unchanged from the previous 2015 target (2.0 kg/min) or 2.5 minutes for a 5-kg (GGE) fill of hydrogen.

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. "Net useful energy" excludes unusable energy (i.e. hydrogen left in a tank below minimum powertrain system pressure requirement, flow and temperature requirements) and hydrogen-derived energy used to extract the hydrogen from the storage medium (e.g. fuel used to heat a hydride or material to initiate or sustain hydrogen release). The system gravimetric capacity refers to end of life net available capacity. The storage system includes interfaces with the refueling infrastructure, safety features, the storage vessel itself, all storage media, any required insulation or shielding, all necessary temperature/humidity management equipment, any regulators, electronic controllers, and sensors, all onboard 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. The target is in units of net useful energy in kWh per maximum system mass in kg. "Maximum system mass" implies that all of the equipment enumerated above plus the maximum charge of hydrogen are included in the calculation. Reactive systems may increase in mass as they discharge hydrogen; in such systems the discharged mass is used.

Storage Parameter	Units	2010	2015	Ultimate
System Gravimetric Capacity: Usable, specific-energy from H_2 (net useful energy/max system mass)	kWh/kg (kg H_2/kg system)	1.5 (0.045)	1.8 (0.055)	2.5 (0.075)

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

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 media standpoint. The term energy density is used interchangeably with the term volumetric capacity. As above, the onboard hydrogen storage system includes every component required to safely accept hydrogen from the delivery infrastructure, store it onboard, 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. As discussed above, the targets account for the demonstrated ability of OEMs to accommodate additional volume for hydrogen and fuel cell subsystems and components on a vehicle without compromising customer expectations. 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. The system volumetric capacity refers to end of life net available capacity. The targets are in units of net usable energy in kWh per system volume in liters.

Storage Parameter	Units	2010	2015	Ultimate
System Volumetric Capacity: Usable energy density from H_2 (net useful energy/max system volume)	kWh/L (kg H_2/L system)	0.9 (0.028)	1.3 (0.040)	2.3 (0.070)

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

Specific storage system cost:

The original cost targets have not been revised at this time. Strategies to appropriately determine the allowable costs for the fuel storage component of hydrogen fueled vehicles are currently under consideration. Revised cost targets are expected to be released at a future date.

Storage Parameter	Units	2010*	2015*	Ultimate
Storage system cost	\$/kWh net (\$/kg H_2)	4 (133)	2 (67)	TBD

* Original cost targets, revised cost targets may be released at a future date.

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

Fuel cost:

This target is meant to provide guidance for chemical hydrogen storage systems where the chemical hydrogen storage material is regenerated off-board. It also includes costs for compression, liquefaction, delivery, chemical recovery, etc. as required. The cost of regenerating the chemical hydrogen storage material must be considered in terms of the fuel/hydrogen cost targets. The storage system cost also includes the first charge of hydrogen fuel which is included. The unit of \$/gallon gasoline equivalent (gge) is approximately equivalent to \$/kg of hydrogen.

Storage Parameter	Units	2010	2015	Ultimate
Fuel cost, delivered and untaxed: 2005 US$/ gallon gasoline equivalent (pump price)	$/gge at pump	3-7	2-6	2-3

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

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 Celsius. The notation (sun) indicates that the upper temperature is a hot soak condition in full direct sun, including radiant heat from the pavement. Note that storage operating temperatures in excess of 60°C can be achieved with solar loading. Thus the hydrogen storage system design should include a shield from this radiant heat or be designed to accommodate temperatures greater than 60ºC. Also note that there are no allowable performance degradation between –20 °C and 40 °C. Allowable degradation outside these limits is to be determined.

Storage Parameter	Units	2010	2015	Ultimate
Durability/Operability				
• Operating ambient temperature, degrees Celsius	ºC	-30/50 (sun)	-40/60 (sun)	-40/60 (sun)

Minimum/maximum delivery temperature of H_2 from tank:

This target refers to the inlet temperature of hydrogen to the fuel cell. Fuel cells currently operate at approximately 80°C. 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 up to 95-105°C with a peak of 120°C may be substituted because fuel cells are likely to operate at increasingly higher temperatures. 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.

Storage Parameter	Units	2010	2015	Ultimate
Durability/Operability				
• Min/max delivery temperature, degrees Celsius	ºC	-40/85	--40/85	-40/95-105

Operational Cycle life:
This target refers to the minimum cycle life for the performance of the storage material/media. The safety critical components (i.e. cylinder, relief valves, etc.) involved in managing pressure or temperature conditions may need additional safety cycle life as specified in the applicable codes and standards. Customers expect the fuel system to last the life of the vehicle, typically 150,000 miles. Assuming a 300-mile 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, 150,000-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.

Storage Parameter	Units	2010	2015	Ultimate
Durability/Operability • Cycle life (1/4 tank to full)	Cycles	1000	1500	1500

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. The minimum and maximum delivery pressures are the only targets that differ between fuel cells and internal combustion engines. This is because the ICE technology relies on high pressure in-cylinder direct fuel injection. The units are in bar (roughly, standard atmospheres) absolute pressure.

Storage Parameter	Units	2010	2015	Ultimate
Durability/Operability • Min delivery pressure from storage system; FC= fuel cell, ICE= internal combustion engine	bar (abs)	5 FC/35 ICE	5 FC/35 ICE	3 FC/35 ICE

Delivery Pressure from hydrogen storage system (maximum acceptable):
This target is for the pressure delivered from the onboard hydrogen storage system to the automotive powerplant. This target ensures that the onboard 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.

Storage Parameter	Units	2010	2015	Ultimate
Durability/Operability • Max delivery pressure from storage system; FC= fuel cell, ICE= internal combustion engine	bar (abs)	12 FC/100 ICE	12 FC/100 ICE	12 FC/100 ICE

Storage System Efficiency:
Hydrogen storage systems must be energy efficient. Two parameters have been defined to account for the energy loss for hydrogen storage systems. The first is the efficiency for the storage system onboard the light-duty vehicle. It is defined as the ratio of the total amount of energy delivered to the powerplant (lower heating value) for the tank rating to the total energy contained in the tank rating. For onboard reversible storage systems, the target is greater than 90% energy efficiency for the energy delivered to the powerplant from the onboard storage system. For example, if a storage tank is rated as holding 5 kg hydrogen, the total amount of energy in the rated tank would be 5 kg multiplied by (33.3 kWh/kg) or approximately 166.5 kWh. For the target to be achieved, at least 90% of 166.5 kWh or 150 kWh needs to be delivered to the powerplant.

For systems generated off-board, the energy content of the hydrogen delivered to the automotive powerplant 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 during regeneration. This efficiency is defined as the onboard efficiency of 90 percent multiplied by the "well-to-tank" efficiency of regenerating the chemical hydrogen storage material. The target total efficiency to the powerplant for off-board regenerable systems is 60 percent.

Storage Parameter	Units	2010	2015	Ultimate
Storage System Efficiency				
• Onboard reversible system efficiency	Percent	90%	90%	90%
• "Well to Powerplant" efficiency for off-board regenerable approaches		60%	60%	60%

<u>Charging/Discharging Rates:</u>

System fill time:
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 to 5 minutes, with small vehicles taking less time and large ones more time. Based on the expected efficiency of fuel cell vehicles, approximately 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 5-kg 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 that stores 10 g of hydrogen in a metal hydride should achieve complete adsorption during recharging within 4.2 minutes to be consistent with 2010 targets.

Storage Parameter	Units	2010	2015	Ultimate
Charging/Discharging Rates • Fill time for 5-kg, min (System fill rate, kg/min)	Min (Kg H_2/min)	4.2 min (1.2 kg/min)	3.3 min (1.5 kg/min)	2.5 min (2.0kg/min)

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-fueled 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 ultimate target even for early vehicles to be competitive with ICEs. These targets will ensure that, whatever the motive technology, the storage systems will be capable of meeting the powertrain fuel requirements. Further, it accounts for the possibility that IC engines fueled by hydrogen may 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 approximately 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.

Storage Parameter	Units	2010	2015	Ultimate
Charging/discharging Rates • Minimum full flow rate	(g/s)/kW	0.02	0.02	0.02

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 (e.g. 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 may be allowed. However, once large-scale production is started, a value near that of an ICE is required. 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 cold start-up time to achieve 50% rated power for the complete fuel cell system at 20°C ambient temperature is 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. NOTE: DOE has a fuel cell system target for start-up/shut-down energy so as to not degrade fuel economy with excessive energy needs. The target is 5MJ from -20°C and 1MJ from 20°C.[10] Storage system start-up energy will, presumably, be a relatively small contribution to the total start-up energy required.

Storage Parameter	Units	2010	2015	Ultimate
Charging/discharging Rates • Start time to full flow (20ºC)	s	5	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 has been desirable to avoid batteries for cold start if possible, unless sizing issues can be resolved. The target cold start-up time to achieve 50% rated power for the complete fuel cell system at –20°C is 15 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.

Storage Parameter	Units	2010	2015	Ultimate
Charging/discharging Rates • Start time to full flow (-20ºC)	s	15	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 0.75 second (2010 and 2015 targets). The transient response is not necessarily 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.

Storage Parameter	Units	2010	2015	Ultimate
Charging/discharging Rates Transient response 10%-90% and 90% -0%[i]	s	0.75	0.75	0.75

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[10] Includes electrical energy and the hydrogen used during the start-up and shut-down procedures.

Fuel Quality:

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. 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 quality targets. The fuel quality requirements are to meet SAE J2719 and ISO specification ISO/PDTS 14687-2. See Appendix C of the EERE Hydrogen, Fuel Cells and Infrastructure Technologies Program's Multiyear Research, Development and Demonstration Plan[11], to be updated as fuel purity analyses progress.

Storage Parameter	Units	2010	2015	Ultimate
Fuel Quality (H_2 from storage)	% H_2	SAE J2719 (99.97, dry basis)		

The hydrogen purity specification is currently in both SAE J2719 and ISO/PDTS 14687-2.

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 cm^3 of hydrogen per hour. Permeation and leakage are 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.

Storage Parameter	Units	2010	2015	Ultimate
Environmental Health & Safety		Meets or exceeds applicable standards		
• Permeation & leakage	Scm^3/h			
• Toxicity	-			
• Safety	-			

SAE J2579 specifies the leak rate/permeation to be less than 75 Ncm^3/min for standard passenger vehicles.

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

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[11] http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/appendix_c.pdf

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.

Storage Parameter	Units	2010	2015	Ultimate
Environmental Health & Safety				
• Loss of useable H_2	(g/h)/kg H_2 stored	0.1	0.05	0.05