DOE Fuel Cell Technologies Office Record	
Record #: 13010	**Date:** June 11, 2013
Title: Onboard Type IV Compressed Hydrogen Storage Systems – Current Performance and Cost	
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Item:

This record summarizes the current status of the projected capacities and manufacturing costs of Type IV, 350- and 700-bar compressed hydrogen storage systems, storing 5.6 kg of usable hydrogen, for onboard light-duty automotive applications when manufactured at a volume of 500,000 units per year. The current projected performance and cost of these systems are presented in Table 1 against the DOE Hydrogen Storage System targets. These analyses were performed in support of the Hydrogen Storage subprogram of the DOE Fuel Cell Technologies Office (FCTO) within the Office of Energy Efficiency and Renewable Energy.

Table 1 Projected Performance and Cost of Type IV Compressed Hydrogen Storage Systems[1]

Storage System Targets	**Gravimetric (kWh/kg sys)**	**Volumetric (kWh/L sys)**	**Cost ($/kWh) (500,000 units/yr)**
2017	1.8	1.3	$12
Ultimate	2.5	2.3	$8
Hydrogen Storage Systems	**Gravimetric (kWh/kg sys)**	**Volumetric (kWh/L sys)**	**Cost ($/kWh) (500,000 units/yr)**[2]
700 bar (Type IV)	1.5	0.8	$17
350 bar (Type IV)	1.8	0.6	$13

[1] Assumes a storage capacity of 5.6 kg of useable H_2

[2] All costs are reported in 2007$ and rounded to the nearest dollar for reporting in DOE documents.

Assumptions and Rational

In FY 2013, Argonne National Laboratory (ANL) and Strategic Analysis (SA) conducted analyses to project system performance and costs for compressed hydrogen storage systems utilizing Type IV 350-bar and 700-bar working pressure tanks with input from key stakeholders based on progressing designs and configurations including the Type IV tank design, balance-of-plant (BOP) components, and filament wet winding process. Results from the analyses were presented by ANL and SA at the 2013 DOE Hydrogen and Fuel Cell Program Annual Merit Review and Peer Review Evaluation meeting.[3,4] It is important to note that all system capacities are "net usable capacities" able to be delivered to the fuel cell. The storage system includes interface with the station fueling dispenser, the storage vessel itself, and all balance of plant components including safety devices, regulators, electronic controllers and sensors, all onboard conditioning equipment necessary to store the hydrogen (e.g., pumps, filters, etc.), as well as mounting hardware and delivery piping.

System Performance Properties

The compressed hydrogen storage system's physical dimensions and performance modeling input parameters, including system BOP, were determined by ANL. The tank was modeled using the finite element code, ABAQUS, with the Wound Composite Modeler extension module. While netting analysis is routinely used by tank manufacturers to obtain initial estimates for carbon fiber (CF) requirements, finite element analysis is needed to accurately predict the tank composite requirements. The ABAQUS results for the composite weight were initially calibrated against selective data obtained from tank manufacturers and further benchmarked against an OEM created "Tank Attribute Estimator" tool.[5] The tool consisted of empirical correlations which were constructed using a wide set of design data provided by a commercial tank manufacturers. For these analysis results, the system BOP configuration and components were developed based on in depth discussions with automotive OEM experts.

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[3] Ahluwalia, R.K., Hua, T.Q., Peng, J-K., Roh, H.S. "System Level Analysis of Hydrogen Storage Options" *Proceedings of the 2013 US DOE Hydrogen and Fuel Cells Program Annual Merit Review*. Crystal City, VA: June 2013. [Online]. [Accessed 10 June 2013] Available: http://www.hydrogen.energy.gov/pdfs/review13/st001_ahluwalia_2013_o.pdf.

[4] James, B.D., Moton, J.M., Colella, W.G. "Hydrogen Storage Cost Analysis." *Proceedings of the 2013 US DOE Hydrogen and Fuel Cells Program Annual Merit Review*. Crystal City, VA: June 2013. [Online]. [Accessed 10 June 2013] Available: http://www.hydrogen.energy.gov/pdfs/review13/st100_james_2013_o.pdf.

[5] Simmons, K.L. "Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage Tanks." *Proceedings of the 2013 US DOE Hydrogen and Fuel Cells Program Annual Merit Review*. Crystal City, VA: June 2013. [Online]. [Accessed 10 June 2013] Available: http://www.hydrogen.energy.gov/pdfs/review13/st101_simmons_2013_o.pdf.

Several important factors related to the effective strength of the CF composite are considered in the model which affect the amount of composite required and are listed in Table 2. A commonly used CF composite for tanks, the Toray T700S fiber-resin composite, with 60% fiber by volume, has a manufactured-listed tensile strength of 2550 MPa (370 ksi). The allowable stress for design purposes is largely affected by two factors. One is the CF manufacturing factor to account for variability in the CF quality at high volume manufacturing, and another is the tank manufacturing factor to account for variation in the winding process and the thick-wall effect (i.e., for cylinders with a radius to wall-thickness ratio of <10 stresses vary significantly between the inside and outside surfaces). ANL used a fiber manufacturing variability factor of 90% and a winding efficiency of 80 - 90%, based on discussions with tank OEMs. The winding efficiency was calibrated to match the model results for composite weight with the tank manufacturer's data. To prevent dome failure and boss blowout at high pressures, the stress ratio was limited to 0.5 for 700-bar tanks and 0.55 for 350-bar tanks (Note: stress ratio is defined as the ratio of fiber stress at operating pressure to fiber stress at burst pressure). Consequently, more carbon fiber is required to maintain low stress ratios.

The ABAQUS model considers the use of "doilies" which are "strips" of carbon fiber composite placed strategically in the dome regions for local reinforcement. The purpose of the doilies is to reduce the stiffness discontinuity between the cylinder and dome sections, and the amount of helical winding needed to maintain the identical stress ratio as without the doilies. In the ABAQUS model the hoop winding angle was varied layer by layer increasing from Θ=75° in the innermost layer to ~Θ=90° in the outermost layer. Varying the hoop winding angle has the effect of transferring part of the load from the inner layers to the outer layers. As a result, the stress distribution across the thickness of the composite is more uniform, and the total amount of carbon fiber composite needed is reduced.

Figure 1 shows a schematic of a typical compressed hydrogen storage system including tank and BOP components. The BOP components were specified in consultation with tank and automotive OEMs as those components deemed necessary for full and safe system functionality while meeting prescribed system codes and standards. A typical BOP system consists of a dedicated fuel system controller, a thermally actuated pressure relief device (TPRD), excess flow and pressure relief valves, fuel filter, high pressure transducer, low pressure automated shutoff valve, pressure regulator and filling/defueling receptacles. Figure 1 represents the current state of the technology and reveals the potential for consolidating components for further optimization and weight and cost reductions.

Results of the tank modeling are shown in Table 3. The total carbon fiber composite weights, including carbon fiber and resin, were determined to be 61.9 and 91.0 kg for the 350-bar and 700-bar Type IV tanks, respectively, each storing 5.6 kg usable H_2. Total system weight and volume for the corresponding storage systems were 104.4-kg, 316.4-L and 127.5-kg, 224.0-L, resulting in gravimetric and volumetric capacities of 5.4 wt.% H_2, 17.7 g-H_2/L and 4.4 wt.% H_2, 25.0 g-H_2/L, for 350- and 700-bar systems respectively.

Table 2 Inputs used to determine composite tank properties.

Tank Parameters	Units	Value	Notes/Comments
Storage Parameters			
Tank Type		IV	
Usable H_2 Mass	kg	5.6	
Total Stored H_2 Mass	kg	5.8	
Nominal Working Pressure	MPa	70.0	
Geometric Parameters			
Liner Thickness	mm	5.0	Thickness in cylinder section
Inside length-to-diameter ratio		3.3	Not including the neck/boss
Gas volume	L	147.3	
Tank Materials			
Liner		HDPE	High-density polyethylene
Carbon Fiber (CF)		T700S	Toray
Resin for CF			May be different for wet and dry (pre-preg) winding
Glass Fiber (GF)			Damage tolerance protection, no structural function
Resin for GF			
Dome Protection		Rigid Foam	
Boss (Al or SS)		Al	
Safety and Service Life			
Design Safety Factor		2.25	Certification performance value
Manufacturing Safety Factor			Design value
Service Life (customer usage)	cycles	1500.0	DOE Target Table
Extended Durability	cycles	5500.0	SAE J 2579 criteria for light duty vehicles
Design Cycle Life	cycles		Certification performance value
Material Properties	**Units**	**Value**	**Notes/Comments**
Mechanical Properties			
CF Tensile Strength, Supplier	MPa	4900.0 (710 ksi)	Toray data sheet
CF Elongation at Break	%	2.1	Toray data sheet
Composite Efficiency	%	87.0	Ratio of composite strength to fiber strength normalized to 60% fiber volume fraction

Composite Tensile Strength, Supplier	MPa	2550.0 (370 ksi)	Toray data sheet
Fiber Strength Variability Factor		0.9	Fiber mechanical property variability due to high volume manufacturing
Composite Tensile Strength, Design Basis	MPa	2295.0 (333 ksi)	Composite knock-down due to fiber variability
Winding Efficiency		0.8	Includes effects of composite thickness, winding tension
Composite Young's Modulus, E1, E2, E3	GPa	135, 9.66, 9.66	
Composite Shear Modulus, G12, G13, G23	GPa	5.86, 5.86, 3.46	
Composite Poisson's Ratio, v12, v13, v23		0.25, 0,25, 0,41	
Glass Fiber Strength	MPa	3450.0 (500 ksi)	Owens Corning E-glass
Glass Fiber Modulus	GPa	70.0	Owens Corning E-glass
Glass Fiber Elongation at Break	%	4.8	Owens Corning E-glass
Physical Properties			
CF Volume Fraction		0.6	Toray data sheet
CF Density	kg/m3	1800.0	Toray data sheet
Resin for CF Density	kg/m3	1250.0	
CF Composite Density	kg/m3	1580.0	
GF Density	kg/m3	2580.0	Dostal, C.A., Engineered Materials Handbook: Composites, Volume 1, ASM International, Metals
Resin for GF Density	kg/m3	1250.0	
GF Composite Density	kg/m3	2048.0	
Liner Density	kg/m3	960.0	
Dome Protection Material Density	kg/m3		
Boss Material Density	kg/m3		
CF Coefficient of Thermal Expansion (CTE)	$1/^{o}C$	-0.38	
Resin for CF CTE	$1/^{o}C$		
GF CTE	$1/^{o}C$	5.4	Owens Corning E-glass
Resin for GF CTE	$1/^{o}C$		
Liner CTE	$1/^{o}C$	200.0	

Table 3 Predicted mass and volume of a Type IV 350-bar and 700-bar compressed hydrogen systems

Storage System	Type IV 350-bar Single Tank		Type IV 700-bar Single Tank	
	Mass (kg)	Volume (L)	Mass (kg)	Volume (L)
Stored Hydrogen[a,b]	6.0	250.4	5.8	145.2
HDPE Liner	11.4	12.0	8.0	8.4
Carbon Fiber Composite	61.9	39.2	91.0	57.6
Dome Protection	5.2	7.7	4.0	5.9
BOP	19.9	7.1	18.7	6.9
System Total	104.4	316.4	127.5	224.0
Gravimetric Capacity (wt.%-H2)	5.4		4.4	
Volumetric Capacity (g-H2/L)		17.7		25.0

a Mass of the stored hydrogen is the total mass required to deliver 5.6 kg to the fuel cell system at 5 bar pressure.
b Volume of stored hydrogen is defined as the internal volume of the tank.

System Cost Analysis

Cost analyses were conducted for 350-bar and 700-bar single tank storage systems to determine a baseline cost of the technology. The cost analyses were conducted by SA using a Design-for-Manufacturing and Assembly costing methodology for the pressure vessel and a price quote based methodology for the balance of plant (BOP) components (such as valves, pressure relief devices, refueling ports, etc.) depicted in Figure 1. System costs are reported in 2007 dollars and were deflated (where appropriate) using the Producer Price Index: (Finished Goods) (PPIFG) as determined by the US Department of Labor/Bureau of Labor Statistics. Key material cost assumptions, as shown in Table 4 at 500,000 systems per year quantities, include $28.67/kg for T700S-grade carbon fiber, $7.09/kg resin cost (including the expected 25% resin wastage associated with the wet-winding operation), and $1.77/kg for the high density polyethylene (HDPE) liner material. Material costs were selected based on discussions with suppliers and coordinated with tank and automotive OEMs for secondary verification. The BOP costs at high-volume manufacturing rates (i.e., 500,000 units) were determined by applying learning curve factors (i.e., price ratio between doublings of annual manufacturing rates) that were established via feedback from tank and automotive OEMs and internal price quotes. Uncertainty in the storage system costs were evaluated through Monte Carlo analyses using estimated parameter value distributions listed in Table 5. Multivariable analyses were performed by varying all the parameters simultaneously, over a specified number of trials, to determine a probability distribution of the costs.

System cost results include material, manufacturing, and assembly costs of the complete storage system that consists of a 10-step fabrication process listed in Table 6. The manufacturing process modeled in the analysis was based on filament wet-winding as it is the most commonly used composite forming technique practiced by tank manufacturers. The costs do not include any markup for the final system assembler for profit, general and administrative expenses, research and development expenses, or non-recurring engineering costs, warranty, etc.

Table 4 Key cost assumption for Type IV bulk tank materials

Key Cost Assumptions	Units	Values - SA
Production Volume	#/year	500,000
Material Unit Cost		
Carbon Fiber	USD/kg	28.67
Resin for CF	USD/kg	7.09
Glass Fiber	USD/kg	Not Used[6]
Resin for GF	USD/kg	Not Used[6]
Liner	USD/kg	1.77
Boss	USD/kg	4.75
Dome Protection	USD/kg	Not Used [7]

The cost modeling utilized the system physical dimensions and material masses determined by ANL as described above. The key results are summarized in Table 7 and indicate that current costs for Type IV compressed hydrogen systems that store 5.6-kg of usable H_2 are projected within 95% certainty to range from \$12-\$16/kWh (μ = \$13/kWh) and \$16-\$20/kWh (μ = \$17/kWh) for 350-bar and 700-bar working pressures, respectively. The ranges reflect uncertainty in the underlying parameter values listed in Table 5. Figure 2 a-b shows the distribution of the costs that comprise the respective systems where the major contributors are the carbon fiber composite and BOP and assembly for both the 350-bar and 700-bar systems.

In 2013, costs for complete systems were also estimated for variable manufacturing volumes (10,000 – 500,000) to demonstrate the projected effect of manufacturing volume and is shown in Figure 3 a-b. For 350-bar systems, the mean cost at low-volumes (10,000 units) is estimated to be $29/kWh, decreasing to $13/kWh once mass production volumes (500,000 units) are reached. Similarly, for 700-bar, the low-volume mean cost is estimated to be approximately $33/kWh decreasing to $17/kWh at 500,000 units.

[6] Previous studies have included glass fiber (GF)and resin for GF in cost estimates; however, these costs are negligible and are not standard across all tank OEMs and are not used to determine the costs in this record.

[7] Dome protection is used in the specification of performance properties but adds negligible costs and are not used in the determination of the costs reported in this record.

Table 5 Parameter values for hydrogen storage system cost Monte Carlo simulations.

Parameter	Unit	Minimum Value	Likeliest Value	Maximum Value
Polymer Base Price	$/kg	$1.33	$1.77	$2.66
Carbon Fiber Base Price Factor		0.9	1	1.2
Blow Molding Capital Cost	$	$444,687	$592,916	$741,145
Blow Molding Total Cycle Time Factor		0.5	1	2
Wet Winding Capital Cost	$	$275,000	$343,719	$600,000
Average Fiber Laydown Rate	m/min	18.2	26	31.2
Curing Oven Capital Cost	$/ft	$1,506	$2,008	$2,511
Curing Conveyor Capital Cost Factor		0.2	1	1.5
B-Stage Dwell Time	hrs	1.875	2.5	3.125
Full Cure Dwell Time	hrs	4	8	12
Compression System Capital Cost	$	$835,633	$1,671,267	$3,342,534
BOP Cost Factor (10k - 100k)		0.75	1	1.25
BOP Cost Factor (500k)		0.75	1	1.48
Resin Cost	$/kg	$2.50	$7.09	$12.00

Table 6 High-pressure Compressed Hydrogen Vessel 10-Step Fabrication, Assembly and Test Process

Step Number	Function
1	HDPE liner formation via blow molding
2	Visual inspection of the liner
3	Liner thermal annealing
4	Liner final bore inspection
5	Fiber wet winding operation
6	B-stage cure of the composite fiber
7	Full-cure of the composite fiber
8	Hydro (water) test in accordance with CGA C-1 protocols
9	Gaseous helium leak test in accordance with ANCI NGV2 protocols

10	Final system assembly and system test

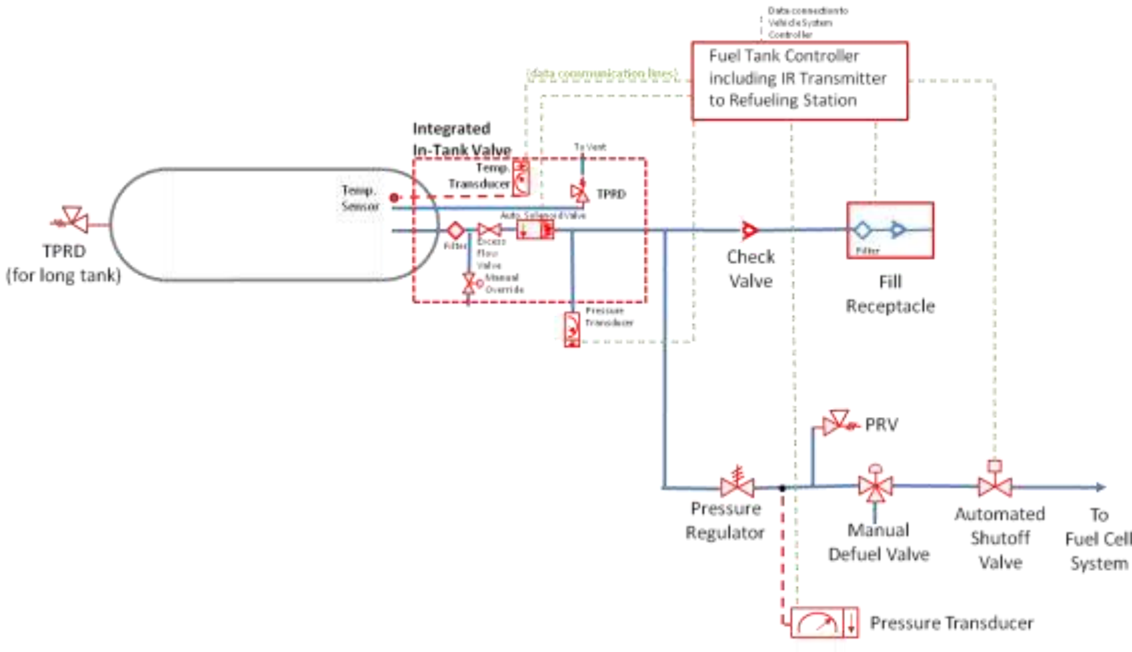

Figure 1 Schematic representation for a single-tank Type IV high-pressure compressed hydrogen storage system. BOP components for 350- and 700-bar are assumed to be different weight and volume, but functionality is considered to be the same.

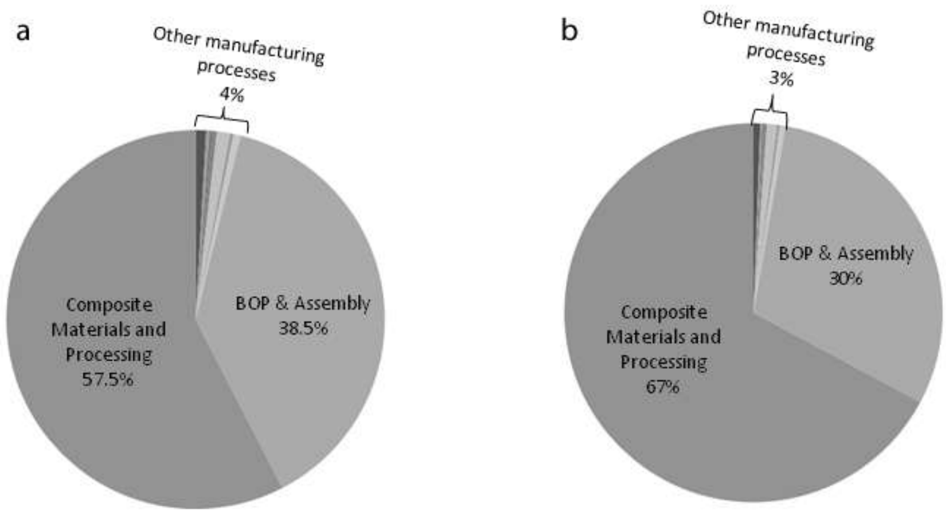

Figure 2 Cost distributions for (a) 350-bar and (b) 700-bar Type IV single-tank compressed hydrogen system at 500,000 units.

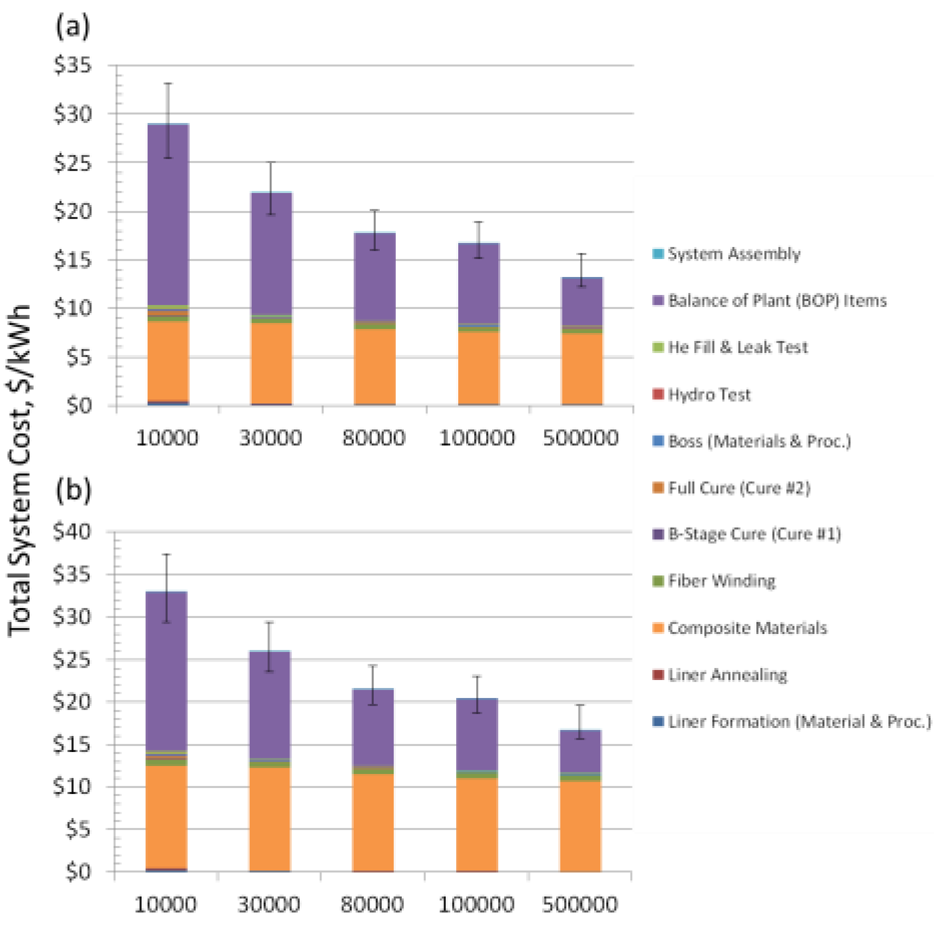

Figure 3 Plots of cost estimates of the variable volume manufacturing for (a) 350-bar and (b) 700-bar compressed hydrogen storage systems.

Table 7 **Summary of projected results for 350-bar and 700-bar Type IV compressed hydrogen storage system performance and cost**

Type of Storage System	System Gravimetric Capacity (wt%)	System Volumetric Capacity (g H_2/L)	Carbon Fiber Composite Weight (kg)	System Cost ($/kWh)	Cost Range ($/kWh)	Year	Source
One-Tank Compressed Hydrogen (700 bar)	4.4	25.0	91.0	$17	$16-$20	2013	2013 ANL AMR Presentation, Slide 9 and 2013 SA AMR Presentation, Slide 14
One-Tank Compressed Hydrogen (350 bar)	5.4	17.7	61.9	$ 13	$12-$16	2013	2013 ANL AMR Presentation, Slide 9 and 2013 SA AMR Presentation, Slide 16

Note: Annual Merit Review Proceedings are available on the DOE/FCT website: http://www.hydrogen.energy.gov/annual_review.html and Annual Progress Reports are available on the DOE/FCT website: http://www.hydrogen.energy.gov/annual_progress.html