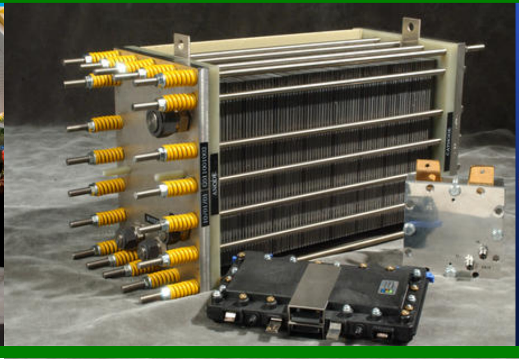
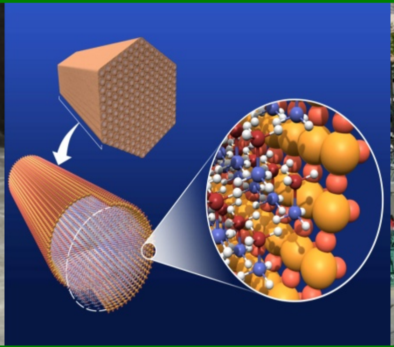
U.S. DEPARTMENT OF
ENERGY





Hydrogen Storage

Ned Stetson

2013 Annual Merit Review and Peer Evaluation Meeting
May 13, 2013

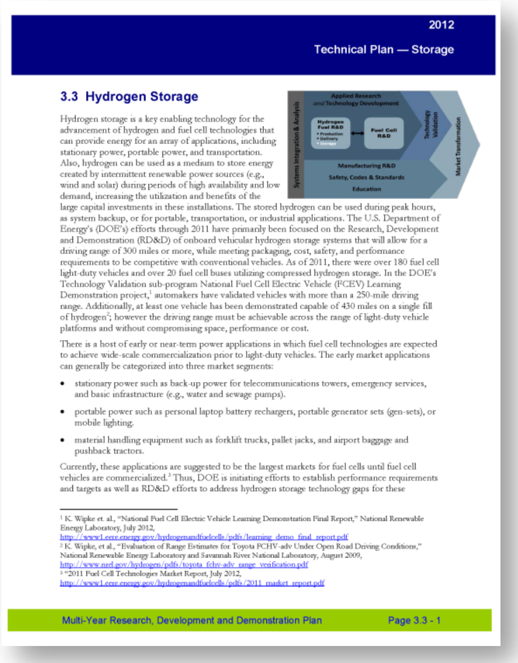
Goal and Objectives:

U.S. DEPARTMENT OF ENERGY

Goal: Develop and demonstrate viable hydrogen storage technologies for transportation, stationary, material handling, and portable power applications

H_2 Storage Mission:

- **Automotive applications:** Enable fuel cell electric vehicles (FCEVs) through the development of hydrogen storage technologies that will provide a 300 mile plus driving range while meeting customer expectations for cost, safety, passenger/cargo space and performance requirements.
- **Non-automotive applications:** Enable cost-effective operation of fuel cells through the development of storage technologies that can provide enough hydrogen to meet customer-driven performance metrics in a safe and convenient package.
  - Support the analysis, research, development and demonstration of hydrogen storage technologies that can help the successful commercialization of fuel cell products.
  - Support the development of technologies to maintain U.S. leadership in technology and manufacturing for the emerging hydrogen – fuel cell industry.



2012

Technical Plan — Storage

3.3 Hydrogen Storage

Hydrogen storage is a key enabling technology for the advancement of hydrogen and fuel cell technologies that can provide energy for an array of applications, including stationary power, portable power, and transportation. Also, hydrogen can be used as a medium to store energy created by intermittent renewable power sources (e.g., wind and solar) during periods of high availability and low demand, increasing the utilization and benefits of the large capital investments in these installations. The stored hydrogen can be used during peak hours, as system backup, or for portable, transportation, or industrial applications. The U.S. Department of Energy's (DOE's) efforts through 2011 have primarily been focused on the Research, Development and Demonstration (RD&D) of onboard vehicular hydrogen storage systems that will allow for a driving range of 300 miles or more, while meeting packaging, cost, safety, and performance requirements to be competitive with conventional vehicles. As of 2011, there were over 180 fuel cell light-duty vehicles and over 20 fuel cell buses utilizing compressed hydrogen storage. In the DOE's Technology Validation sub-program National Fuel Cell Electric Vehicle (FCEV) Learning Demonstration project,[1] automakers have validated vehicles with more than a 250-mile driving range. Additionally, at least one vehicle has been demonstrated capable of 430 miles on a single fill of hydrogen[2]; however the driving range must be achievable across the range of light-duty vehicle platforms and without compromising space, performance or cost.

There is a host of early or near-term power applications in which fuel cell technologies are expected to achieve wide-scale commercialization prior to light-duty vehicles. The early market applications can generally be categorized into three market segments:

- stationary power such as back-up power for telecommunications towers, emergency services, and basic infrastructure (e.g., water and sewage pumps).
- portable power such as personal laptop battery rechargers, portable generator sets (gen-sets), or mobile lighting.
- material handling equipment such as forklift trucks, pallet jacks, and airport baggage and pushback tractors.

Currently, these applications are suggested to be the largest markets for fuel cells until fuel cell vehicles are commercialized.[3] Thus, DOE is initiating efforts to establish performance requirements and targets as well as RD&D efforts to address hydrogen storage technology gaps for these

[1] K. Wipke et. al., "National Fuel Cell Electric Vehicle Learning Demonstration Final Report," National Renewable Energy Laboratory, July 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/learning_demo_final_report.pdf
[2] K. Wipke, et al., "Evaluation of Range Estimates for Toyota FCHV-adv Under Open Road Driving Conditions," National Renewable Energy Laboratory and Savannah River National Laboratory, August 2009, http://www.nrel.gov/hydrogen/pdfs/toyota_fchv-adv_range_verification.pdf
[3] "2011 Fuel Cell Technologies Market Report, July 2012, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2011_market_report.pdf

Multi-Year Research, Development and Demonstration Plan Page 3.3 - 1

MYRD&D Update Released May 2013

Challenges: Automotive

U.S. DEPARTMENT OF ENERGY

To enable a driving range of >300 miles, while meeting packaging, cost and performance requirements across all vehicle platforms to achieve significant market penetration

Storage Targets	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Costs ($/kWh) (projected to 500,000 units/yr)
2017	**1.8 (0.055)**	**1.3 (0.040)**	**$12 ($400)**
Ultimate	**2.5 (0.075)**	**2.3 (0.070)**	**$8 ($266)**

H_2 Storage System	Gravimetric (kWh/kg sys)	Volumetric (kWh/L sys)	Costs ($/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 (NaAlH4) [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

[a] Assumes a storage capacity of 5.6 kg of usable H_2 , [b] Based on Argonne National Laboratory performance and TIAX cost projections, [c] Based on Hydrogen Storage Engineering Center of Excellence performance projections

Note: there are ~20 specific onboard storage targets that must be met simultaneously

Near-Term Option: Compressed gas storage offers a near-term option for initial vehicle commercialization and early markets though the cost of composite tanks is still a challenge.

Long-Term Option: Materials-based solutions targeted to meet all on-board storage targets, at once

- Improving gravimetric and volumetric capacities
- Having sufficient kinetics within appropriate temperature and pressure ranges
- Lowering cost of overall engineered system

Challenges: Non-Automotive

U.S. DEPARTMENT OF **ENERGY**

Storage to enable cost-effective operation of fuel cells that are able to meet customer-driven performance metrics in a safe and convenient package

Material Handling Equipment Targets	Volumetric kWh/L (kg H_2/L sys)	System Cost $/kWh net ($/kg H_2)	System Fill Time (2kg) min
2015	1.0 (0.03)	20 (667)	4.0
2020	1.7 (0.05)	15 (500)	2.8

Fuel Cell Forklifts

Portable Power Targets		Gravimetric kWh/kg (kg H_2/kg sys)	Volumetric kWh/L (kg H_2/L sys)	System Cost $/kWh net ($/g H_2)	
				<2.5W	>2.5-150W
2015	Single-Use	0.7 (0.02)	1.0 (0.03)	0.09 (3.0)	0.2 (6.7)
	Rechargeable	0.5 (0.015)	0.7 (0.02)	0.75 (25)	1.0 (33)
2020	Single-Use	1.3 (0.04)	1.7 (0.05)	0.03 (1.0)	0.1 (3.3)
	Rechargeable	1.0 (0.03)	1.3 (0.04)	0.4 (13)	0.5 (17)

Portable Power

Targets developed from RFI with industry and stakeholder input.
For full targets see MYRD&D, http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/storage.pdf

H_2 Storage Challenges & Strategy

U.S. DEPARTMENT OF ENERGY

Comprehensive strategy to address barriers for near-term and long-term technologies

Barriers
Cost
Volume
Weight
Refill time
Cycle-life

Strategy

Near-term
High-pressure Compressed H_2 Systems

Long-term
Cold/Cryo-compressed H_2
Materials-based H_2 storage

R&D Focus (near-term)
- Cost reduction
- Advanced designs
- Improved manufacturing

R&D Focus (long-term)
- Advanced designs
- Novel materials discovery
- Performance Analysis

KEY AREAS

Pressure Vessels
- Lower cost carbon fiber
- Improved composite
- Conformable designs
- Lower cost BOP

Cold/Cryo-compressed
- System engineering
- Advanced insulation
- Improved dormancy
- Composite development

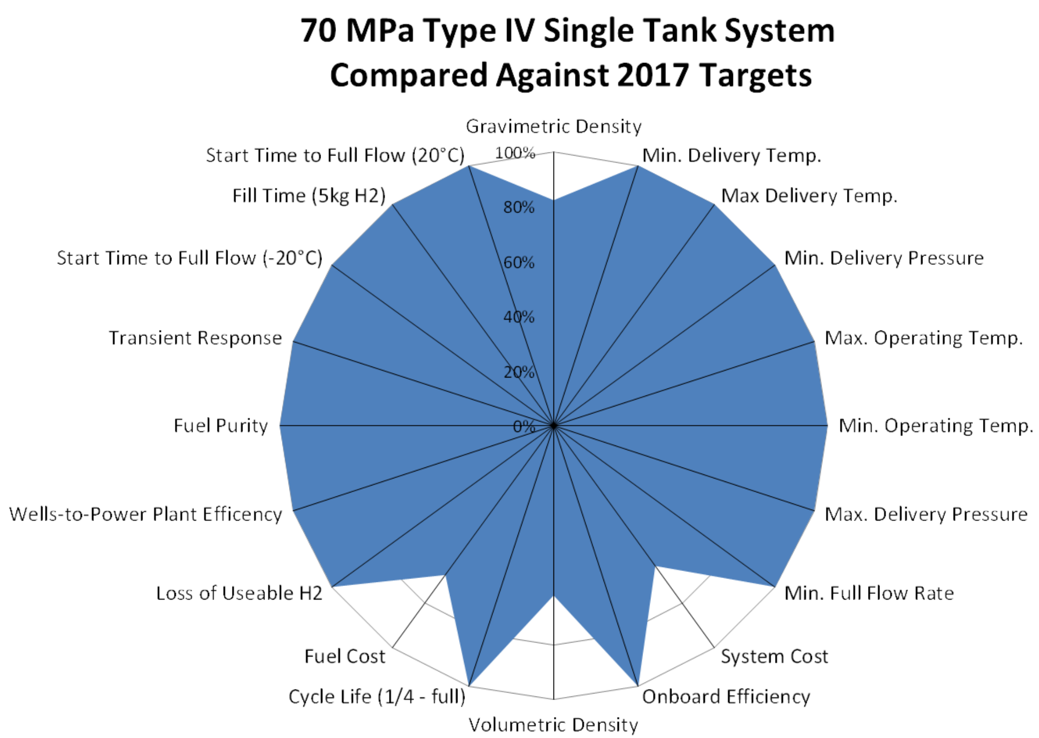
Materials-based H_2 Storage
- Materials development
- Materials characterization
- System engineering
- Materials/system manufacture

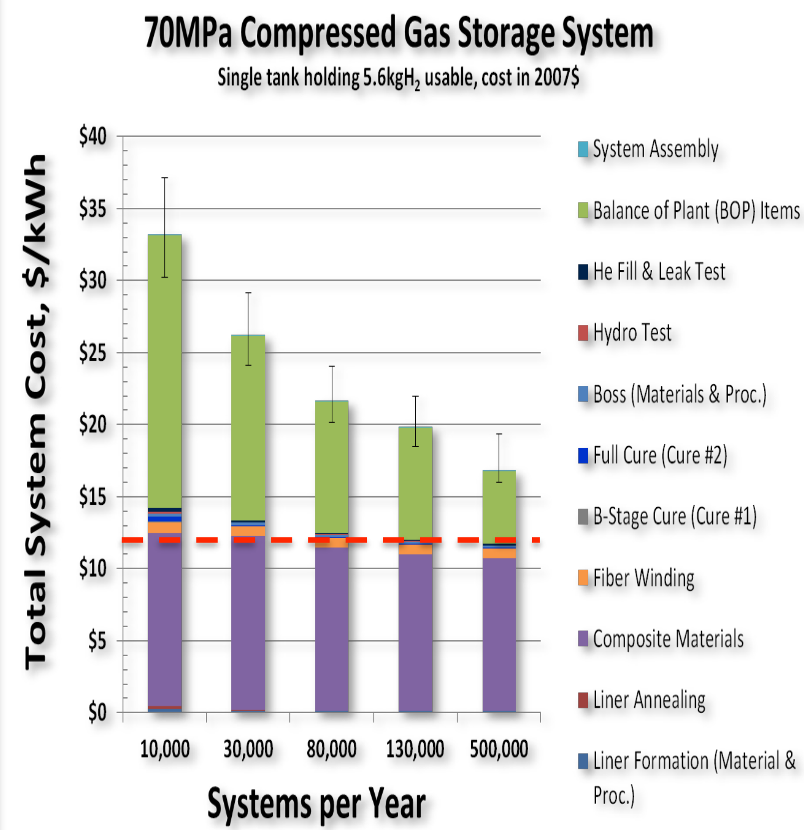
H_2 Storage MYRD&D available at:
http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html

Near-term strategy for lowering costs

U.S. DEPARTMENT OF ENERGY

Compressed Gas Tanks – Unable to meet all onboard storage targets, however offer a near-term path to commercialization if costs are reduced





Key Barriers:
- **Cost**
- **Volumetric Capacity**
- **Gravimetric Capacity**
- **Fill Time**

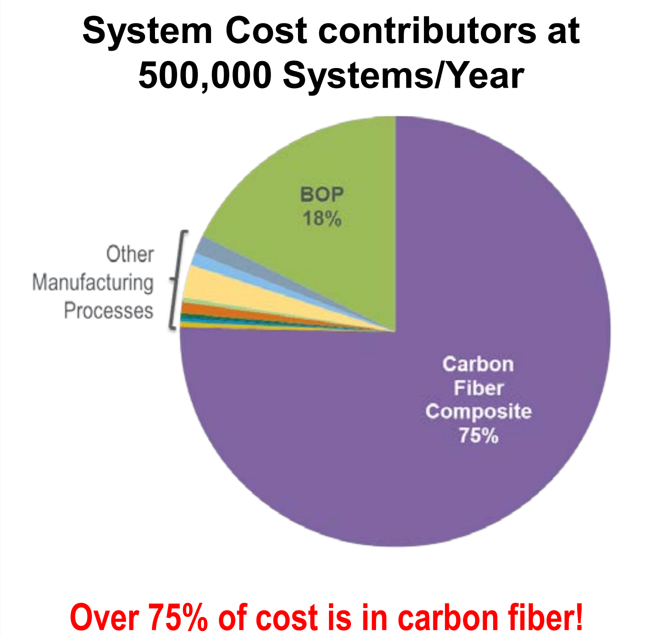
ANL (ST01)

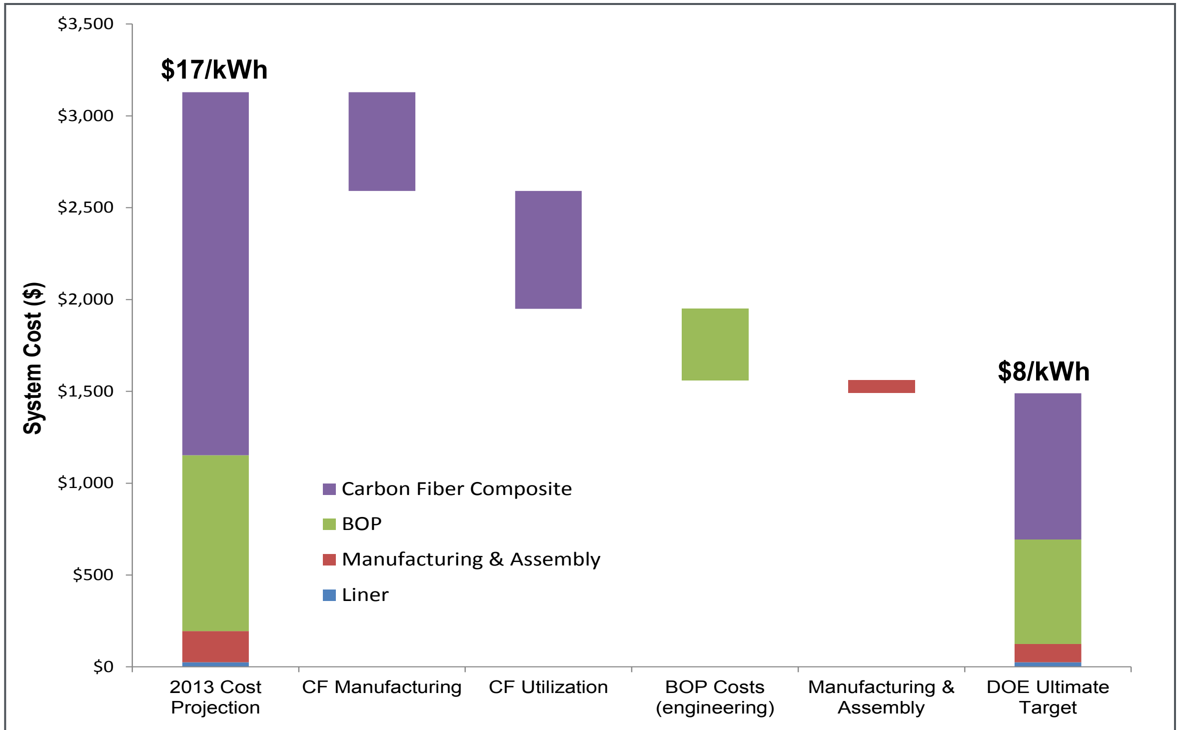
Strategic Analysis, Inc. (ST100)

Near-term strategy for lowering costs

U.S. DEPARTMENT OF ENERGY

Cost reduction strategies must emphasize reducing cost and quantity of carbon fiber composite used in systems





Near-term Focus

Cost reductions required to meet DOE cost target:

- **~40% Reduction in composite structure**
- **~10% Reduction in Balance of Plant**

Projects Addressing R&D Needs:

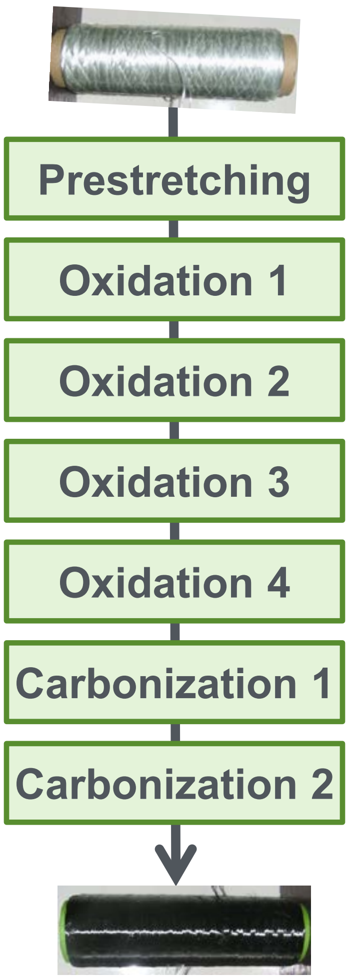
- ST101 – Holistic Tank Design approach
- ST099 – Low-cost Precursor
- ST093 – Precursor Processing
- ST105 – Resin Fillers (SBIR)
- ST109 – Laminate Strengthening (SBIR)
- ST110 – Graded Carbon Fiber (SBIR)

2013 Progress: Reducing CF precursor cost

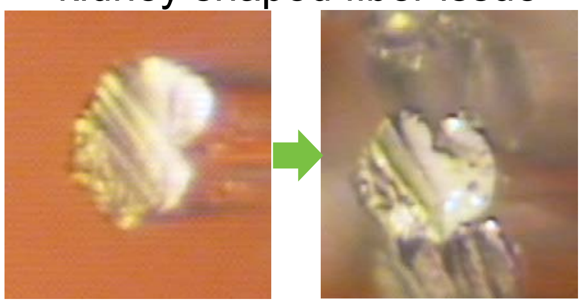
U.S. DEPARTMENT OF ENERGY

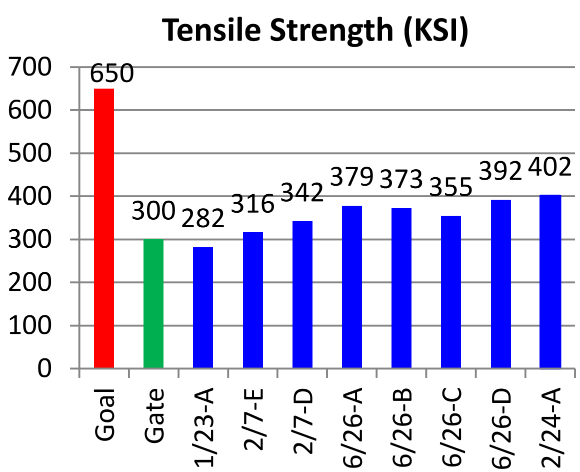
PAN precursor fibers account for over 50% of cost of manufacturing carbon fiber, lower cost precursors offer opportunity to reduce CF costs

Optimization of conversion processing for textile-grade PAN/MA underway



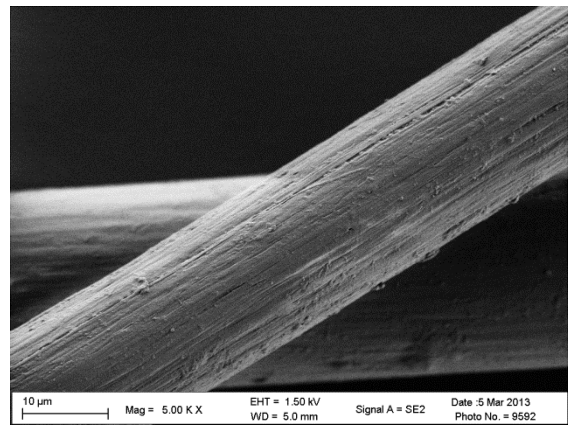
<u>Air Gap Spinning</u>
introduced to help resolve kidney shaped fiber issue





ORNL with FISIPE (ST099)

Significant improvement obtained with post stretched melt-spun PAN fibers



Post treatment stretching results in smooth, smaller diameter PAN fibers

Date of carbonization	Sample	Peak stress [ksi]	Modulus [Msi]
Feb. 2012	VT_201201	Could not be unspooled	
Apr. 2012	VT_201203	76.5	16.1
Jun. 2012	VT_201205	77.4	6.2
Mar. 2013	VT_20121129_S6_B	222.4 (84.0)	22.4 (2.6)
	VT_20121129_S7_A	**261.4 (67.2)**	**25.3 (3.1)**
	VT_20121129_S7_B	212.0 (31.8)	20.8 (1.1)
	VT_20121129_S9_B	215.7 (113.2)	27.0 (2.5)

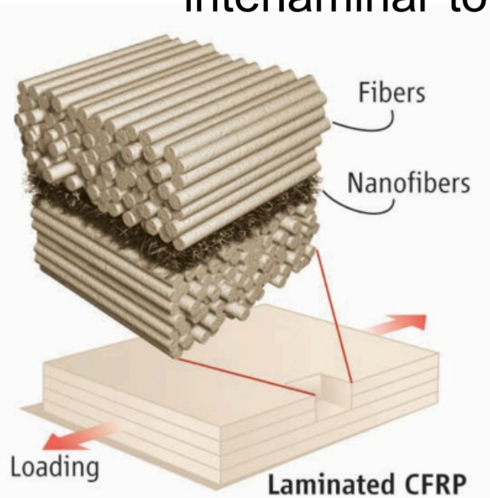
ORNL with Virginia Tech (ST093)

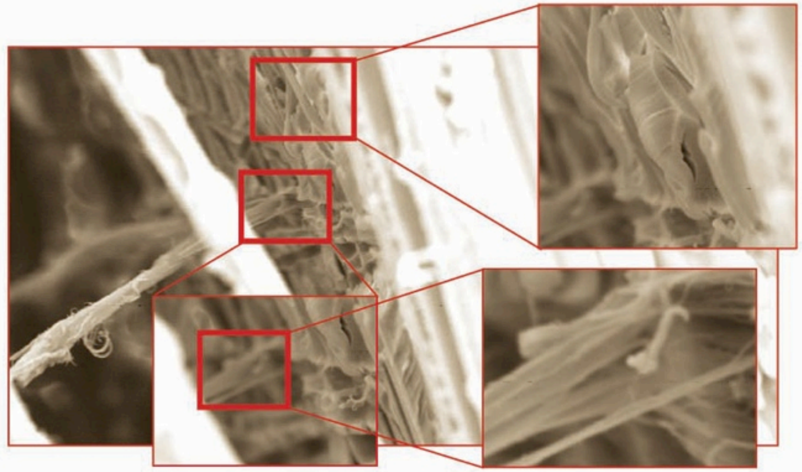
2013 Progress: Improved CF composites for lower cost

U.S. DEPARTMENT OF ENERGY

Improved carbon fiber composites, and optimized use of carbon fiber properties can lead to lower cost hydrogen storage

Initiated new SBIR project to develop integrated nanoreinforcement to improve interlaminar toughness and performance of composite pressure vessels

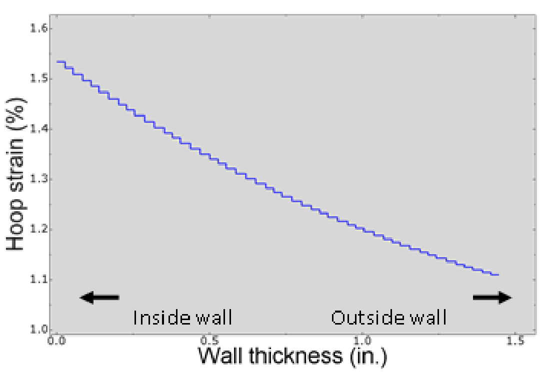




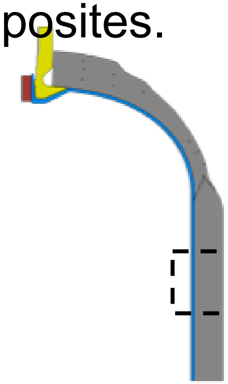
Nanofibers deposited between CF composite layers will improve damage resistance, interlaminar toughness, shear strength and burst strength.

NextGen Aeronautics (ST109)

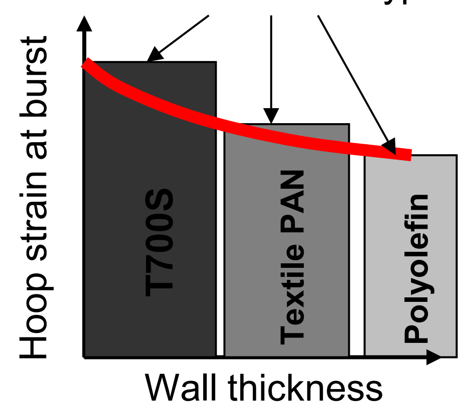
Initiate new SBIR project to investigate use of graded construction to optimize cost and performance of carbon fiber composites.



Thick wall effects leads to lower strain in outer wrappings, so optimizing CFC properties can lead to reduced costs.



Composite Technology Development (ST110)

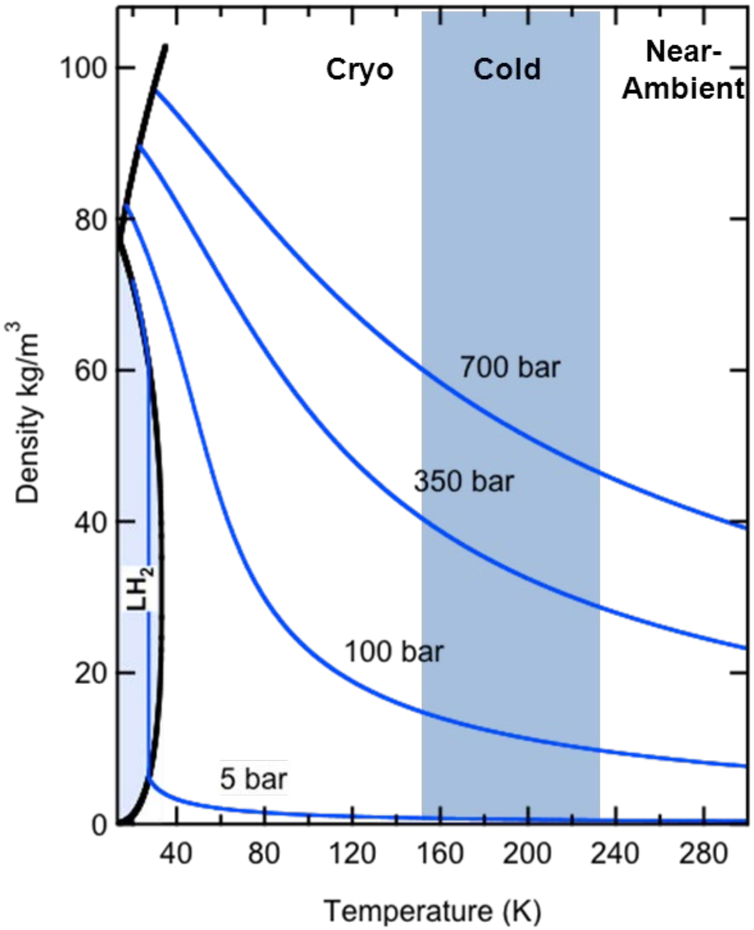


Long-term Strategies

U.S. DEPARTMENT OF ENERGY

Both lower temperatures and materials-based technologies offer long-term potential to meet onboard system targets

Higher H_2 densities are achievable through use of lower temperatures



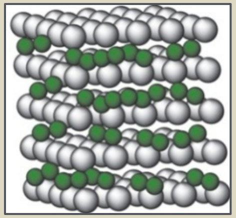
Investigating potential for cold and cyro-compressed H_2

- Developing and validating pressure vessels for operating conditions
- Understanding implications and costs at forecourt

Developing materials-based H_2 storage technologies

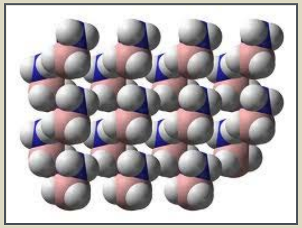
- Developing materials with required capacity, thermodynamic and kinetic properties
- Developing balance-of-plant components
- Understanding implications and costs at forecourt

Materials-based Storage



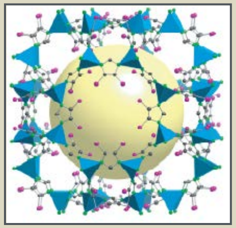
interstitial hydrides

~100-150 g H_2/L



chemical storage

~70-150 g H_2/L



sorbents

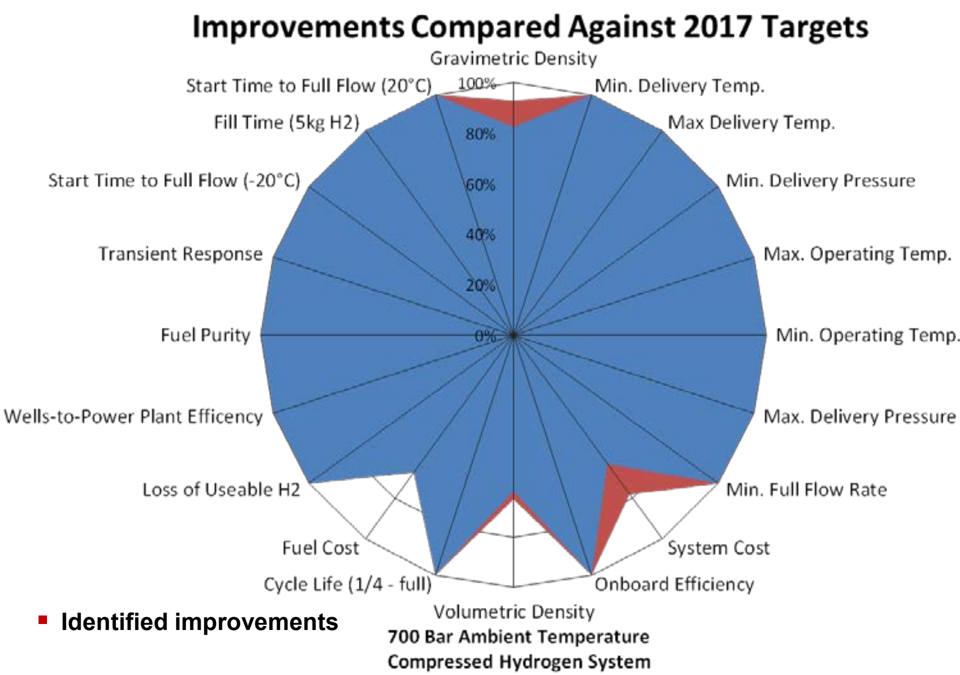
≤ 70 g H_2/L

2013 Progress: Cold/Cryo compressed H_2

U.S. DEPARTMENT OF ENERGY

Higher hydrogen densities are achieved through use of lower temperatures, thereby reducing system volume

Enhanced Materials and Design Parameters for Reducing the Cost of Hydrogen Storage

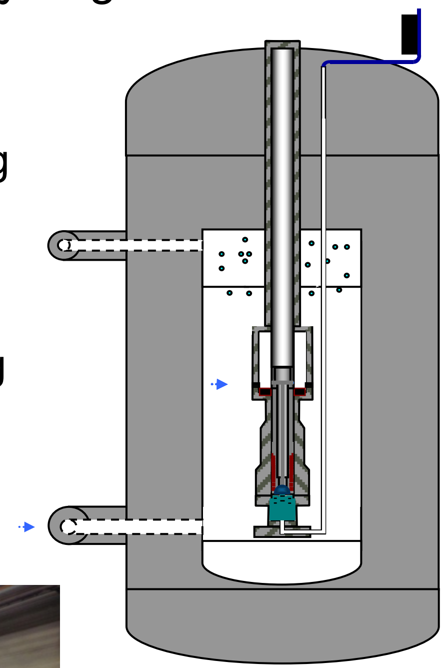


PNNL w/ Ford, Toray, AOC & Hexagon Lincoln (ST101)

Potential cost savings of 15% has been identified through low cost resins, resin modifications and alternative fiber placement.

Cryo-compressed storage offers potential to exceed liquid hydrogen densities

A liquid cryopump allows the direct fueling of supercritical hydrogen into a pressure capable cryogenic tank, offering potential for increased hydrogen densities.



A 900 bar rated liquid hydrogen cryopump is being installed at LLNL. (PD092)

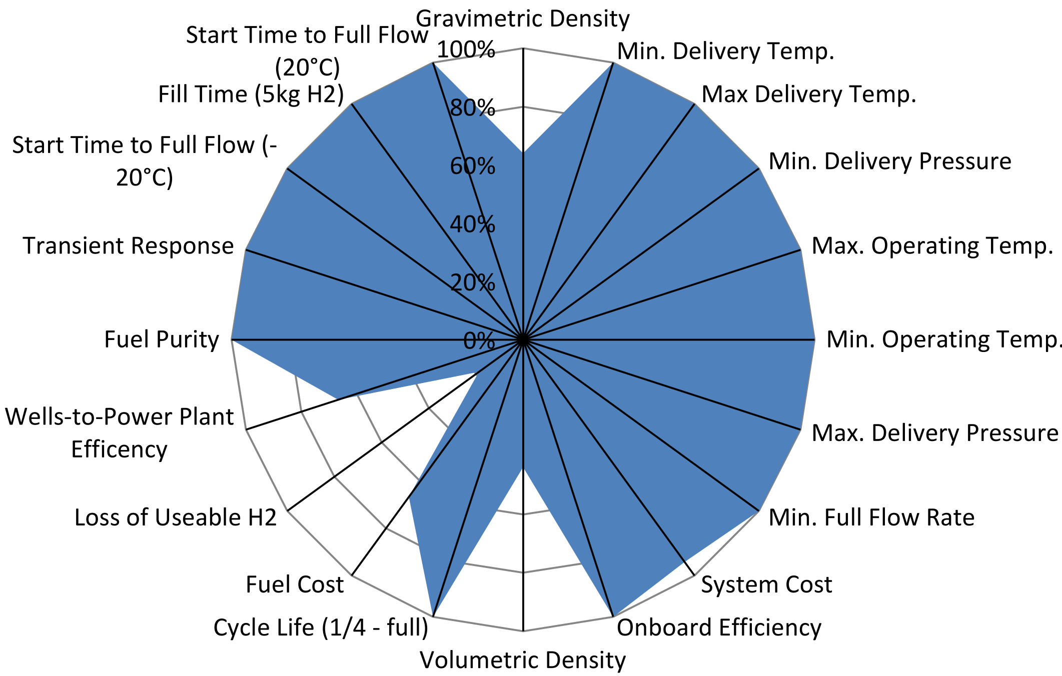
2013 Progress: Hydrogen Sorbents

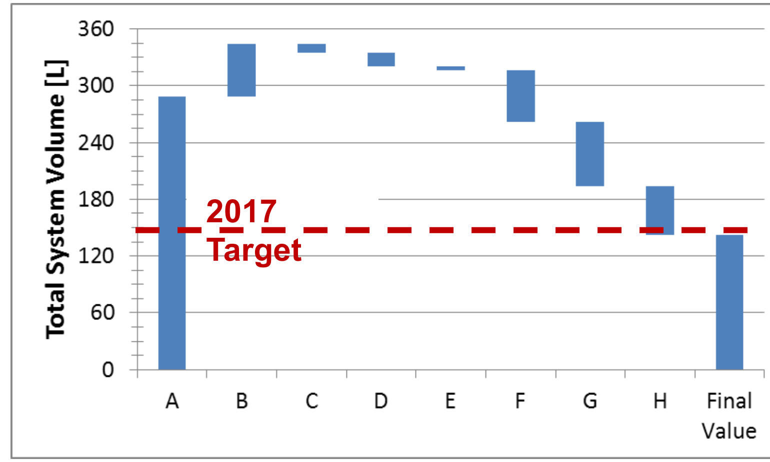
U.S. DEPARTMENT OF ENERGY

Cryo-sorbents offer potential for significantly lower hydrogen storage pressures without sacrificing volumetric density

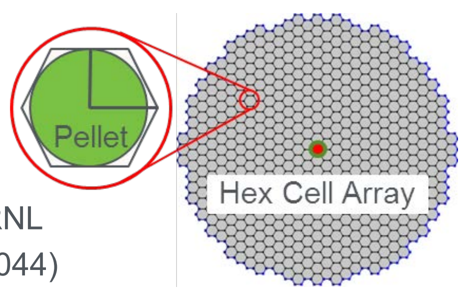
Sorbent System vs 2017 Targets

MOF-5 Powder, HexCell HX, Type 1 Al tank, 100 bar, 80 K





Step	Description
A	Phase 1 Baseline – Activated Carbon; Type 3 tank; Full at 80K, 200 bar; FT Cooling + Generic Resistance Heater
B	Set Operating Conditions to 80 K, 100 bar, Type 1 Al Tank
C	Identify Internal Heat Exchanger Design: HexCell w/ Resistance Heater
D	Replace Activated Carbon with Powder MOF-5
E	Improve BOP (reduces mass & volume by 25%)
F	Maintain Capacity with increased Operating Temperature (reduce MLVI by 50%; remove LN_2)
G	Increase Material Capacity to 140% of Powdered MOF-5
H	Increase Material Capacity to 200% of Powdered MOF-5



SRNL (ST044)

SRNL (ST004)

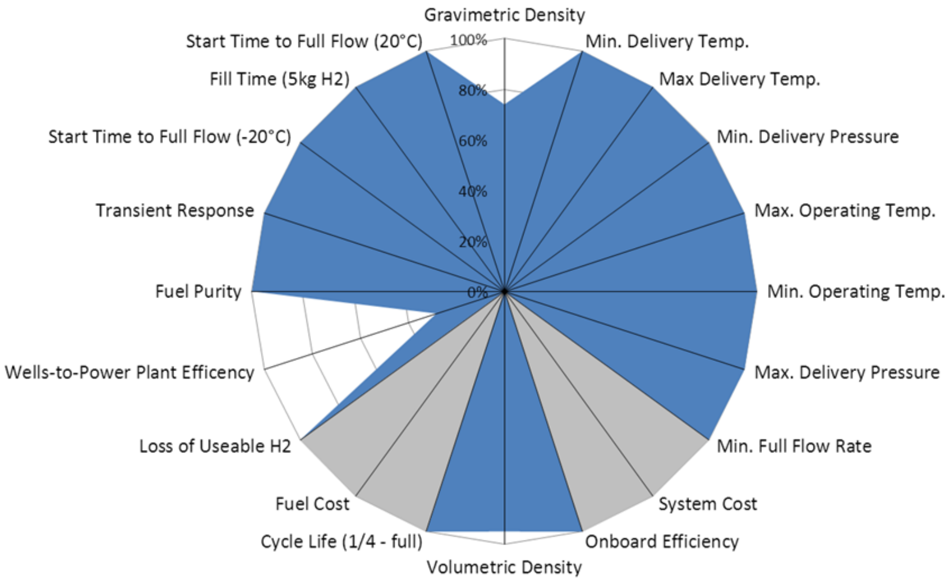
2013 Progress: Chemical Hydrogen Storage

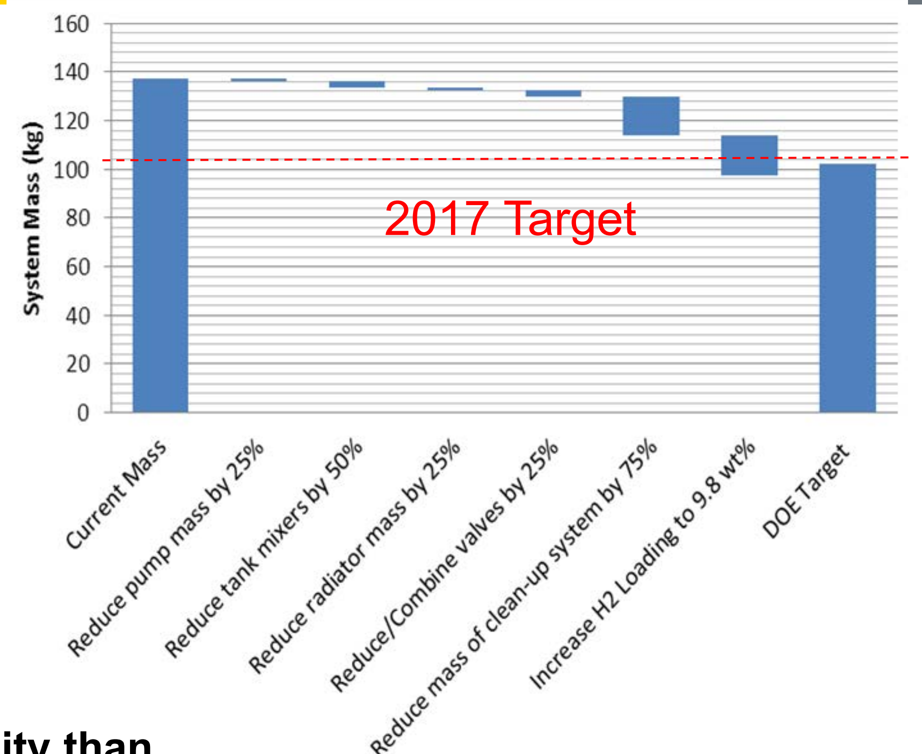
U.S. DEPARTMENT OF ENERGY

Chemical hydrogen storage materials offer the potential to meet volumetric density targets while maintaining liquid state; however, regeneration costs must be reduced

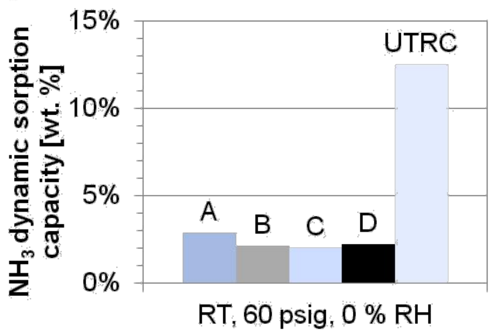
Chemical System vs 2017 Targets

50 wt% AB slurry in silicon oil





- **Developed NH_3 scrubber with 6X higher capacity than commercial adsorbents** **(UTRC ST006)**
- **Developed pathways to exceed gravimetric & volumetric targets** **(LANL ST007, PNNL ST005)**
- **Developed novel liquid phase CHS materials that remain as liquids** **(LANL ST040, UO ST104)**
- **Increased efficiency of AlH_3 regen** **(SRNL ST063)**



Progress – Best Practices for Characterization of Hydrogen Storage Materials

U.S. DEPARTMENT OF ENERGY

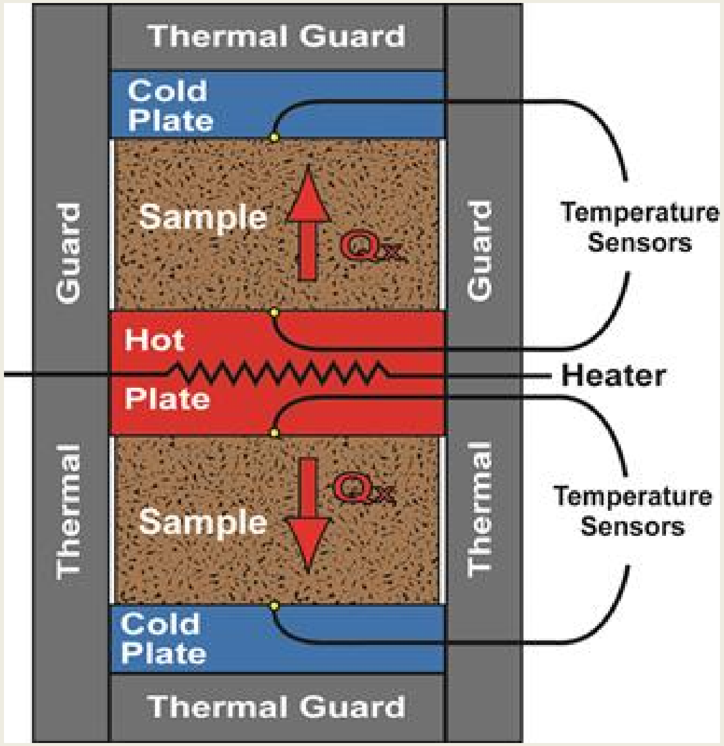
The best practices document for the characterization of hydrogen storage materials has been expanded to include engineering related properties

Two New Sections

- **Task 6: Engineering Thermal Properties**
  - Review measurement techniques in current use for determining thermal conductivity and heat capacity properties of hydrogen storage materials.
  - Evaluate common thermal property measurement methods used in other applied materials fields that may be appropriate for hydrogen storage materials.
- **Task 7: Engineering Mechanical Properties**
  - Examine benefits and limitations of methods for measuring porosity, skeletal, apparent, and packing densities.
  - Validate that small sample measurements scale to full system performance.
  - Present currently used and alternative methods for measuring material expansion forces.

(ST052)

Example: **Measurements Methods - Engineering Thermal Properties of Hydrogen Storage Materials**



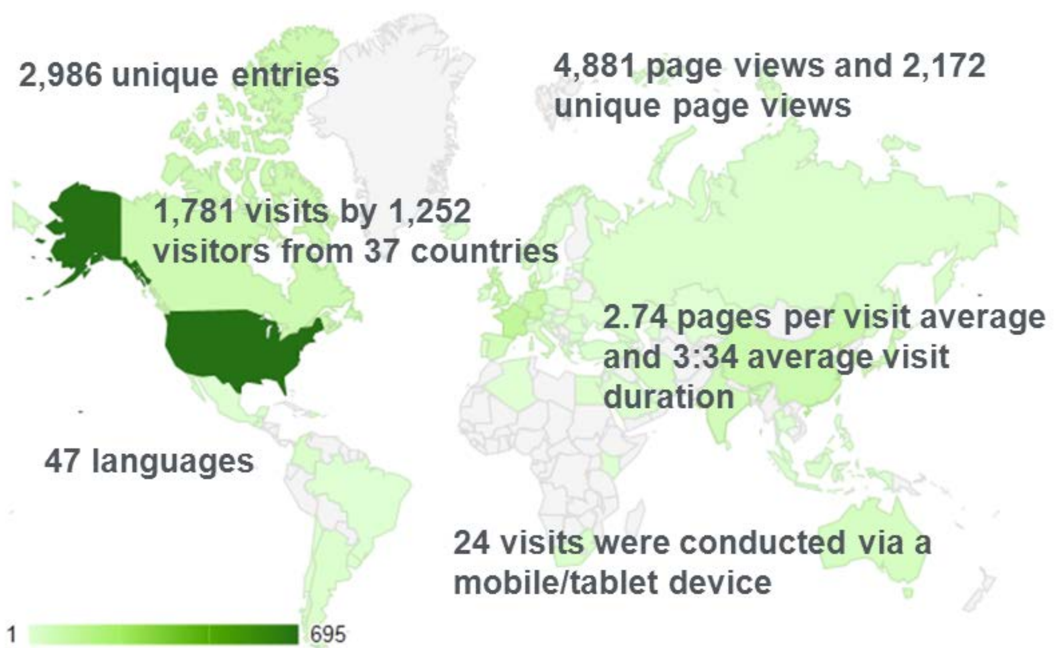
Schematic of Basic Guarded Hot Plate Design.

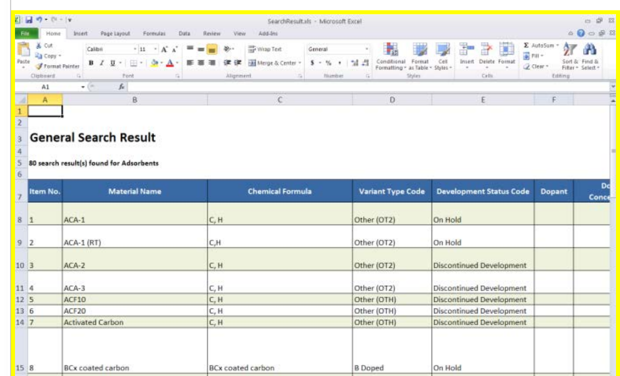
Hydrogen Storage Materials Database

Launched a comprehensive hydrogen storage materials database to collect and disseminate materials data and accelerate advanced materials research and development

Launched open source database* on Hydrogen Storage Materials Properties

http://hydrogenmaterialssearch.govtools.us/





Item No.	Material Name	Chemical Formula	Variant Type Code	Development Status Code	Dopant
1	ACA-1	C, H	Other (OT2)	On Hold	
2	ACA-1 (RT)	C,H	Other (OT2)	On Hold	
3	ACA-2	C, H	Other (OT2)	Discontinued Development	
4	ACA-3	C, H	Other (OT2)	Discontinued Development	
5	ACF10	C, H	Other (OTH)	Discontinued Development	
6	ACF20	C, H	Other (OTH)	Discontinued Development	
7	Activated Carbon	C, H	Other (OTH)	Discontinued Development	
8	BCx coated carbon	BCx coated carbon	B Doped	On Hold	

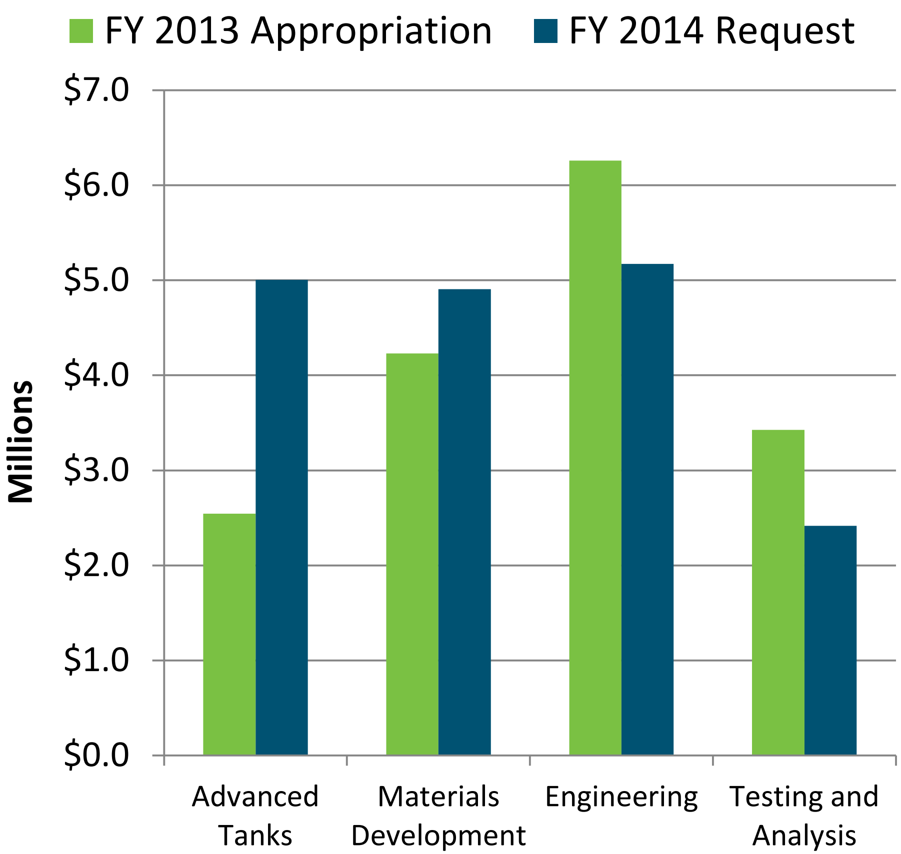
Search results exported to Excel

* Included in President's Materials Genome Initiative (MGI), http://www.whitehouse.gov/mgi

Hydrogen Storage Budget

U.S. DEPARTMENT OF ENERGY

FY 2013 Appropriation = $16.5M
FY 2014 Request = $17.5M



FY14 funds subject to appropriations and FOA decisions.

EMPHASIS

- Systems approach through the Engineering CoE, in collaboration with independent materials development projects, to achieve light-duty vehicle targets
- Continued close coordination with Basic Energy Science in 2013 & 2014 and improve coordination with National Science Foundation, ARPA-e, and Energy Frontier Research Centers activities
- Focus on cost reduction for high pressure tanks
- Increased analysis efforts for low to high production volumes
- Increased emphasis on early market storage applications

FOA Release Planned

U.S. DEPARTMENT OF ENERGY

Funding Opportunity Announcement for Research and Development Activities for Hydrogen Storage Technologies*

New opportunities for applied research and development activities to advance hydrogen storage technologies. Applications sought for automotive and non-automotive applications.

- Reducing the Cost of Compressed Hydrogen Storage Systems
- Lower Cost Carbon Fiber Composites and Balance of Plant Components for Hydrogen Storage Systems
- Novel Materials Discovery for Hydrogen Storage

Tentative Schedule

May 14th, 2013:
FOA Workshop
6:00PM – Crystal Gateway Marriott

May 23, 2013
Notice of Intent Issued

June 2013:
FOA Issued

July 2013:
Concept Papers Due

September 2013:
Final Applications Due

1st Quarter FY14:
Selections Announced

***Subject to FY14 appropriations**

Hydrogen Storage Collaborations

U.S. DEPARTMENT OF ENERGY

Applied R&D is coordinated among national and international organizations

DOE Intra-agency
- BES
- ARPA-E
- Other EERE

INTERNATIONAL ACTIVITIES
- IEA-HIA
- IPHE

DOE – EERE
Hydrogen Storage Applied R&D
- Hydrogen Storage Engineering Center of Excellence
- Independent projects:
  - Physical Storage
  - Hydrogen Sorbents
  - Chemical Storage
  - Metal Hydrides

INDUSTRY
- U.S. DRIVE Partnership Tech teams:
  - H_2 Storage
  - Fuel Cells
  - Fuel Pathways
  - Vehicle Systems
- Codes & Standards Organizations

TECHNOLOGY VALIDATION

>180 vehicles & 25 stations

National Collaborations (interagency efforts)

DOT
Material Handling/Transport

DOD – DLA
System Development & Deployment

NASA
Tanks & Engineering

NIST
Neutron Characterizations

NSF
Basic & Fundamental R&D

For more information contact:

The Hydrogen Storage Team

Ned Stetson - Team Lead **202-586-9995** **ned.stetson@ee.doe.gov**	
Grace Ordaz 202-586-8350 grace.ordaz@ee.doe.gov	Jesse Adams 720-356-1421 jesse.adams@go.doe.gov
Scott McWhorter On Assignment from SRNL 202-586-7009 christopher.mcwhorter@ee.doe.gov	Katie Randolph 720-356-1759 katie.randolph@go.doe.gov
Channing Ahn IPA from California Institute of Technology 202-586-9490 channing.ahn@ee.doe.gov	Kathleen O'Malley Support contractor 202-586-4786 kathleen.o'malley@ee.doe.gov