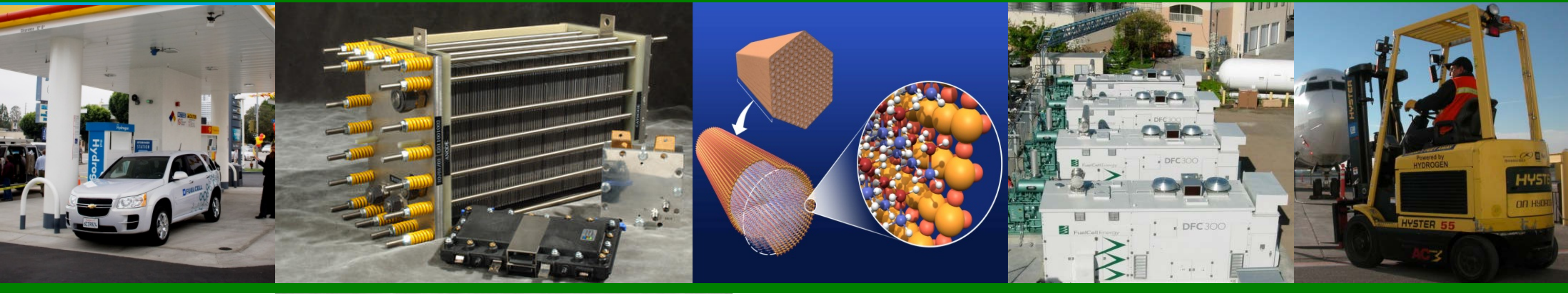
U.S. DEPARTMENT OF
ENERGY



Hydrogen Storage

-Session Introduction -

Ned Stetson

2013 Annual Merit Review and Peer Evaluation Meeting

May 14, 2013

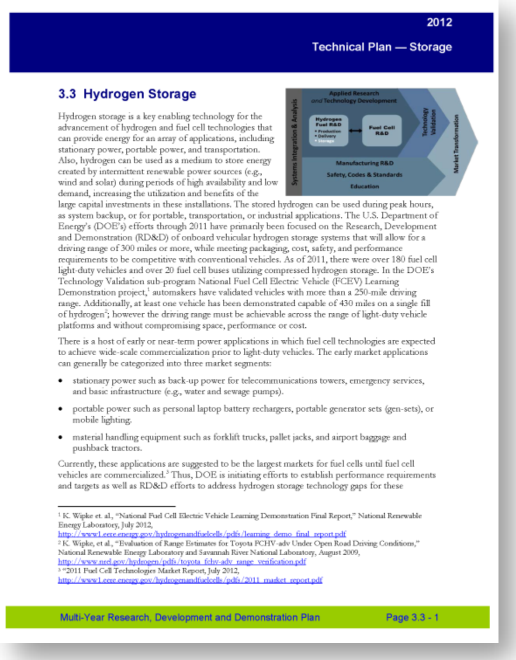
Goal and Objectives:

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

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

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

[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

Challenges: Non-Automotive

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

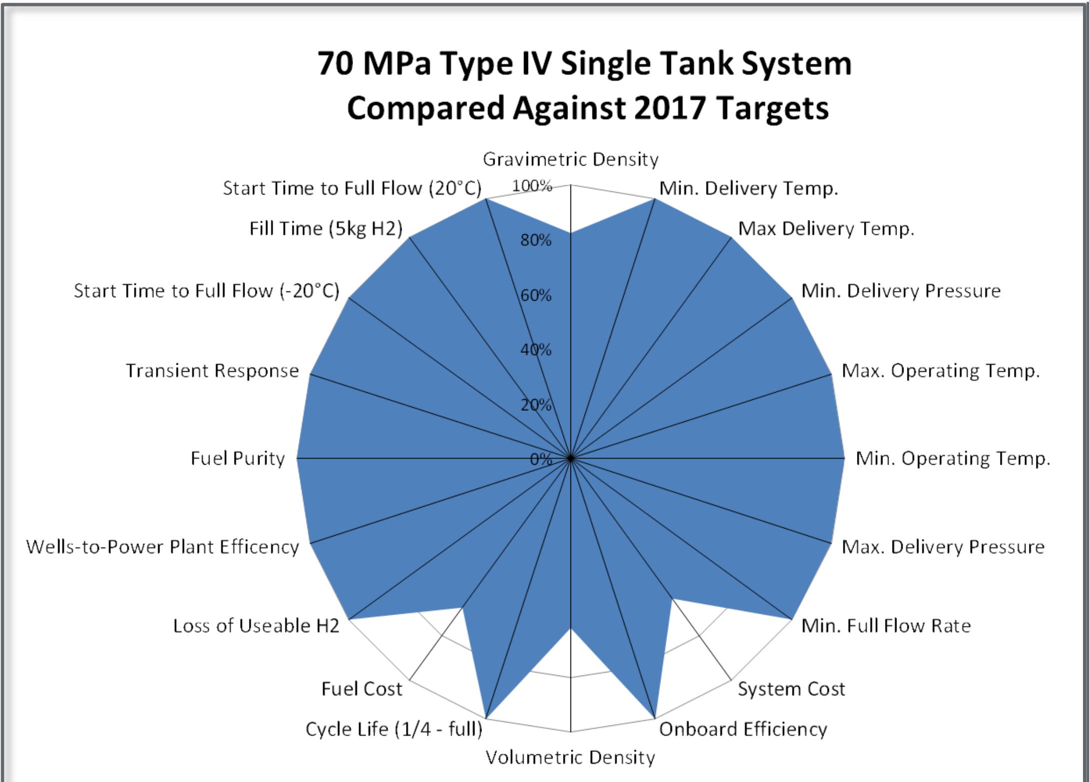
Portable Power Targets		Gravimetric kWh/kg (kg H_2/kg sys)	Volumetric kWh/L (kg H_2/L sys)	System Cost \$/kWh net (\$/g H_2)	
				<2.5W	>2.5-150W
2015	**Single-Use**	0.7 (0.02)	1.0 (0.03)	0.09 (3.0)	0.2 (6.7)
	Rechargeable	0.5 (0.015)	0.7 (0.02)	0.75 (25)	1.0 (33)
2020	**Single-Use**	1.3 (0.04)	1.7 (0.05)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

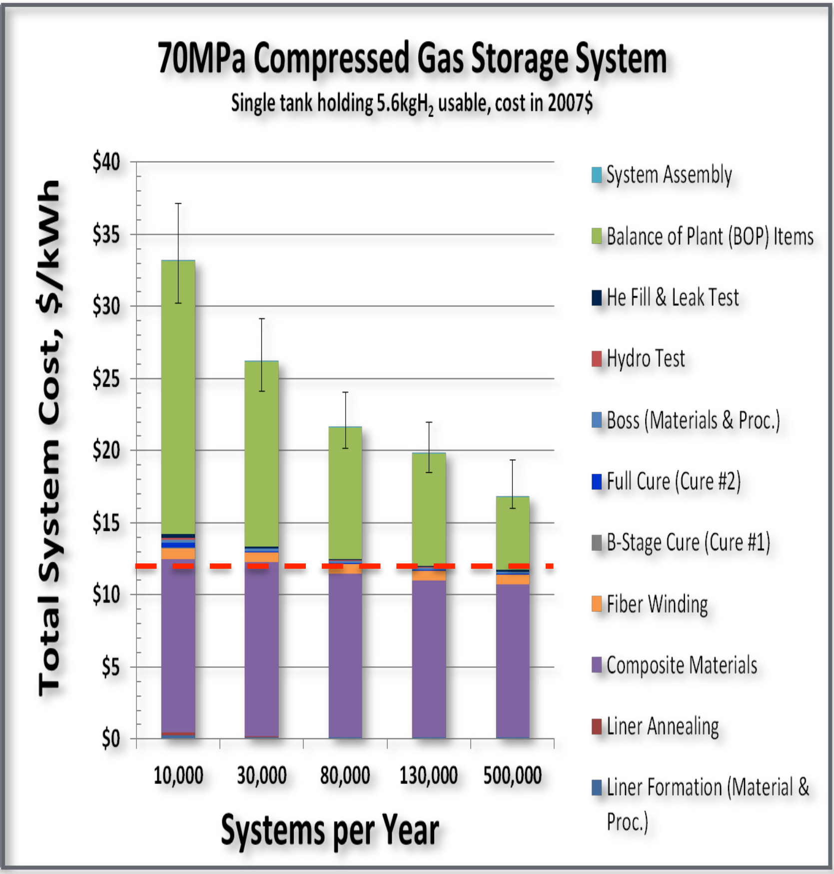
Portable Power

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

Near-term strategy for lowering costs

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**

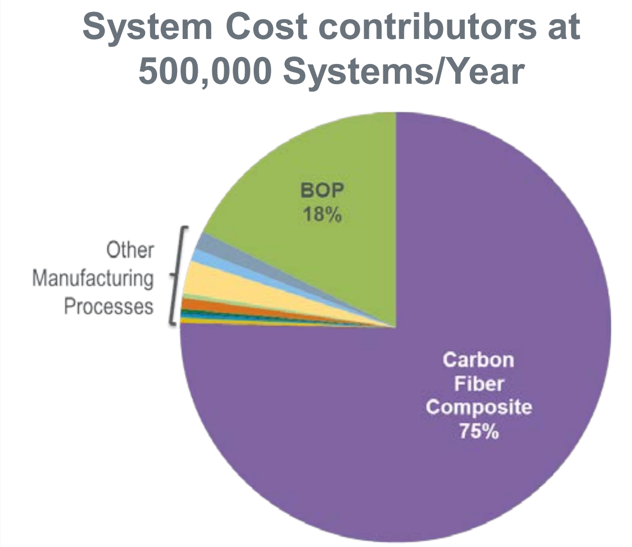
ANL (ST001)

Strategic Analysis, Inc. (ST100)

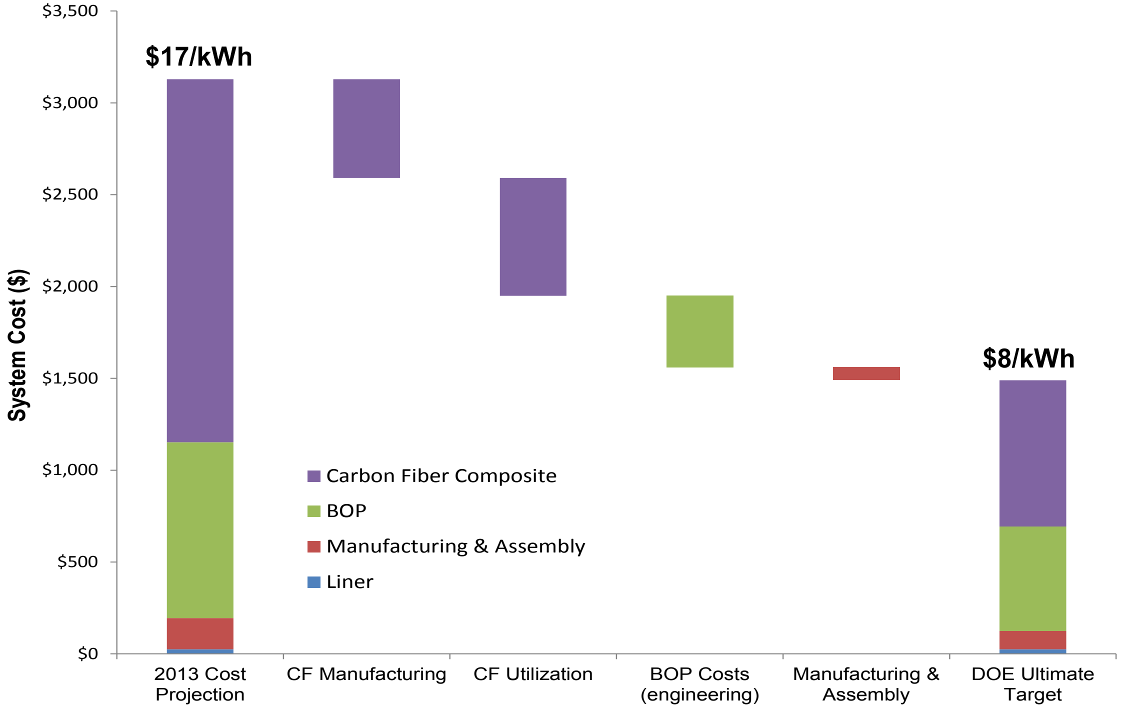
Near-term strategy for lowering costs

U.S. DEPARTMENT OF ENERGY

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



Over 75% of cost is in carbon fiber!



Near-term Focus

Cost reductions required to meet DOE cost target:

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

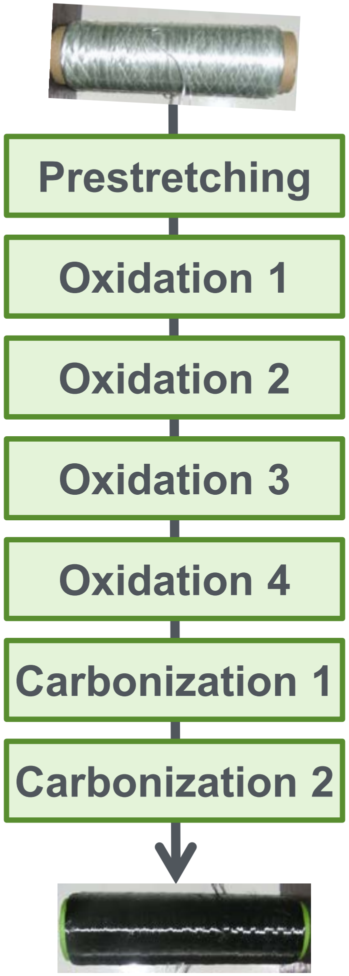
Projects Addressing R&D Needs:

- 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

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



Prestretching

Oxidation 1

Oxidation 2

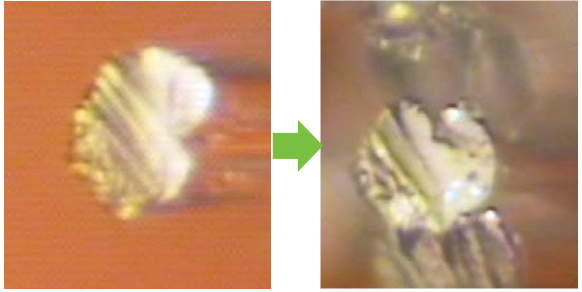
Oxidation 3

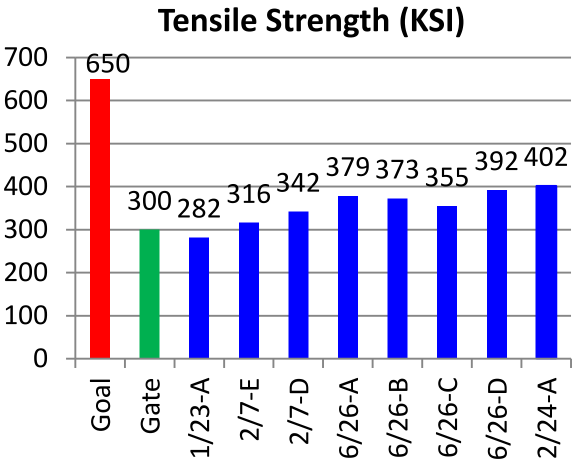
Oxidation 4

Carbonization 1

Carbonization 2

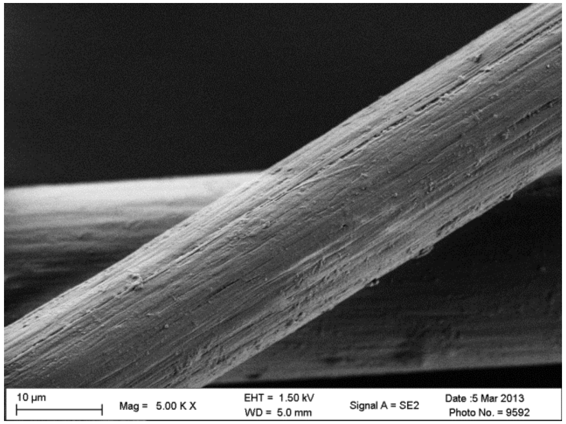
<u>Air Gap Spinning</u> introduced to help resolve kidney shaped fiber issue





ORNL with FISIPE (ST099)

Significant improvement obtained with post stretched melt-spun PAN fibers



Post treatment stretching results in smooth, smaller diameter PAN fibers

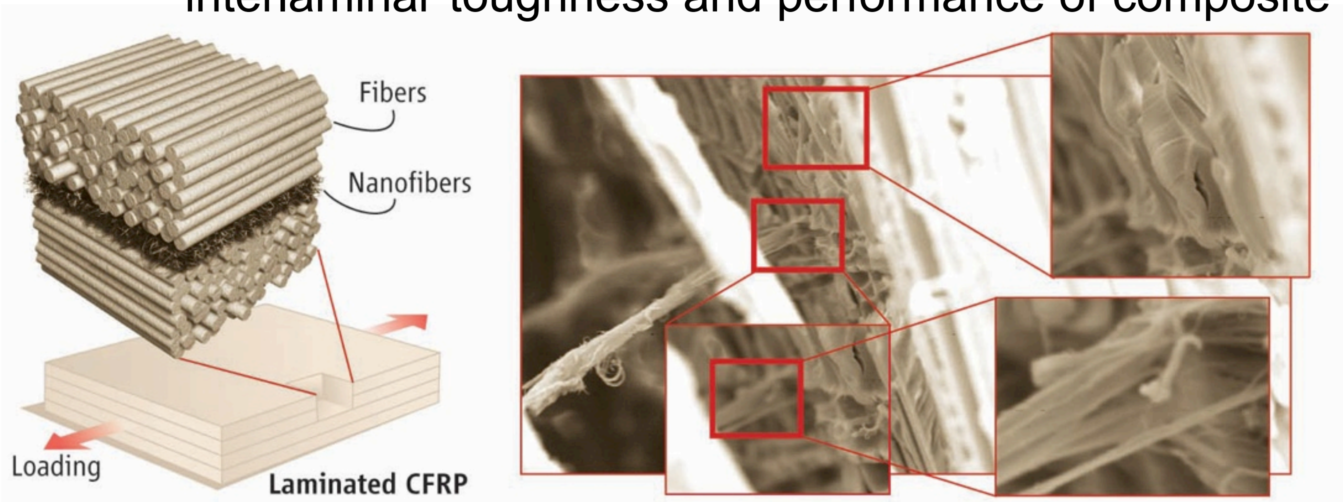
Date of carbonization	Sample	Peak stress [ksi]	Modulus [Msi]
Feb. 2012	VT_201201	Could not be unspooled	
Apr. 2012	VT_201203	76.5	16.1
Jun. 2012	VT_201205	77.4	6.2
Mar. 2013	VT_20121129_S6_B	222.4 (84.0)	22.4 (2.6)
	VT_20121129_S7_A	**261.4 (67.2)**	**25.3 (3.1)**
	VT_20121129_S7_B	212.0 (31.8)	20.8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

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

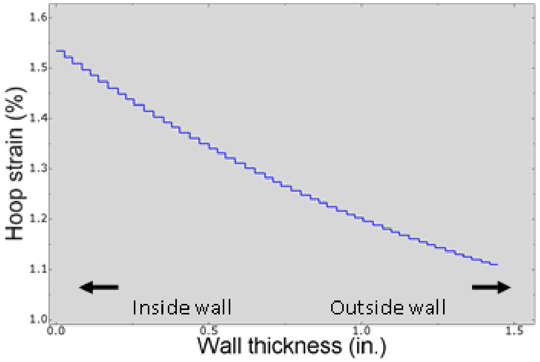
Initiated new SBIR project to develop integrated nanoreinforcement to improve interlaminar toughness and performance of composite pressure vessels



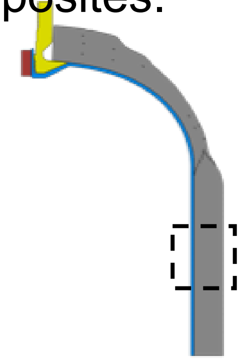
Nanofibers deposited between CF composite layers will improve damage resistance, interlaminar toughness, shear strength and burst strength.

NextGen Aeronautics (ST109)

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

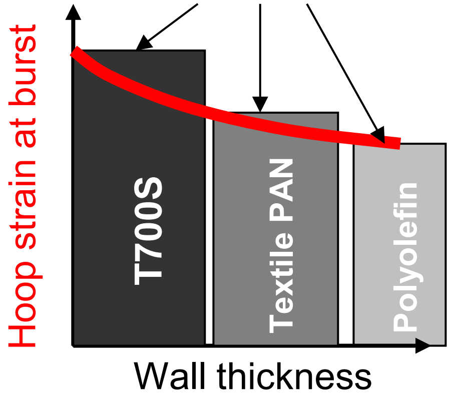


Thick wall effects leads to lower strain in outer wrappings, so optimizing CFC properties can lead to reduced costs.



Composite Technology Development (ST110)

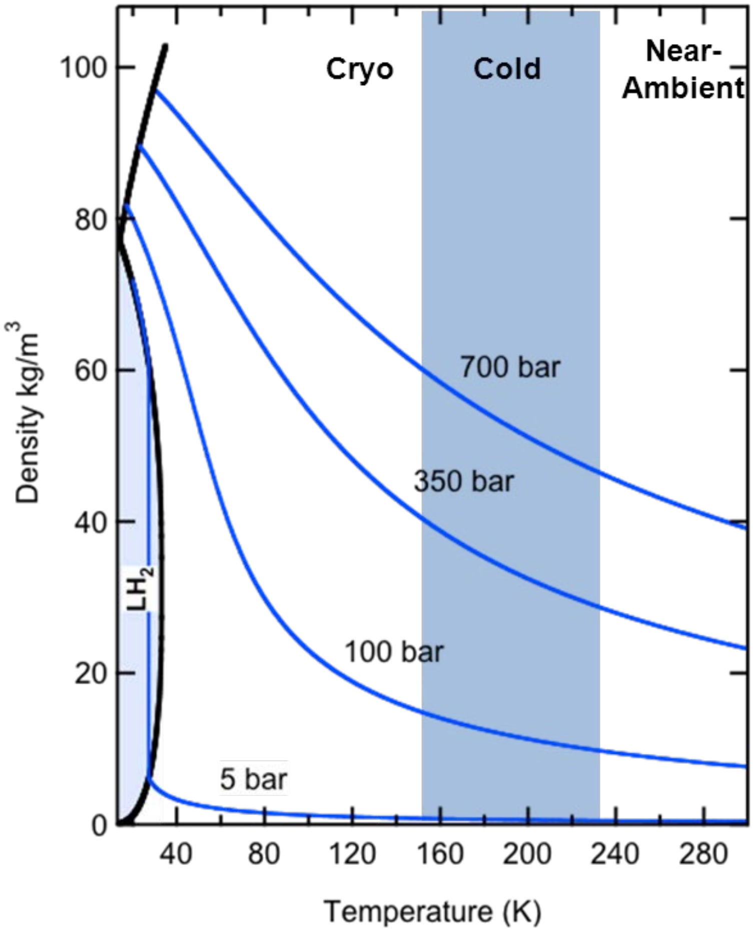
Allowable failure strains for different fiber types



Long-term Strategies

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



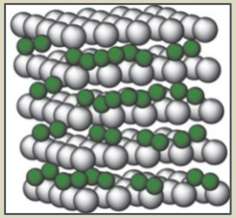
Investigating potential for cold and cyro-compressed H_2

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

Developing materials-based H_2 storage technologies

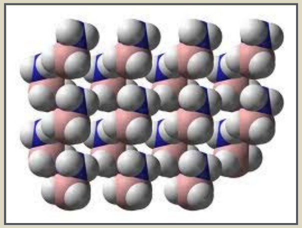
- Developing materials with required capacity, thermodynamic and kinetic properties
- Developing balance-of-plant components
- Understanding implications and costs at forecourt

Materials-based Storage



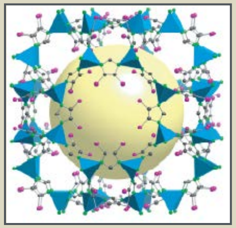
interstitial hydrides

~100-150 g H_2/L



chemical storage

~70-150 g H_2/L



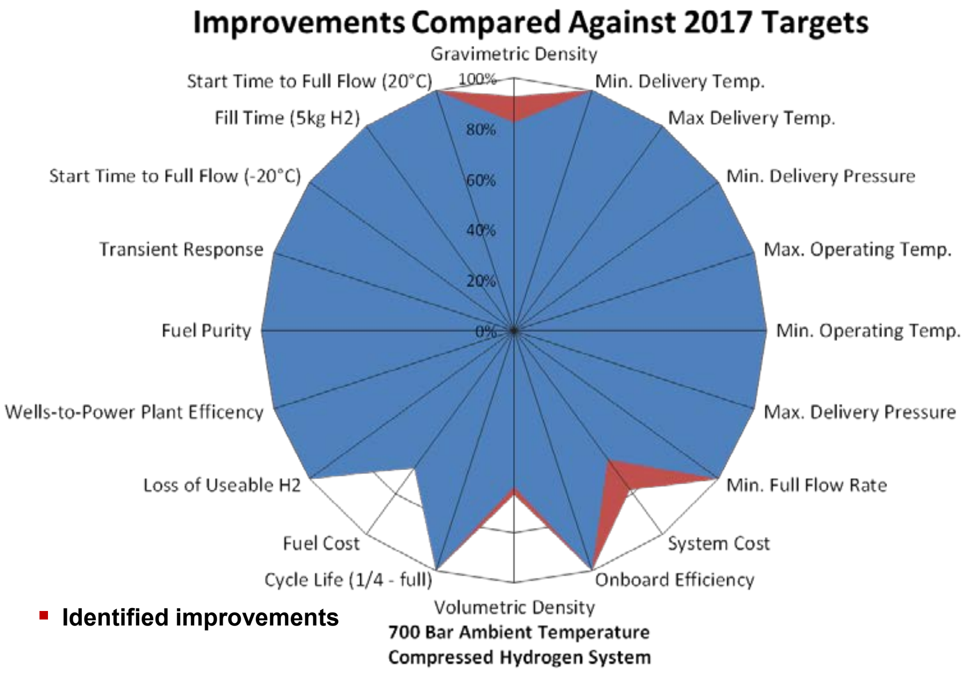
sorbents

≤ 70 g H_2/L

2013 Progress: Cold/Cryo compressed H_2

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



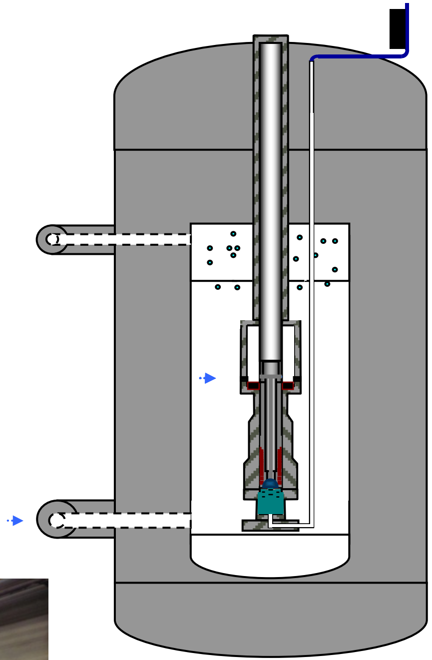
700 Bar Ambient Temperature Compressed Hydrogen System

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.



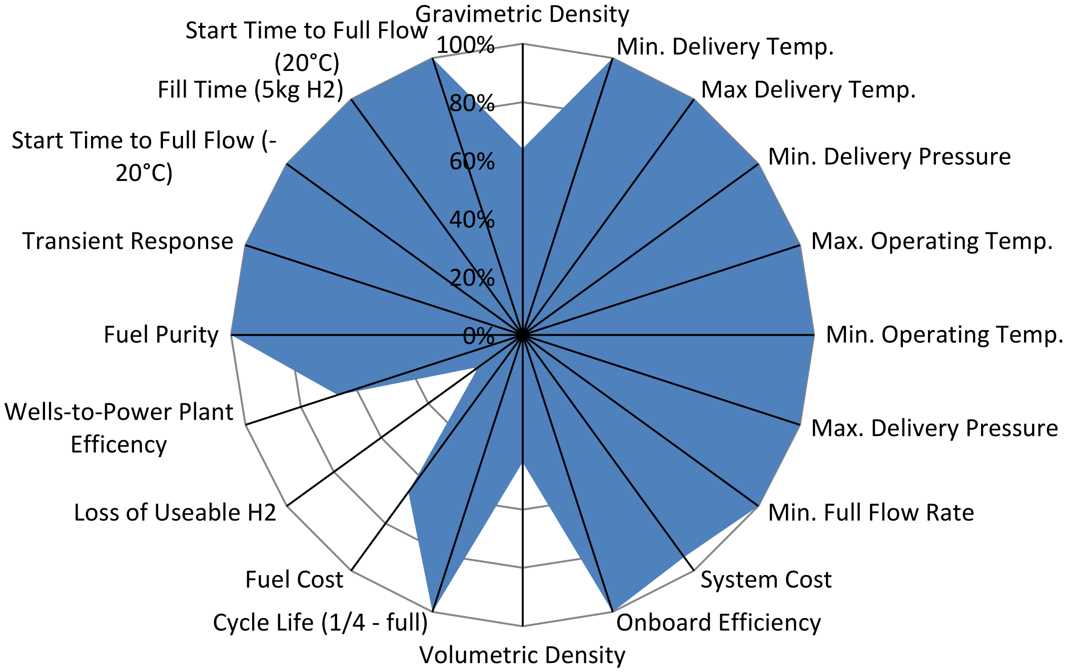
A 900 bar rated liquid hydrogen cryopump is being installed at LLNL. (PD092)

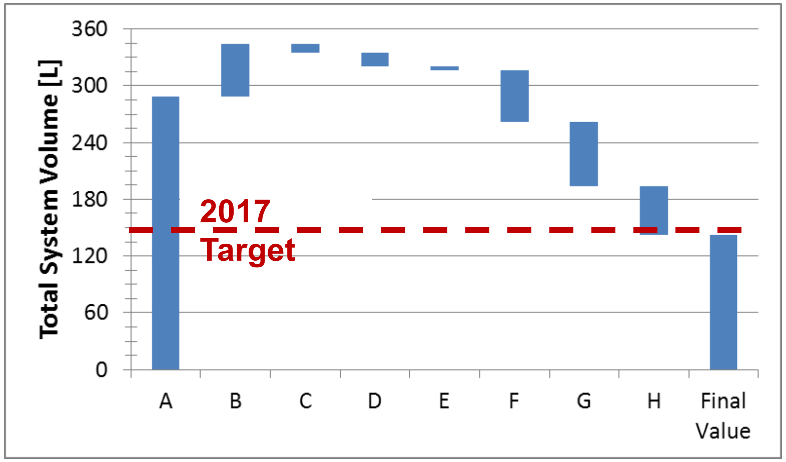
2013 Progress: Hydrogen Sorbents

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

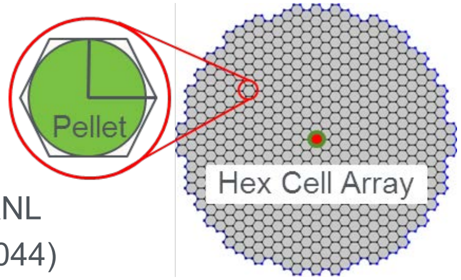
Sorbent System vs 2017 Targets

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)

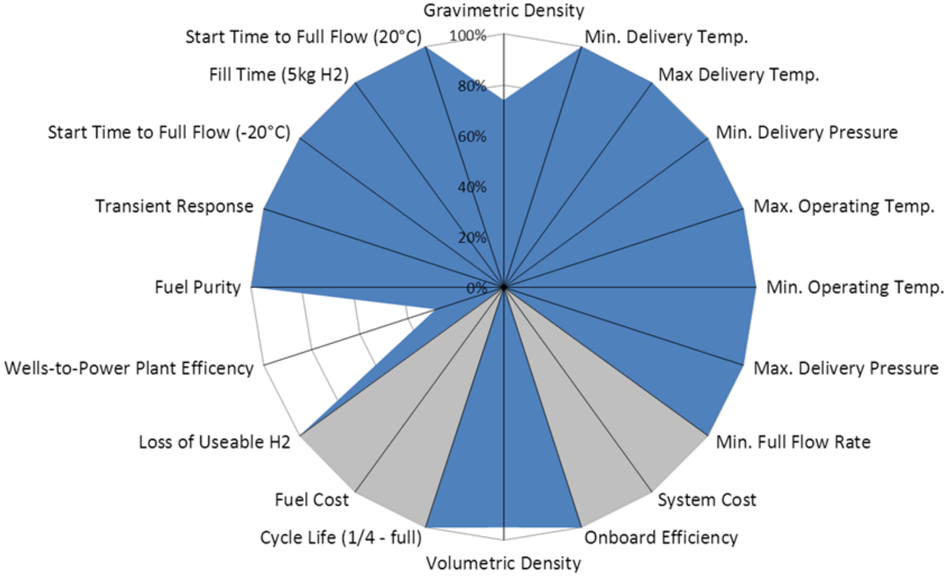
SRNL (ST004)

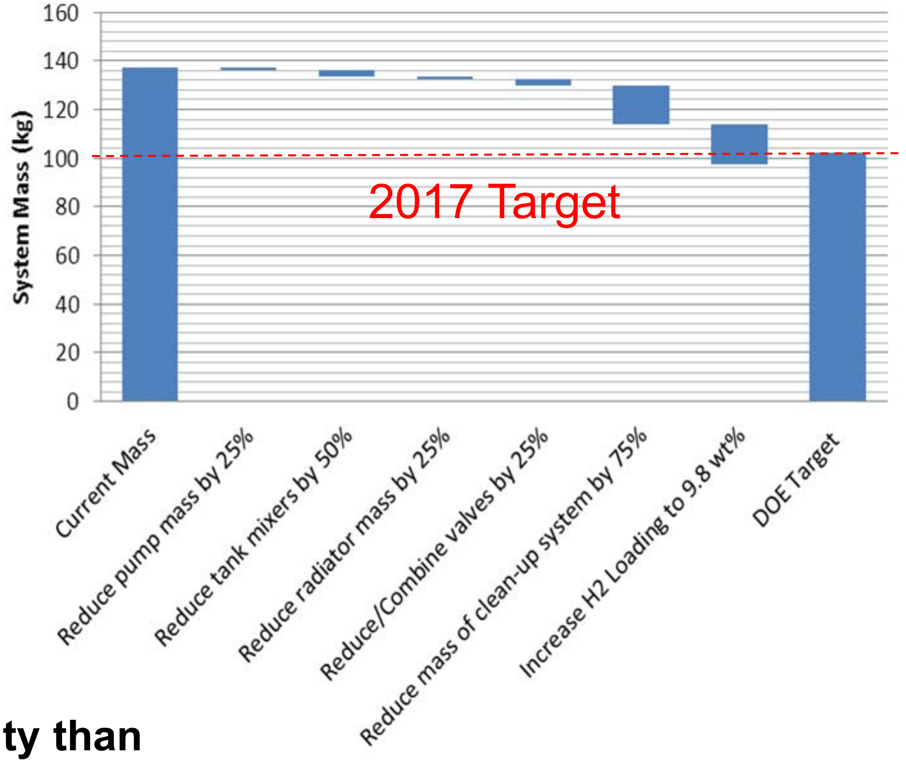
2013 Progress: Chemical Hydrogen Storage

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

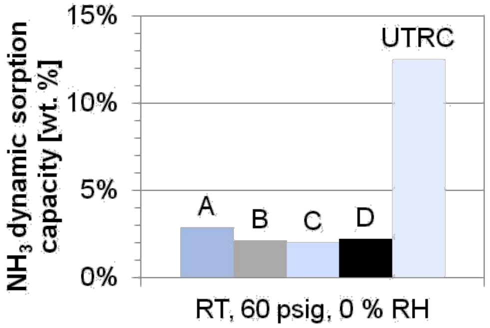
Chemical System vs 2017 Targets

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 post dehydrogenation** (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

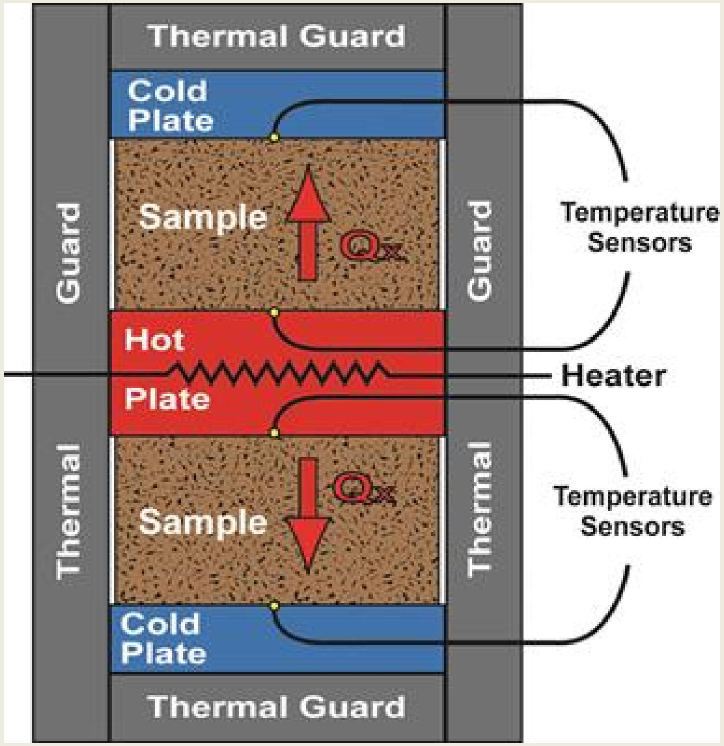
Two New Sections

- **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.

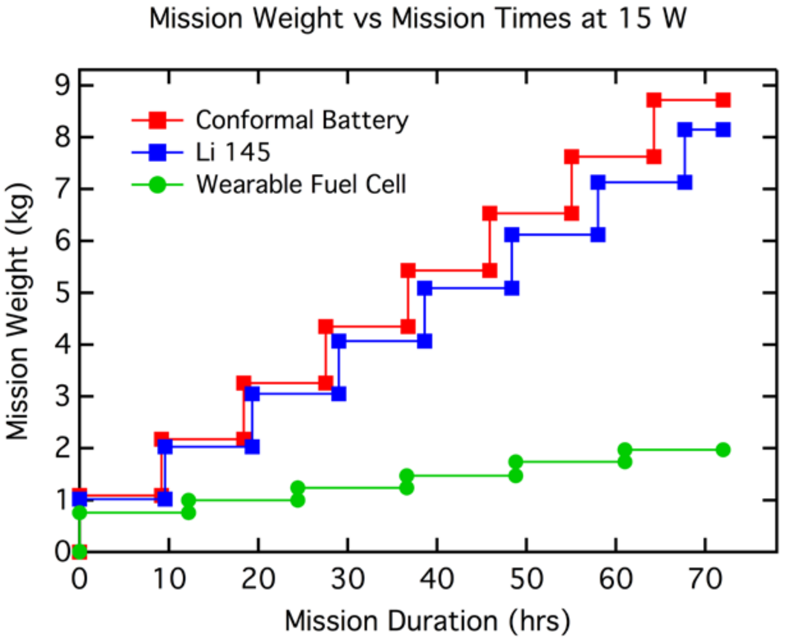
Non-automotive Strategies –

Advanced H_2 storage technologies can enable near-term commercialization of H_2 fuel cell devices in non-automotive applications

Portable Power

- H_2-FC devices can offer lower mass compared to batteries when longer runtimes required.

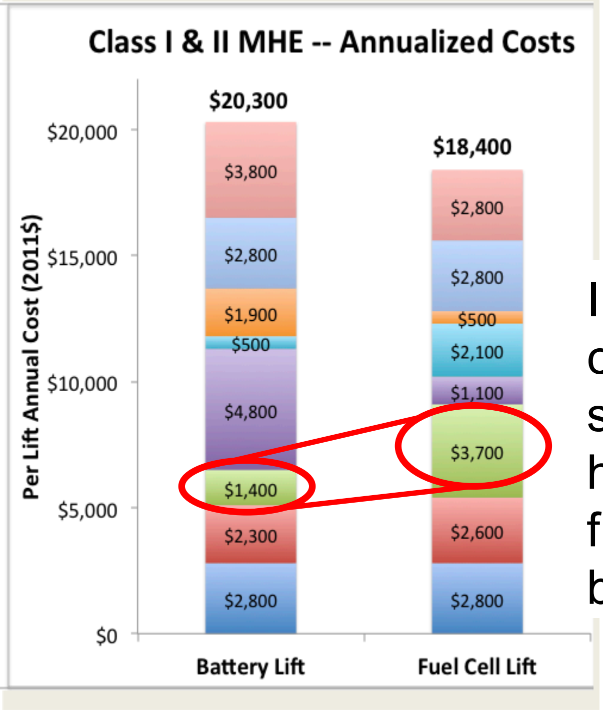
A 6⁺ kg mass savings for AlH_3 fueled FC vs batteries for a 72 hour mission[1]



Material Handling Equipment

- Low-pressure H_2 storage may expand market for small MHE fleets

Infrastructure costs a major barrier for hydrogen fuel cell forklifts[2]



Infrastructure costs significantly higher for H_2 fuel cell vs battery forklifts

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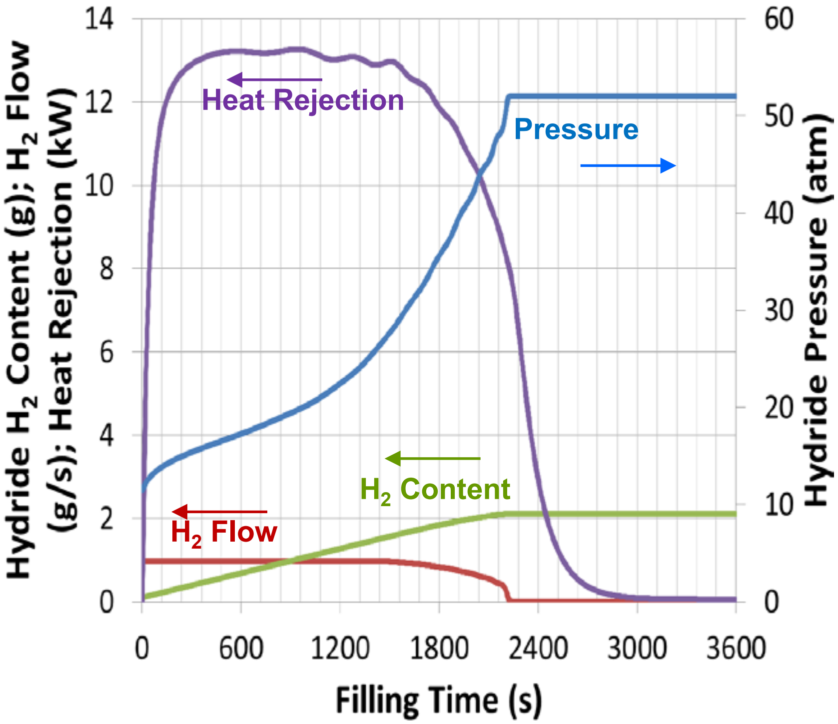
[1] M. Dominick, T. Thampan, J. Novoa, S. Shah, U.S. Army CERDEC's Soldier-Wearable Fuel Cell Developments and Testing, Proc. 45th Power Sources Conf., Las Vegas, June 2012.

[2] J. Kurtz, S. Sprik, T. Ramsden, G. Saur, C. Ainscough, "What We've Learned from 2.5 Years of Early Market Fuel Cell Operation," http://www.nrel.gov/hydrogen/cfm/pdfs/57759.pdf

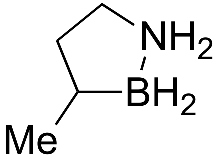
Progress – Non-automotive applications

Material Handling Equipment - Demonstrated significantly shorter charging times (37 minutes for full charge vs ~40% charge in 60 minutes) with constant H_2 flow vs constant H_2 pressure methods (SBIR – Phase 2)

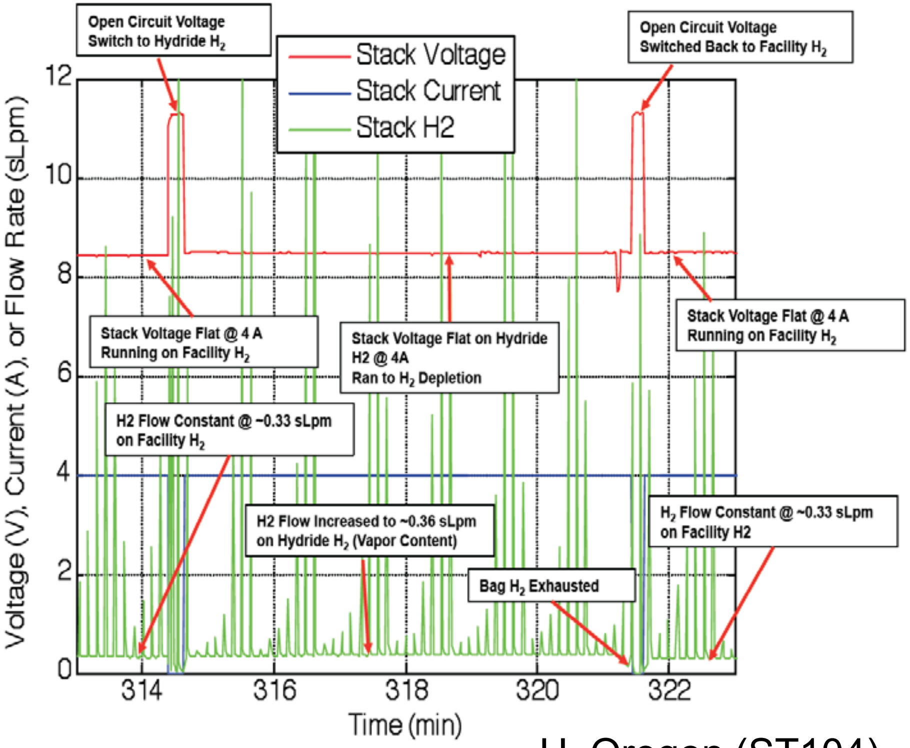


HHC (ST095)

Portable Power Devices - Demonstrated stable fuel cell operation with hydrogen released from CBN materials - Compound B:



(23 minutes runtime on 33W, 4A Protonex fuel cell system)

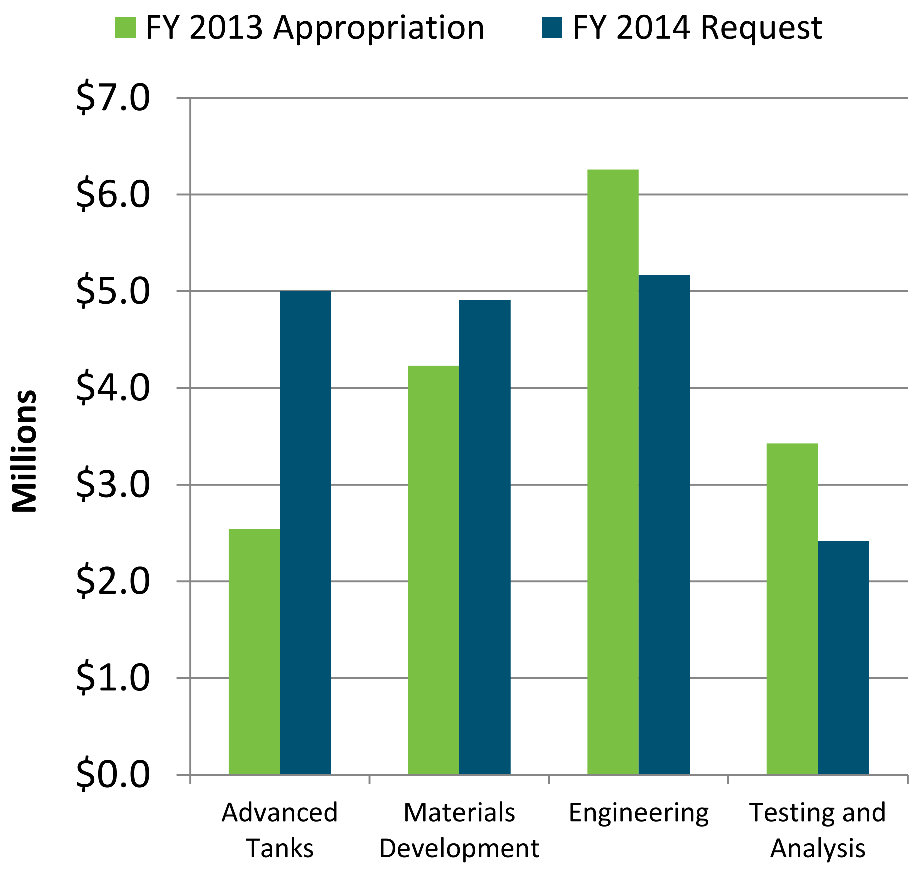


U. Oregon (ST104)

Hydrogen Storage Budget

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

*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**

Summary

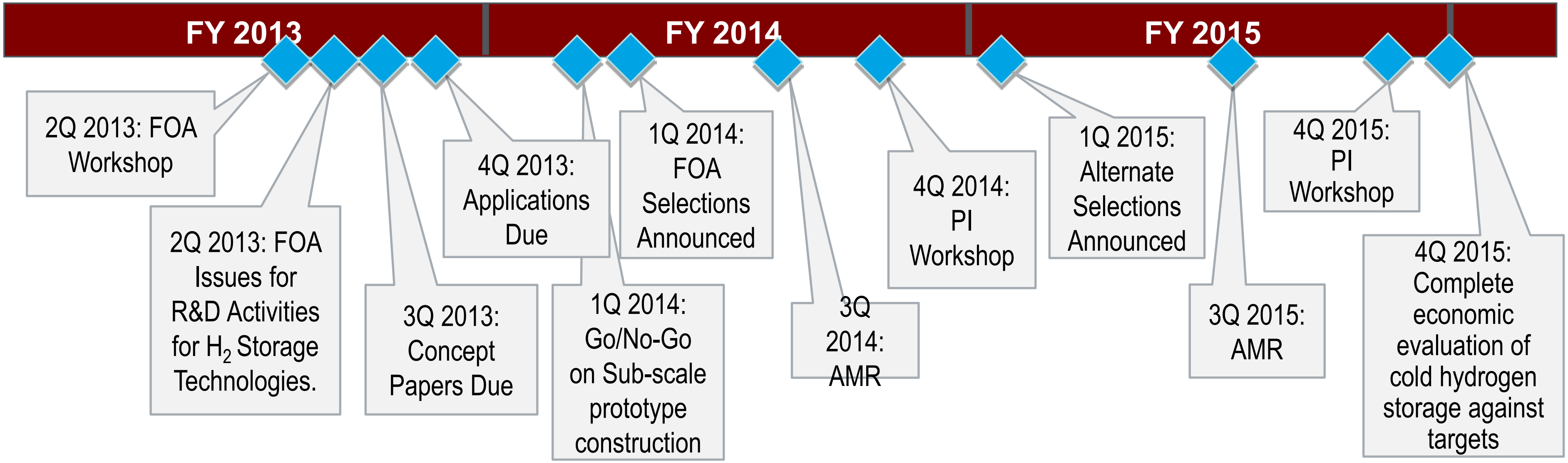
Key milestones and future plans

Physical Storage

- Projects underway to reduce the cost of carbon fiber precursors
- Initiated new efforts through SBIR and Funding Opportunity Announcement topics

Material-based Storage

- Hydrogen Storage Engineering Center of Excellence is transitioning to Phase 3: System Prototyping to validate modeled projections and proving design concepts
- Continued to improve materials-based performance through independent projects
- Released performance targets for material handling equipment and portable power



2Q 2013: FOA Workshop

2Q 2013: FOA Issues for R&D Activities for H_2 Storage Technologies.

3Q 2013: Concept Papers Due

4Q 2013: Applications Due

1Q 2014: Go/No-Go on Sub-scale prototype construction

1Q 2014: FOA Selections Announced

3Q 2014: AMR

4Q 2014: PI Workshop

1Q 2015: Alternate Selections Announced

3Q 2015: AMR

4Q 2015: PI Workshop

4Q 2015: Complete economic evaluation of cold hydrogen storage against targets

For more information contact:

U.S. DEPARTMENT OF ENERGY

The Hydrogen Storage Team

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Session Instructions

- This is a review, not a conference.
- Presentations will begin precisely at scheduled times.
- Talks will be 20 minutes and Q&A 10 minutes.
- Reviewers have priority for questions over the general audience.
- Reviewers should be seated in front of the room for convenient access by the microphone attendants during the Q&A.
- Please mute all cell phones and other portable devices.
- Photography and audio and video recording are not permitted.

Reviewer Reminders

- Deadline to submit your reviews is Friday, **May 24th at 5:00 pm EDT.**

- ORISE personnel are available on-site for assistance.
  - **Reviewer Lab Hours:**
    - Monday, 5:00 pm – 8:00 pm (Gateway ONLY)
    - Tuesday – Wednesday, 7:00 am – 8:00 pm (Gateway)
    - Thursday, 7:00 am – 6:00 pm (Gateway)
    - Tuesday – Thursday, 7:00 am – 6:00 pm (City)
  - **Reviewer Lab Locations:**
    - Crystal Gateway Hotel—*Rosslyn Room* (downstairs, on Lobby level)
    - Crystal City Hotel—*Roosevelt Boardroom* (next to Salon A)