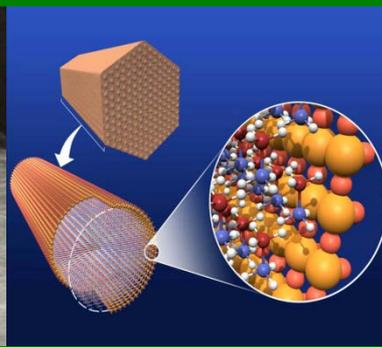




U.S. DEPARTMENT OF
ENERGY



Hydrogen Storage

Ned T. Stetson

*2011 Annual Merit Review and Peer Evaluation Meeting
May 9, 2011*

Goal: On-board hydrogen storage for > 300 mile driving range across different vehicle platforms, without compromising passenger/cargo space or performance

Develop on-board storage systems that meets **all** DOE system targets simultaneously.

- **System Engineering / Systems Analysis**
 - Demonstrate the technologies required to achieve the 2015 DOE on-board vehicle hydrogen storage goals
 - Continue storage system analysis/projections for advanced storage system capabilities & development of system models for on-board storage systems
 - Determining performance gaps for early market applications
- **R&D on materials for breakthrough storage technologies**
 - Increased focus on carbon fiber to reduce the cost of physical storage systems
 - Continue new hydrogen storage material discovery R&D for advanced storage systems
 - Strengthen coordination between basic & applied research within DOE and across agencies

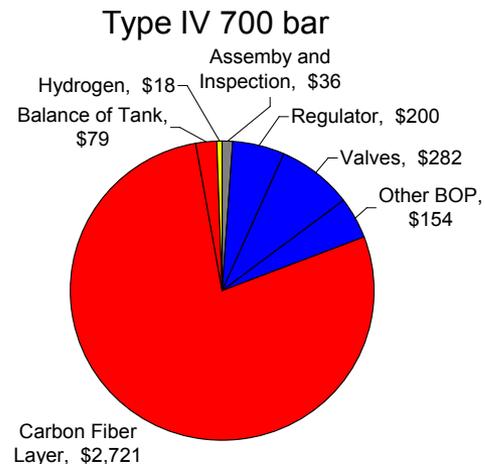
For all applications: Storing an adequate amount of hydrogen in an acceptably small volume efficiently at a reasonable temperature, pressure and cost

Near-term Option

Compressed gas storage offers a near-term option for initial vehicle commercialization* and early markets

- **Cost** of composite tank is challenging
- **> 75%** of the cost is projected to be due to the carbon fiber layer
- **50%** of the carbon fiber cost is estimated to be in the precursor

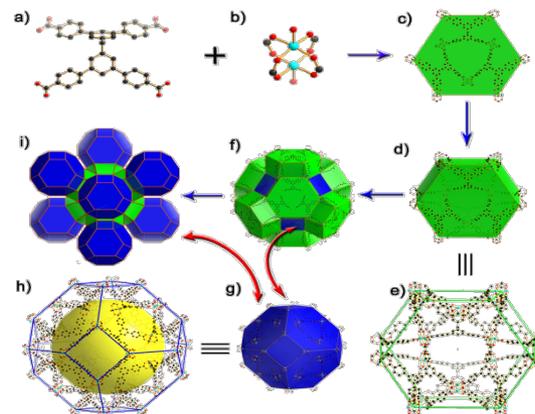
Cost is in the CF Matrix!



Long-term Options

Materials-based solutions targeted to meet all on-board storage targets simultaneously

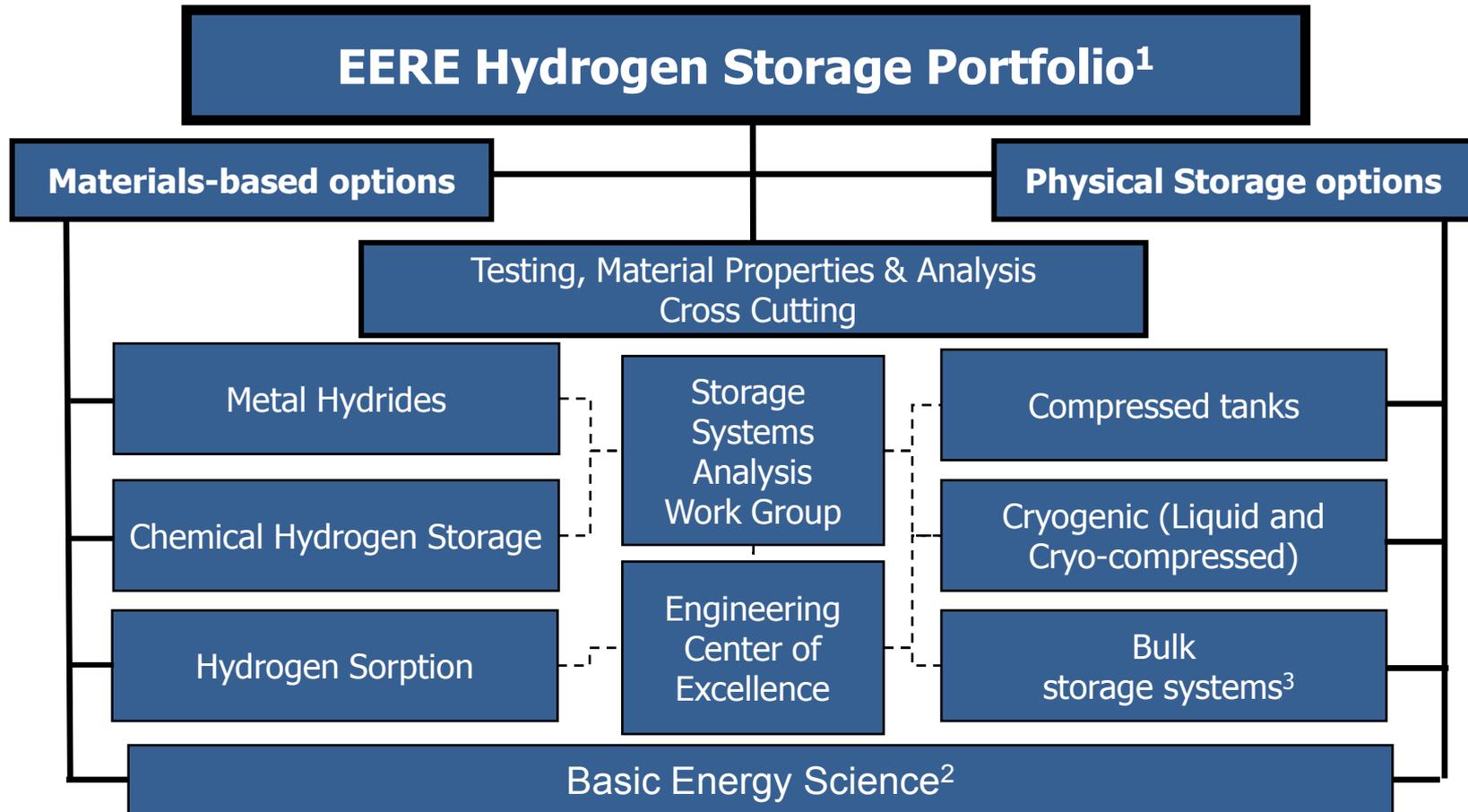
- Improving gravimetric and volumetric capacities
- Having sufficient kinetics within appropriate temperature and pressure ranges
- Lowering cost of overall engineered systems



*: Greater than a 400 mile driving range independently validated for a Toyota Advanced FCEV with 700 bar Type IV composite cylinders, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/toyota_fchv-adv_range_verification.pdf

Strategy: *Diverse, Balanced Portfolio*

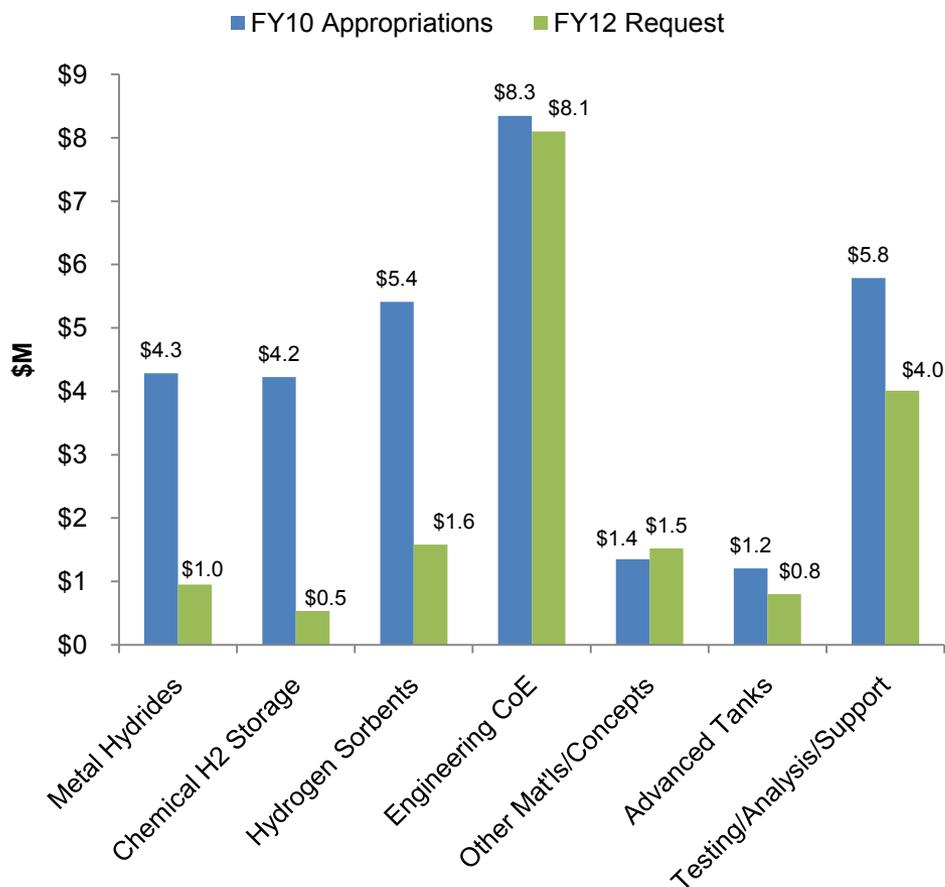
DOE maintains a balanced portfolio which focuses on advanced physical and materials-based storage technologies and innovative systems engineering concepts.



1. Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program and Energy Storage elements

Hydrogen Storage Budget

FY 2010 Appropriation = \$32.0M
FY 2012 Request = \$17.5M



Note: FY11 appropriation to be determined.

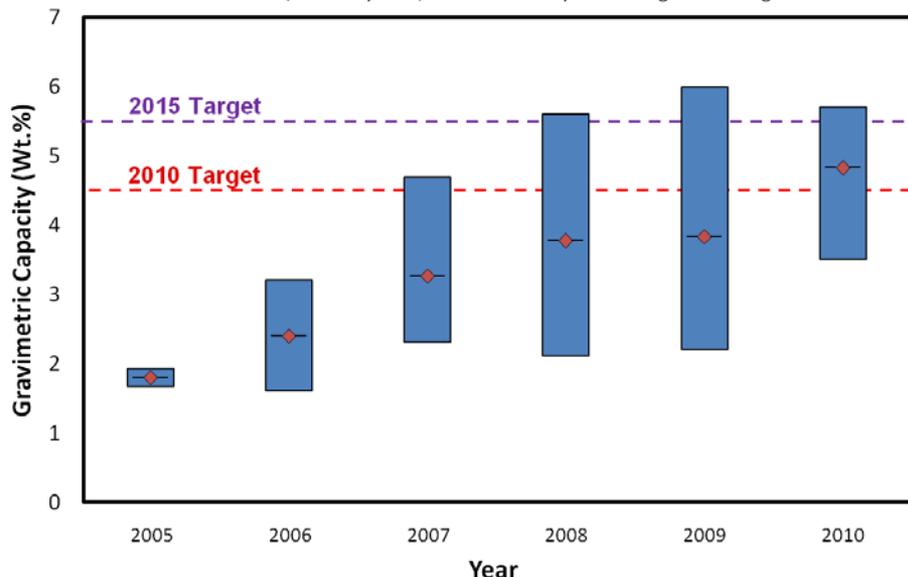
EMPHASIS

- 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 2010 & 2011 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 both low and high production volumes
- Increased emphasis on early market storage applications

Progress is being made, but no technology meets all targets simultaneously.

Projected Ranges of System Gravimetric Storage Capacity

For Chemical, Metal Hydride, Sorbent and Physical Storage Technologies

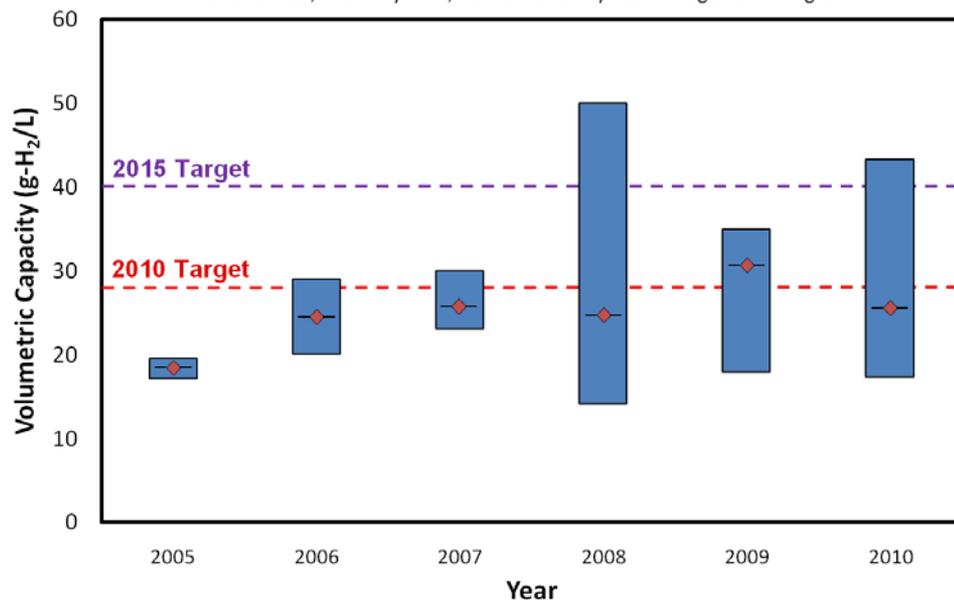


- Bars represent the capacity range of technologies modeled in the given year, overall average for all technologies analyzed indicated.
- Projections performed by Argonne National Laboratory using the best available materials data and engineering analysis at the time of modeling.

Projected Capacities for Complete 5.6-kg H₂ Storage Systems

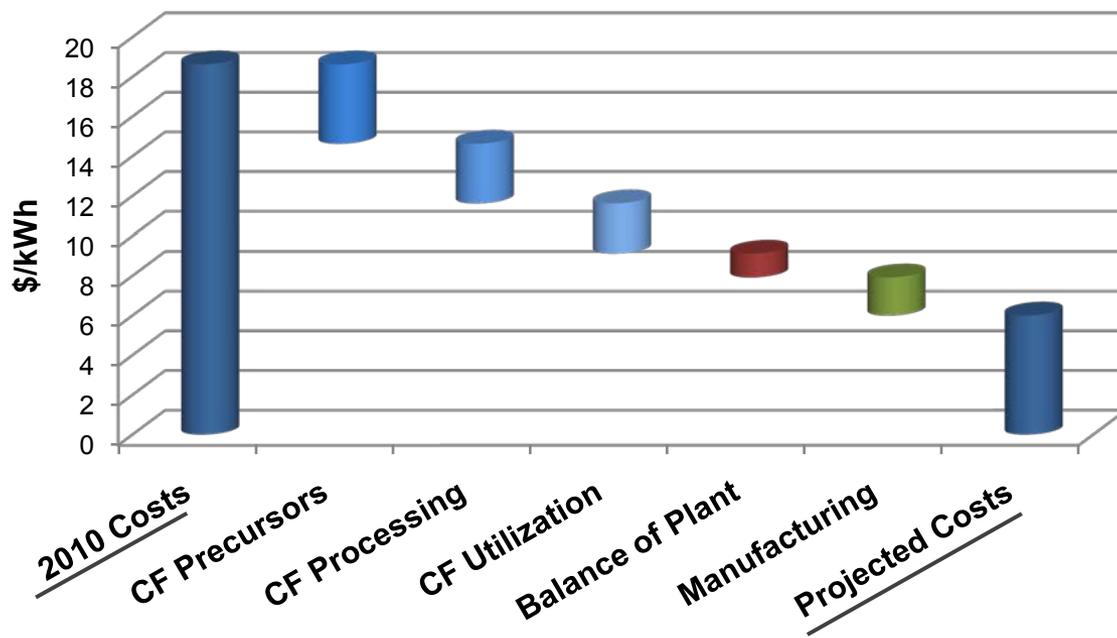
Projected Ranges of System Volumetric Storage Capacity

For Chemical, Metal Hydride, Sorbent and Physical Storage Technologies



Identified opportunities for cost reduction of composite cylinders for compressed hydrogen storage

- NAS recommended greater emphasis be put on reducing the cost of high-pressure composite hydrogen storage tanks*
- Workshop with various stakeholders held in Arlington, VA in February 2011.
http://www2.eere.energy.gov/hydrogenandfuelcells/wkshp_compressedcryo.html
- Competed new SBIR and FOA topics on lower cost tanks/carbon fiber (CF) in FY 2011.

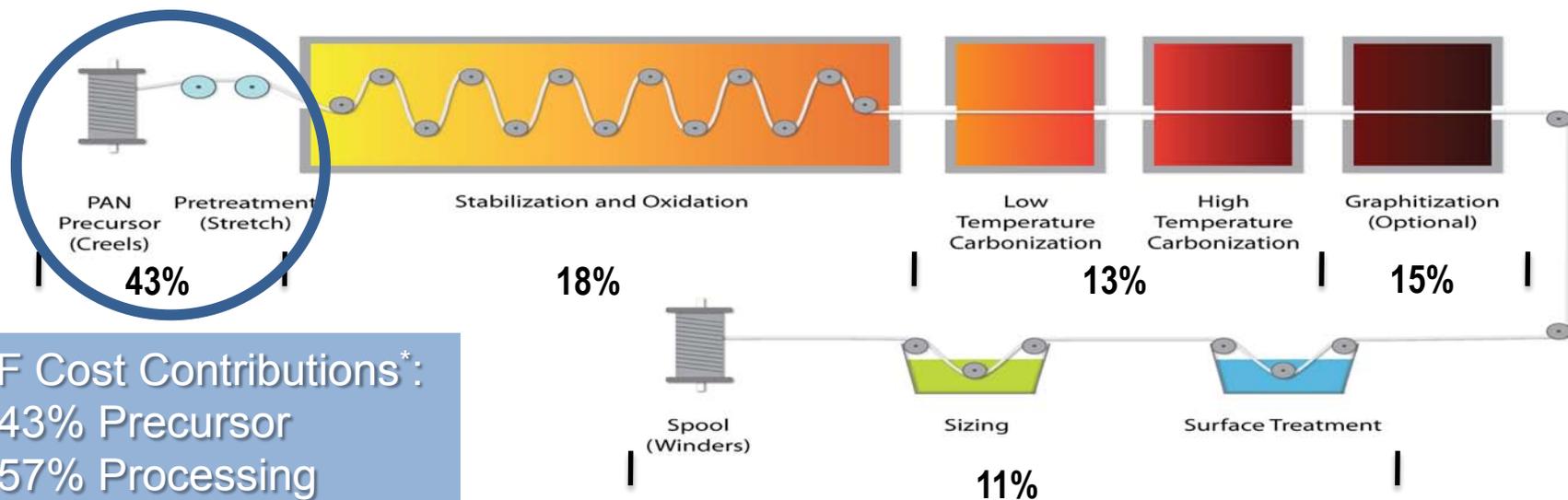


TIAX cost analysis shows that CF can contribute more than 75% of composite cylinder costs.

* Review of the Research Program of the FreedomCAR and Fuel Partnership, 3rd Report, *The National Academies Press*, Washington, DC, 2010, Recommendations 3-9:3-15.

Progress: Lower Cost Precursors

Initiated program on use of low cost commercial textile-grade PAN with Methyl Acrylate comonomer as a high-strength CF precursor



*Kline and Company, 2007, in a study commissioned by the Automotive Composites Consortium.

Objective: To produce high strength CF from commodity textile based precursors.

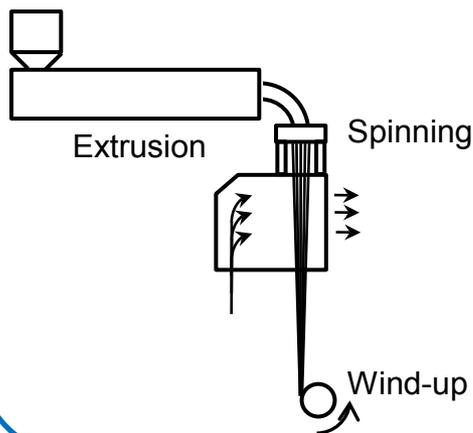
- Leverages prior successful low-strength CF work using vinyl acetate (VA) comonomers.
- Previous results indicate methyl acrylate (MA) comonomer leads to improved mechanical properties over fibers with VA.

This project is 50% cost shared by an industrial producer of textile-grade PAN fibers and co-funded with the Materials Group of the DOE/EERE Vehicle Technologies Program.

*Melt-spun PAN precursor technology has the potential to reduce the production cost of the high strength CF's by ~ 30%.**

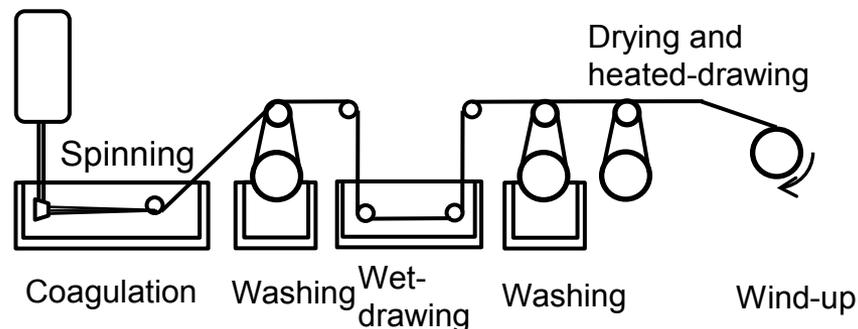
Melt spin processing much less capital intensive than traditional wet spin technology

Melt-processing



- Low production cost
- High production rate
- Environment-friendly

Solution-processing



ORNL-Virginia Tech team has demonstrated melt spinnable PAN/MA with physical properties approaching commodity grade PAN

Benefits vs Traditional Wet Spun Processing:

- ~ 30% lower precursor plant capital investment
- ~ 30% lower precursor plant operating cost
- Typical precursor line speed increased by $\geq 4X$ at winders

*: [Kline & Company, 2007]

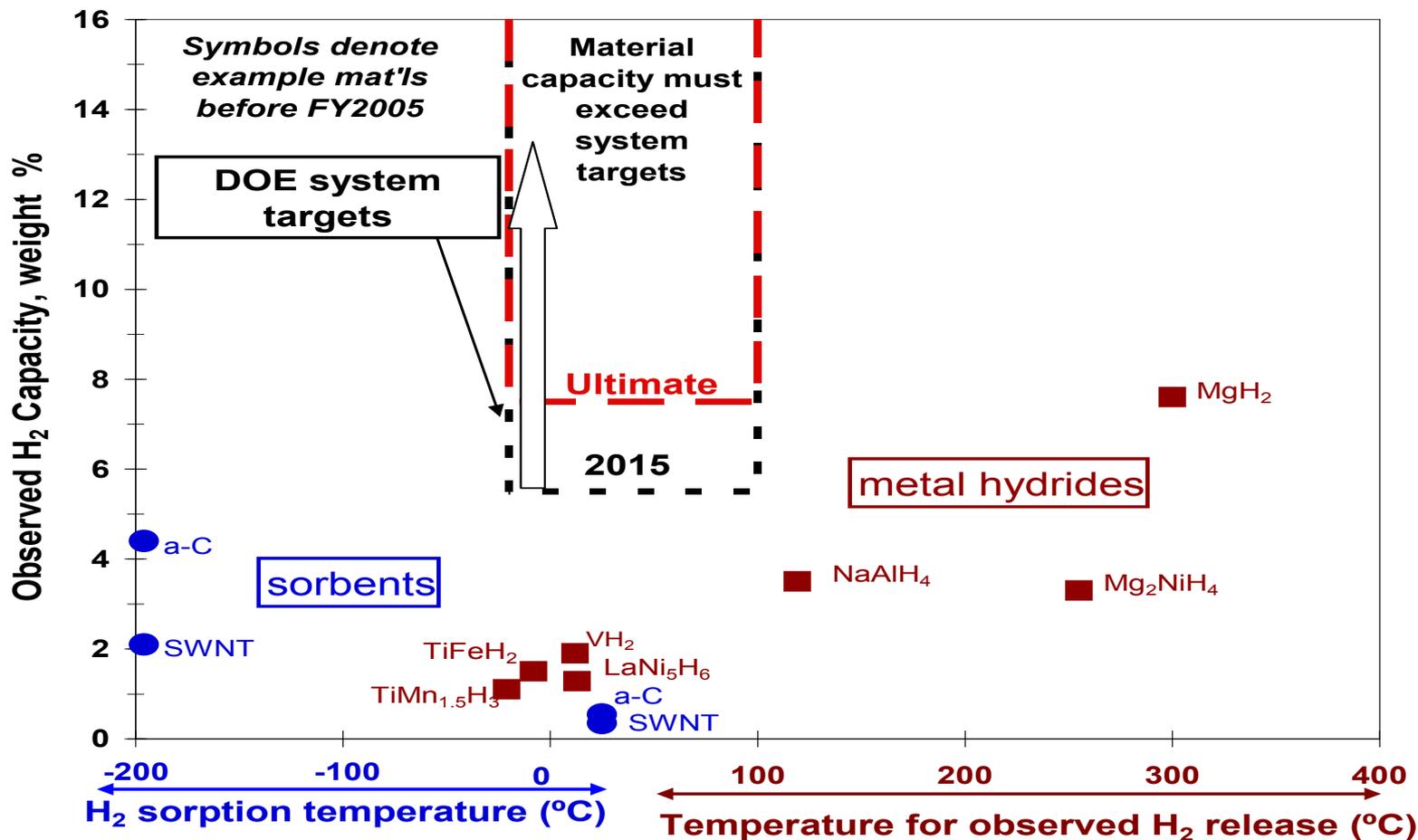
The 3 Materials Centers of Excellence investigated over 420 materials and combinations experimentally and millions computationally.

- **Centers of Excellence: Hydrogen Sorbents; Chemical Hydrogen Storage Materials and Reversible Metal Hydrides**
- **51 partners: 13 Federal Laboratories, 29 Universities and 9 Companies**
- **Over 550 peer-reviewed scientific publications**
- **Accomplishments include:**
 - **Sorbents: increased gravimetric capacity by >40% and volumetric capacity by ~150% and produced materials with > 6000 m²/g.**
 - **Chemical H₂ Materials: developed 10 regeneration strategies for spent ammonia borane (~19 wt.%) leading to a simple, one-pot regeneration scheme with low process costs (*Science* 331, 1426 (2011)).**
 - **Metal Hydrides: demonstrated >12 wt.% reversible capacity, approaches to increase release kinetics by 60x and developed computational methods to rapidly screen millions of discreet compositions.**

Many accomplishments also applicable to other areas, e.g., Batteries, Chemical processing, sensors, CO₂ Sorbents, etc.

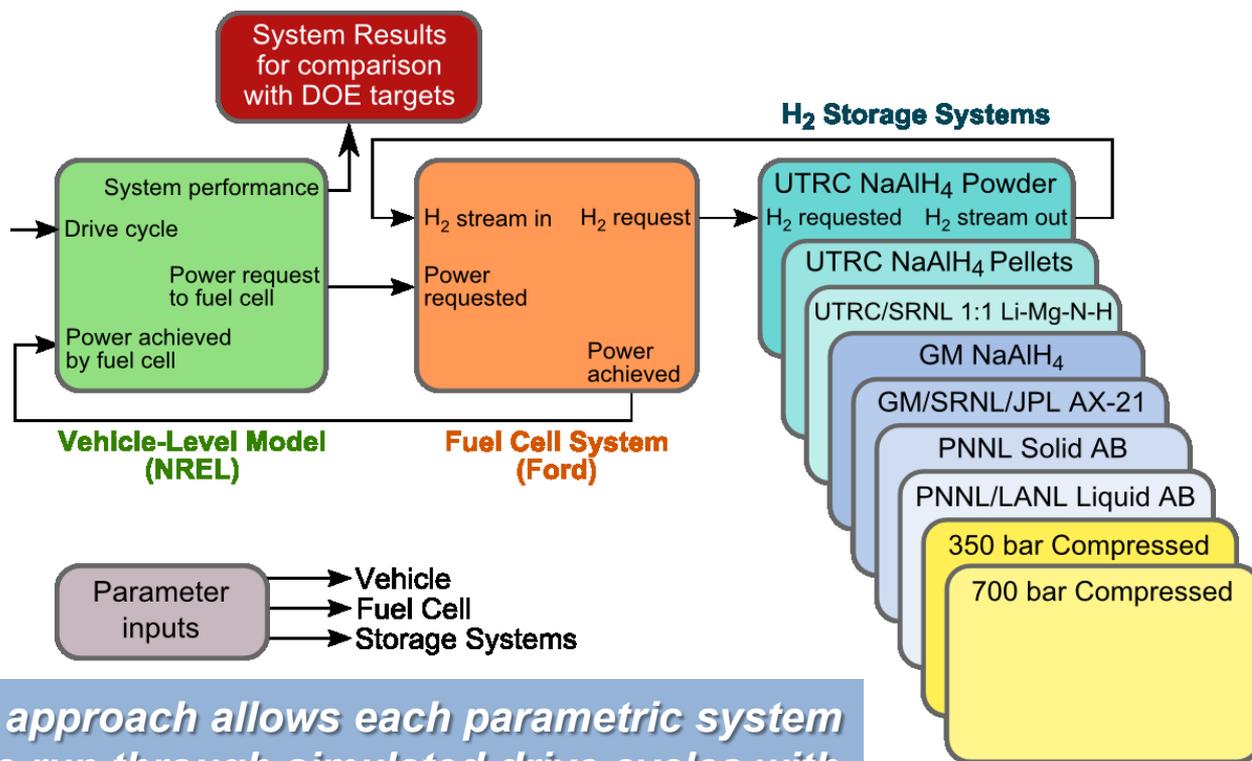
Materials Progress: Prior to 2005

Prior to DOE's accelerating R&D in H₂ storage materials research, only a limited number of H₂ storage materials were well characterized.



The HSECoE effort helps to determine required material properties to guide materials development efforts.

- Developed complete, integrated systems models for 3 material classes
- Established baseline system performance with state-of-the-art design and best-of-class materials



Modular approach allows each parametric system model be run through simulated drive cycles with fuel cell and vehicle-level models to predict performance.

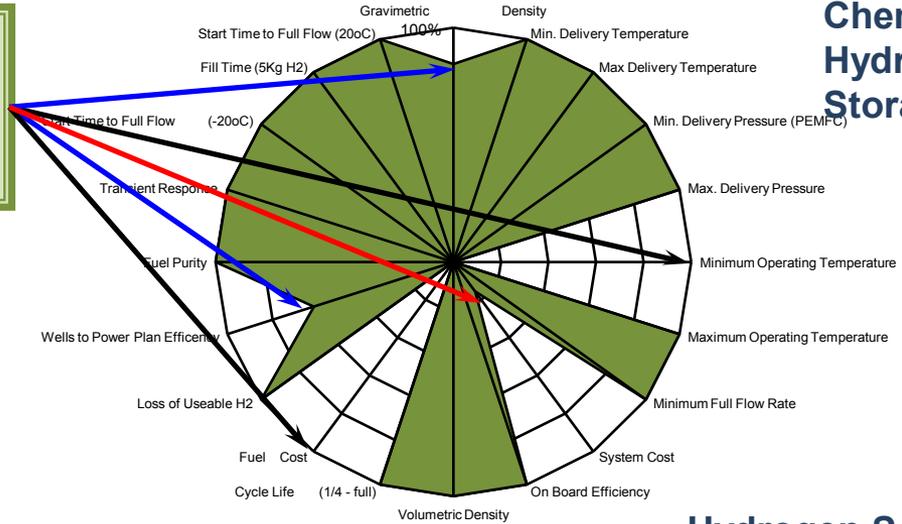


Progress: Projections against 2010 targets

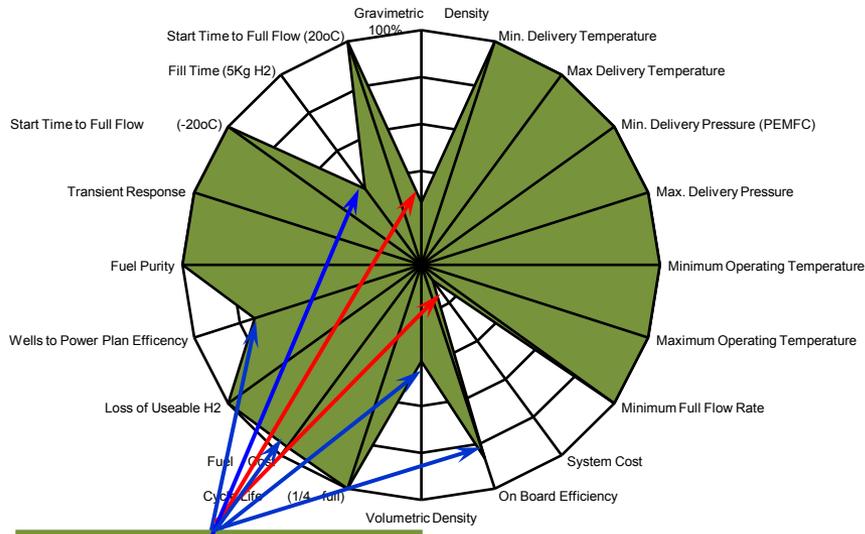
Modeled projections enable identification of technology gaps and knowledge gaps to focus R&D efforts.

1. Gravimetric Density
2. Minimum Operating Temp.
3. System Cost
4. Fuel Cost
5. WTPP Efficiency

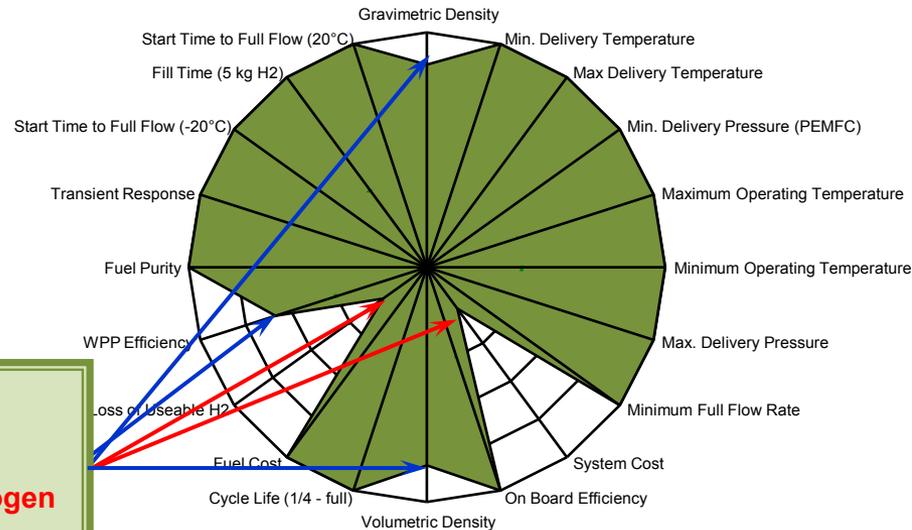
Chemical Hydrogen Storage



Reversible Metal Hydrides



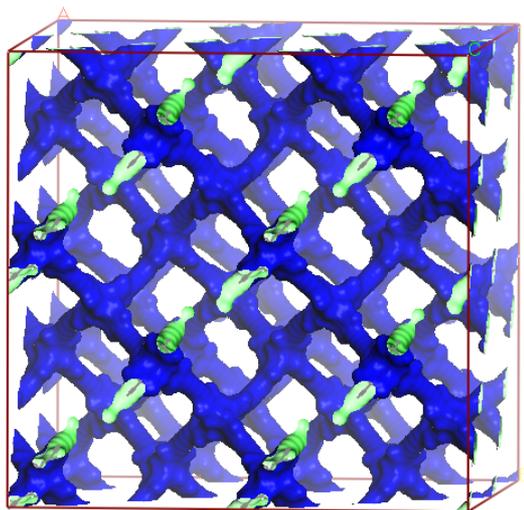
Hydrogen Sorbents



1. Gravimetric Density
2. System Cost
3. On-board Efficiency
4. Volumetric Density
5. Fuel Cost
6. WTPP Efficiency
7. Fill Time

1. Gravimetric Density
2. System Cost
3. Volumetric Density
4. Loss of Useable Hydrogen
5. WTPP Efficiency

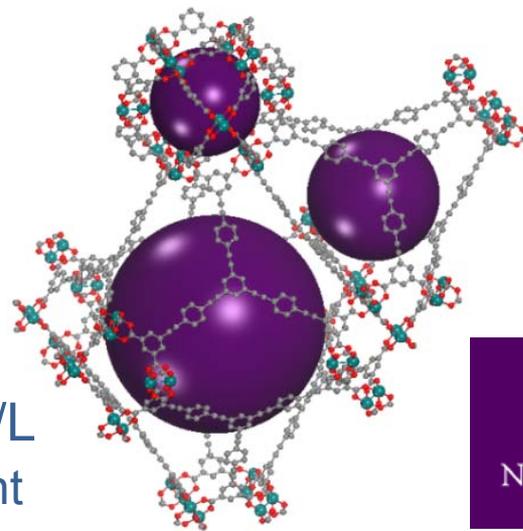
*New sorbent materials synthesized with surface areas of >6000 m²/g
with material capacities over 8 wt% at 77K and <100bar*



- Demonstrated air and water stable, metal-free porous polymer networks (PPN)
- Independently verified excess uptake of 8.5 wt.% at 60.4 bar (28-56 g/L)



- Computational modeling used to guide synthesis efforts
- Predicted BET surface area 6600 m²/g; validated 6143 m²/g experimentally
- Measured 9 wt% excess uptake and 28 g/L at 77K and 70 bar for NU-100, independent verification underway



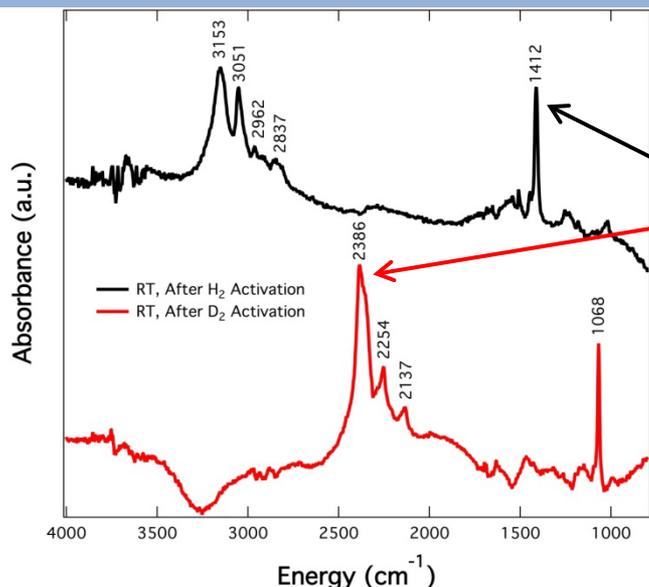
Progress: Room Temperature Chemisorption Validation

International taskforce established to confirm if excess adsorption at room temperature can be increased by spillover effect.

Goals:

- Ascertain H/H₂-catalyst-substrate interactions & mechanisms
- Establish reproducibility of synthesis and validity of measurements
- Establish whether DOE targets can be reached

DRIFTS analysis gives insight into carbon activation

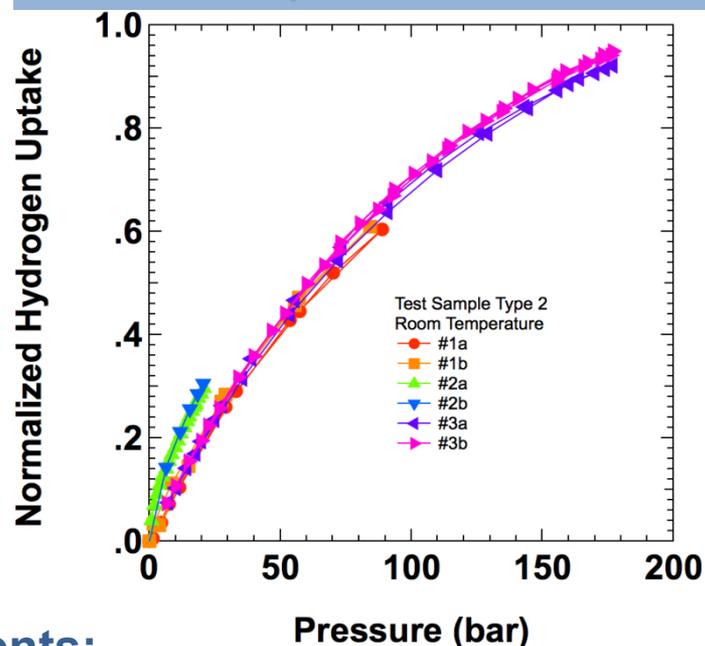


IR Stretches for C-H, C-D

Accomplishments:

- Measurement protocols validated
- Round-robin testing of samples continues
- Spectroscopic evidence of spillover demonstrated

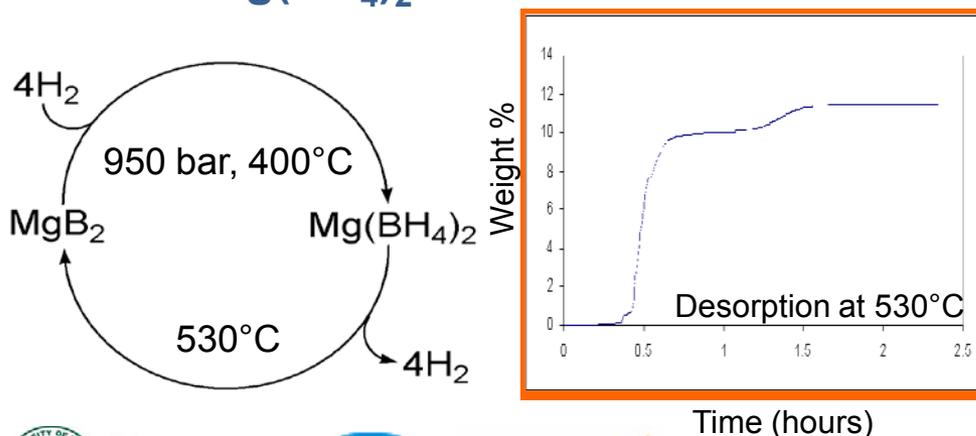
Initial volumetric measurements demonstrate reproducible protocols



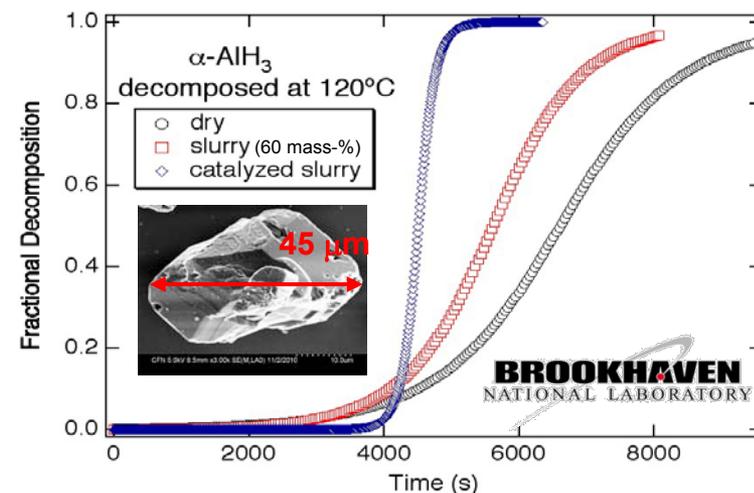
Progress: Storage Materials

Demonstrated >12 wt.% reversible capacity of $Mg(BH_4)_2$; fast kinetics for a 60 % mass-loaded AlH_3 slurry and air & thermally stable CBN

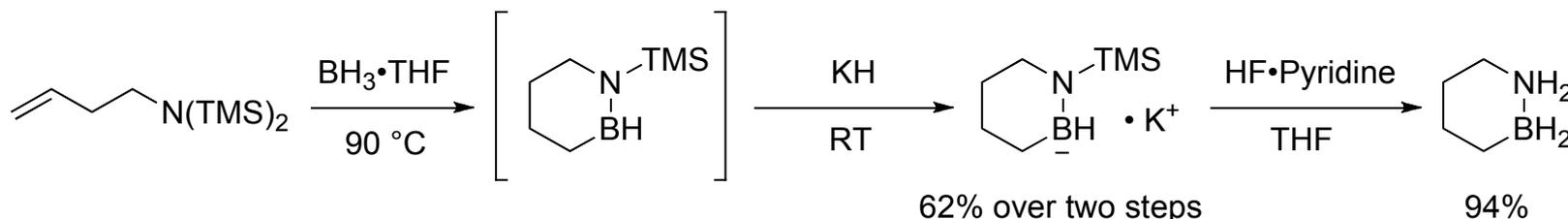
Reversible of near theoretical capacity of $Mg(BH_4)_2$ demonstrated.



Ti-Catalyzed AlH_3 slurry 2x faster H₂ desorption than dry powder



Parent Carbon-Boron-Nitrogen (CBN) heterocycle compound synthesized that is air and thermally stable and delivers up to 1.5 equiv. H₂



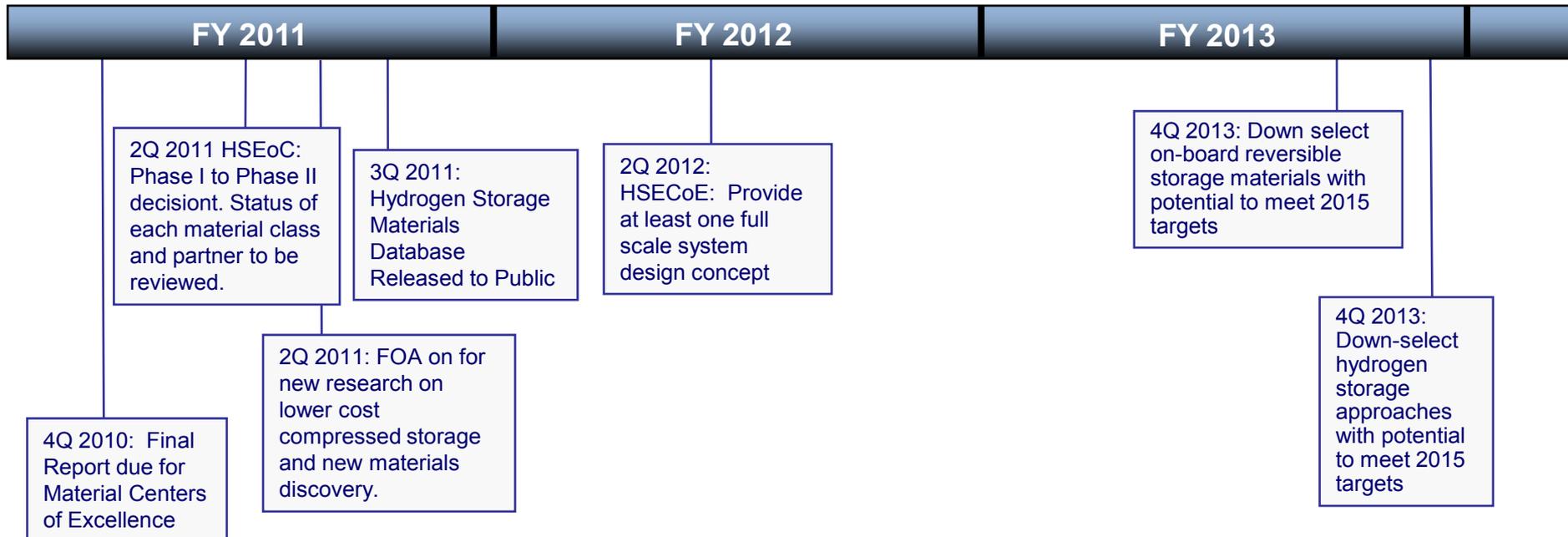
Key Milestones and Future Activities

Physical Storage

- Two projects underway to reduce the cost of carbon fiber precursors
- Competed new efforts through SBIR and Funding Opportunity Announcement topics

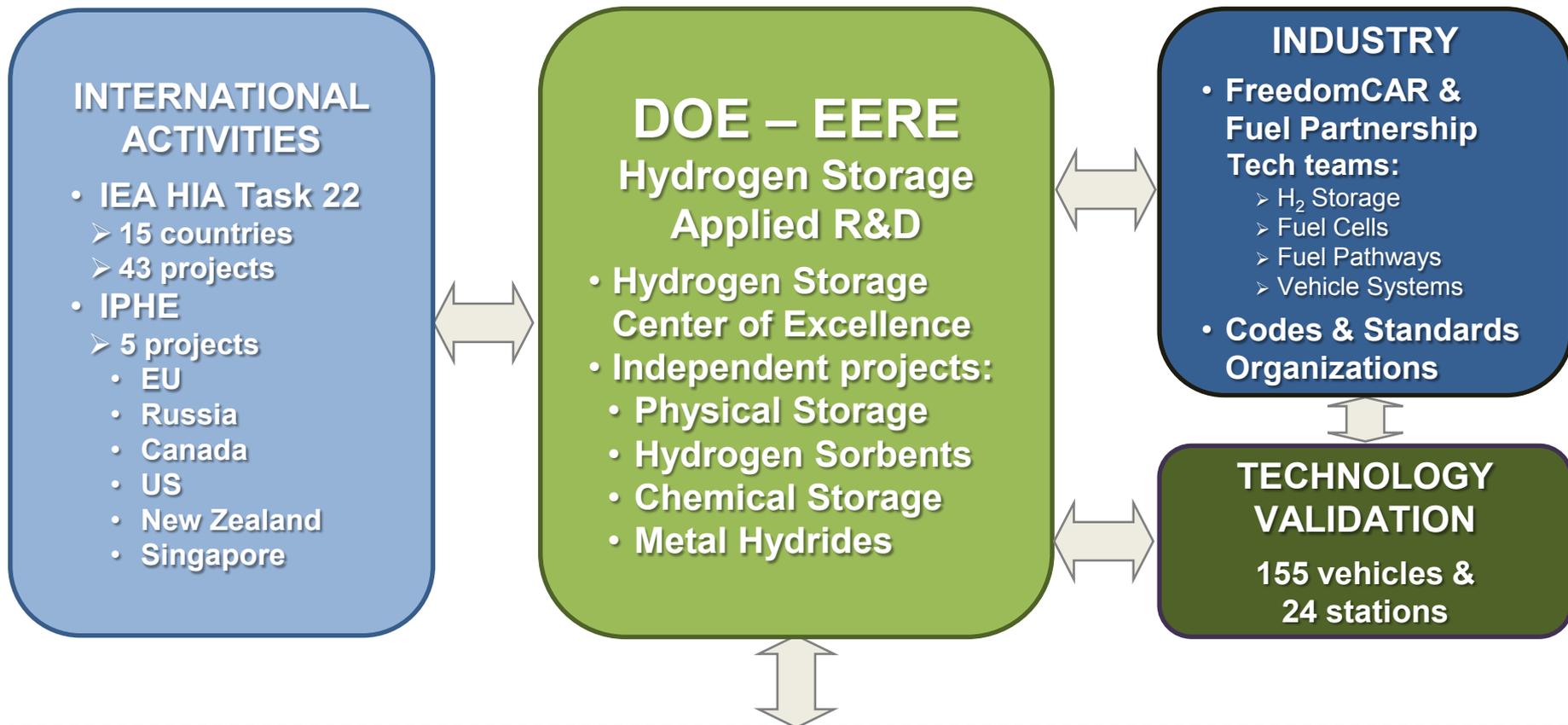
Material-based Storage

- Hydrogen Storage Engineering Center of Excellence completed model development and established baseline for current materials-based system status
- Continued to improve materials-based performance through independent projects
- Carried out Funding Opportunity Announcement topic or new materials discovery.



Hydrogen Storage Collaborations

Applied R&D is coordinated among national and international organizations.



National Collaborations (inter- and intra-agency efforts)

DOE – BES

~25 Projects

DOT

Material handling/transport

DOD – DLA

5 Projects

NASA

- Tanks
- Engineering

NIST

- Neutron scattering
- Measurements

NSF

New projects to be selected

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Golden Field Office:

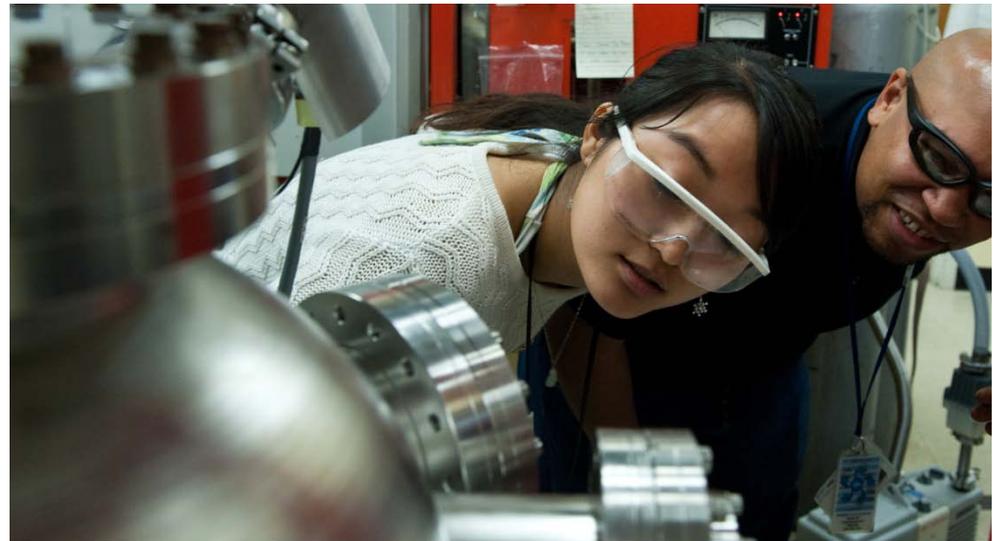
Jesse Adams

James Alkire

Paul Bakke

Katie Randolph

- Fuel Cell Technologies Program Opportunities Available
 - Conduct applied research at universities, national laboratories, and other research facilities
 - Up to five positions are available in the areas of hydrogen production, hydrogen delivery, hydrogen storage, and fuel cells
 - ❑ Applications are due June 30, 2011
 - ❑ Winners will be announced mid-August
 - ❑ Fellows will begin in mid-November 2011



**Postdoctoral fellowships in
hydrogen and fuel cell research ▶**

www.eere.energy.gov/education/postdoctoral_fellowships/

Key Stakeholders – Hydrogen Storage

Metal Hydrides

Industry:

HRL Laboratories;
UTRC

Universities:

CalTech;
Stanford;
Pittsburgh/Ga. Tech;
Hawaii/UNB;
Illinois;
Ohio State;
Nevada-Reno;
Utah;
Northwestern;

Federal Labs:

Brookhaven; NIST;
Jet Propulsion Lab;
Oak Ridge; Savannah
River; Sandia

Hydrogen Sorbents

Industry:

Air Products

Universities:

CalTech;
Duke U.;
Texas A&M;
Michigan;
North Carolina;
Penn State;
Rice;
Missouri-Columbia;
UCLA;
Northwestern;

Federal Labs:

Argonne; Oak Ridge;
Lawrence Livermore;
NIST; NREL

Chemical Hydrogen Storage Materials

Industry:

Dow;
U.S. Borax

Universities:

Penn State;
Alabama;
California-Davis;
Missouri-Columbia;
Pennsylvania;
Oregon;
Washington

Federal Labs:

Los Alamos;
Pacific Northwest;
Idaho

System Engineering

Industry:

Ford;
General Motors;
Lincoln Composites;
UTRC;
Hawaii Hydrogen Carriers

Universities:

Oregon State;
CalTech;
L'Université du Québec à
Trois-Rivières

Federal Labs:

Savannah River;
Jet Propulsion Lab;
Los Alamos;
NREL;
Pacific Northwest

Testing, Analysis, Physical Storage and Novel Concepts

Industry

Air Products and Chemicals; UTRC;
Gas Technology Institute; SiGNa;
TIAX; Hawaii Hydrogen Carriers ;
H₂ Technology Consulting LLC;
Quantum Technologies; GM

Universities & Institutes

Hydrogen Education Foundation; Purdue;
Southwest Research Institute; SUNY – Syracuse;
U. of Arkansas; UC Berkeley; UC Santa Barbara;
UNLV

Federal Labs

Argonne; Savannah River;
Lawrence Livermore ; Sandia;
Oak Ridge; Pacific Northwest;
NREL