U.S. DEPARTMENT OF ENERGY

Hydrogen Storage

Sara Dillich

2009 DOE Hydrogen Program & Vehicle Technologies Program

Merit Review and Peer Evaluation Meeting

May 19, 2009

Goal and Objectives

Goal: On-board hydrogen storage for > 300 mile driving range across different vehicle platforms, ***Without Compromising*** passenger/cargo space, performance (wt, vol, kinetics, safety, etc.).

Objective: Develop on-board storage systems to meet *all* DOE system targets simultaneously i.e., fueling rates, durability, cost, safety, etc., as well as capacity.

Goal: Develop storage options to facilitate deployment and market growth of fuel cell power systems for early market applications; define role of hydrogen for utility storage.

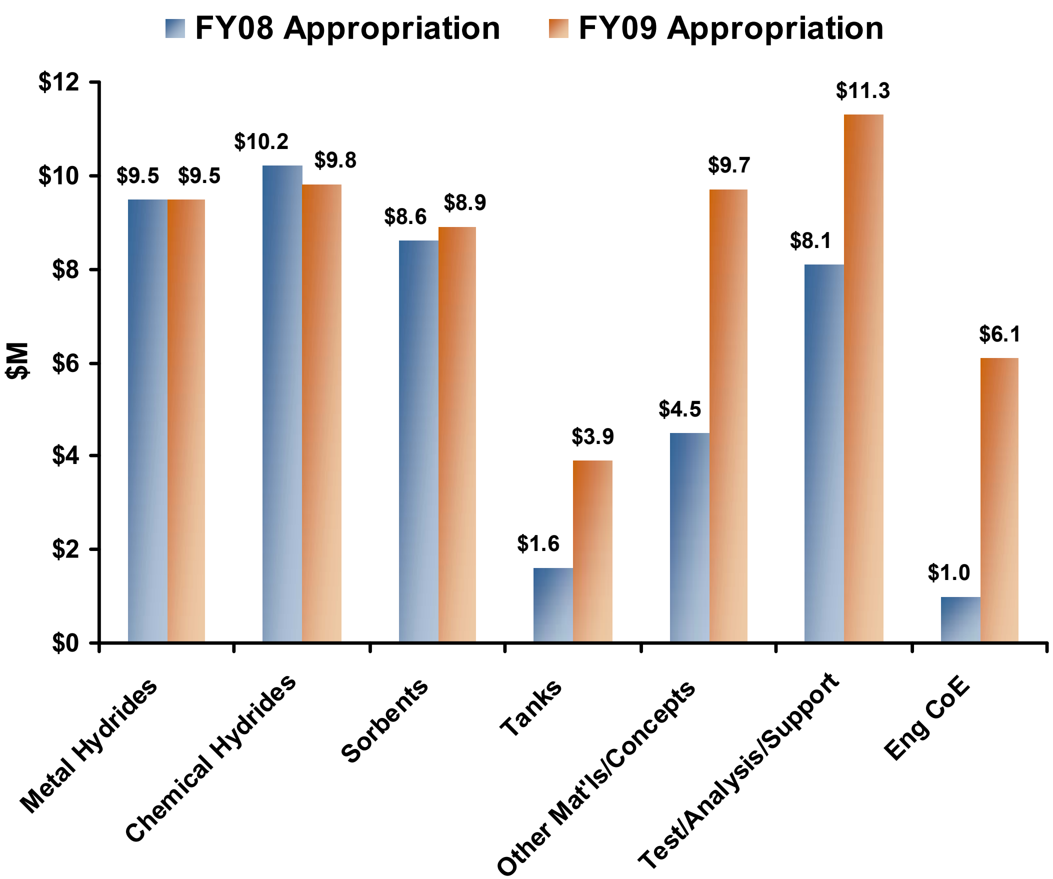
Objective: Identify performance targets and develop advanced storage technologies for stationary, portable and back-up power systems.

See: http://www1.eere.energy.gov/hydrogenandfuelcells/storage/pdfs/targets_onboard_hydro_storage.pdf

Budget

Increased focus on systems integration and early market applications

FY 2009 Appropriation = $59.2M
FY 2008 Appropriation = $43.5M



EMPHASIS

- Systems approach through the Engineering CoE, in collaboration with materials CoEs and independent projects, to achieve light-duty vehicle targets.
- Initiate identification of priorities and targets for storage for early market applications.
- Focus on cost reduction and advanced materials-based concepts for bulk storage.
- ***Continued close coordination with Basic Science in 2009 & 2010.***

Challenges

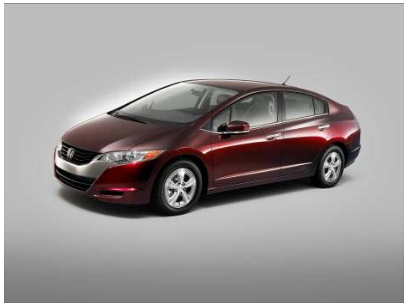
Storage for Early Market Applications As Well As for Light-Duty Vehicles

Light Duty Vehicles:

- Performance, space on-board and cost are still challenges for mass market penetration…
- Low pressure alternatives still to be developed.

Early Market Applications:

- Storage performance requirements and options not fully identified.



Revised Performance and Cost Targets

Performance targets revised in 2009 based on real-world experience with hydrogen fuel cell vehicles.

Target	2015	2015	Ultimate*
	new	*old*	***new***
System Gravimetric Density [wt.%] (kWh/kg)	**[5.5] (1.8)**	[9] (3.0)	**[7.5] (2.5)**
System Volumetric Density [g/L] (kWh/L)	**[40] (1.3)**	[81] (2.7)	**[70] (2.3)**
System fill time for 5-kg fill [min] (kgH_2/min)	**[3.3] (1.5)**	[2.5] (2.0)	**[2.5] (2.0)**
System cost [$/$kgH_2$] ($/kWh_{net})	**TBD**	[67] (2)	**TBD**

***Ultimate** targets are intended to facilitate the introduction of hydrogen-fueled propulsion systems across the majority of vehicle classes and models

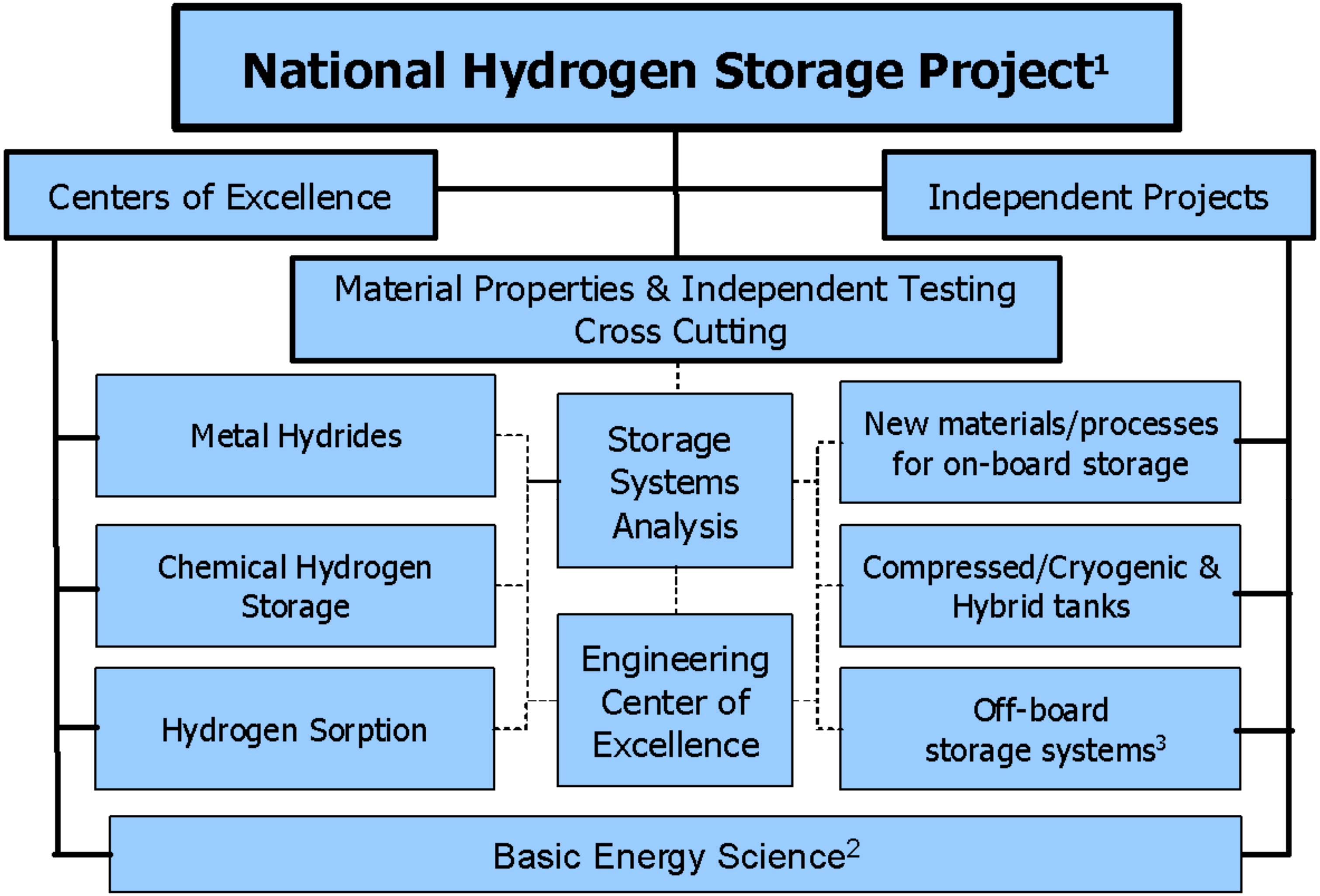
Explanation of Target Revisions

The key assumption remains unchanged:
Acceptable driving range for most light-duty vehicles.

- **Assumption used for both original and revised targets:**
  - Targets are based on application requirements (not current hydrogen storage technology capabilities)
- **Changed assumptions between original and revised targets:**
  - Vehicle architecture –
    - Original – no difference between gasoline ICE and H_2 FCs
    - Revised – Vehicle architecture will change between gasoline ICE and H_2 FCs; Current targets based on packaging and design of current FC vehicle fleets
  - Fuel Economy –
    - Original – 2.5 to 3 times improvement for H_2 FCs over ICE
    - Fuel economy based on current FC vehicle fleet data

Portfolio Structure

Diverse, Highly Integrated Program

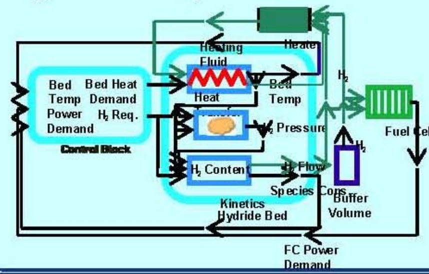


1. Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program element

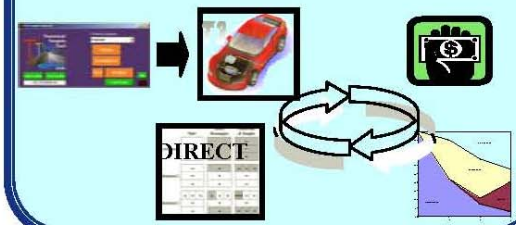
Expanded Engineering Effort

Hydrogen Storage Engineering Center of Excellence:
Initiated to address systems integration and prototype development.

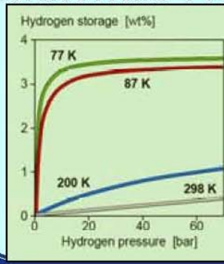
Integrated System Modeling



Performance Analysis



Materials Requirements



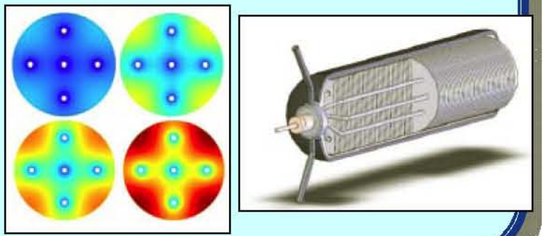
Balance of Plant Parameters from System Models

Storage System

Forecourt Parameters from Models and External Input

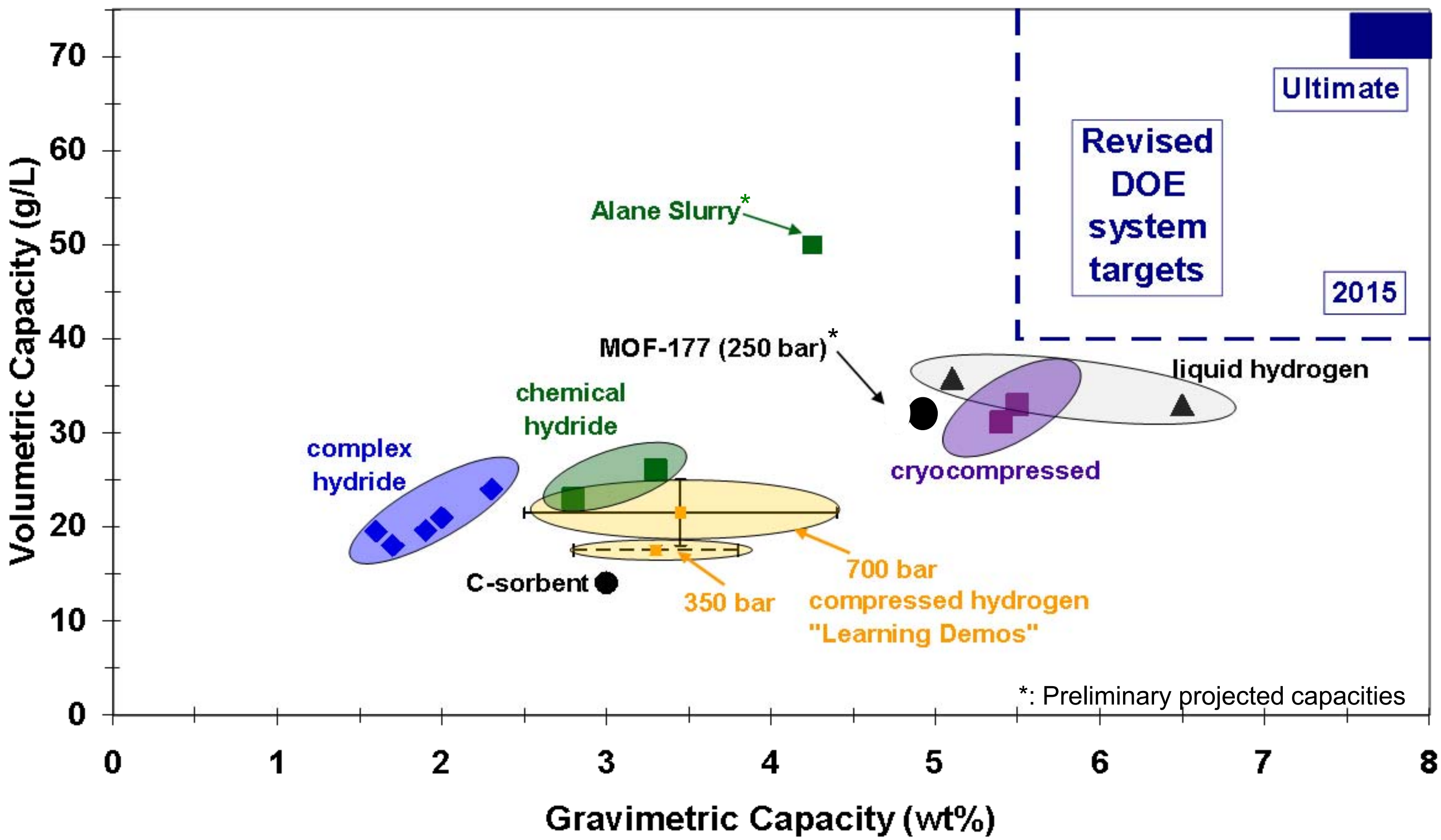
Enabling Technologies

Transport Phenomenon



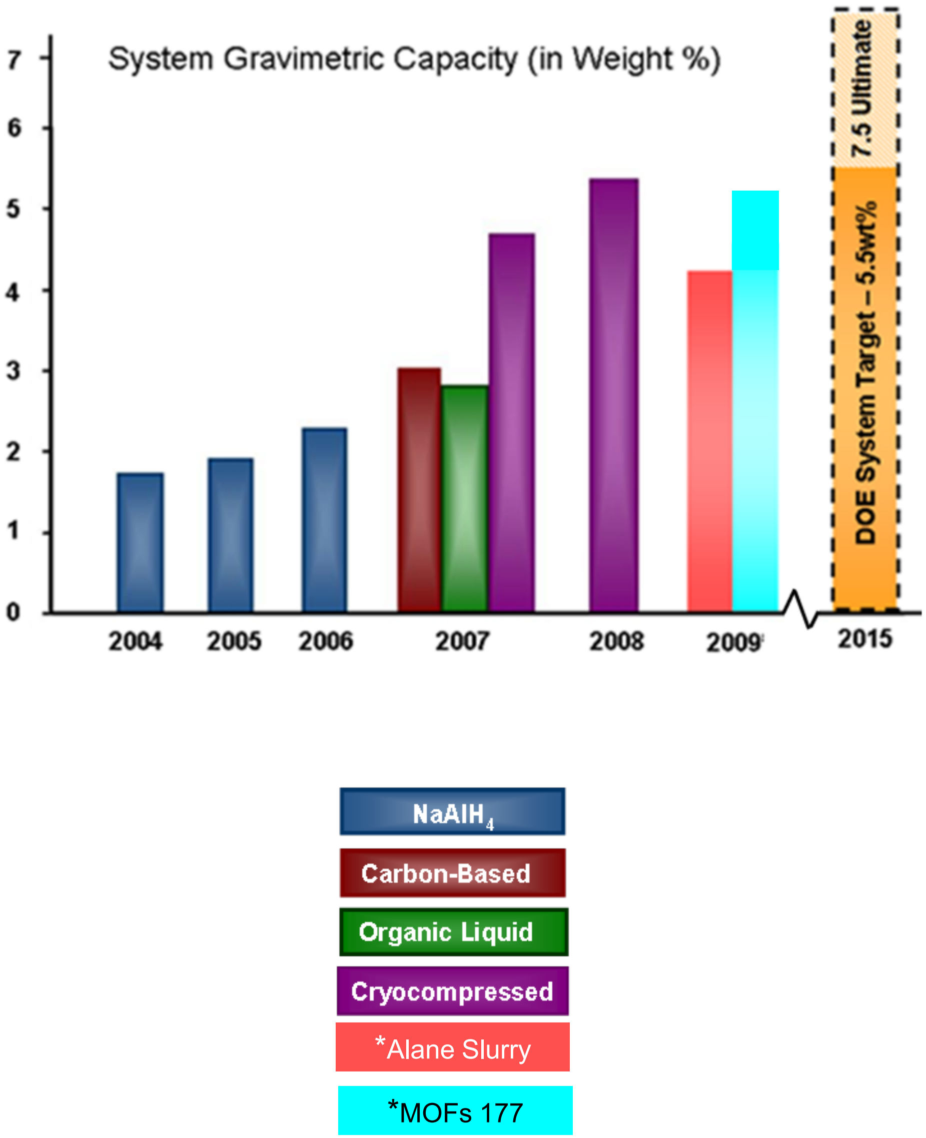
Prototype Testing

2009 - Current Status

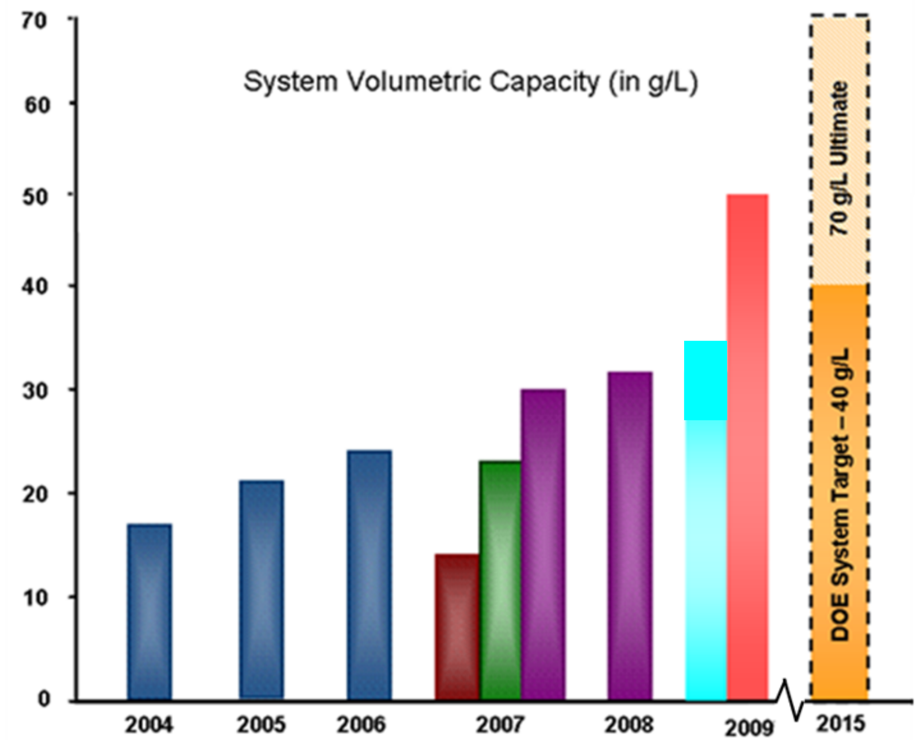


- Currently no technology is able to meet the revised 2015 targets
- New Ultimate targets remain very challenging
- Focus is on materials-based technologies that have potential to meet Ultimate targets and revised 2015

Progress: System Capacity



- *Projected system capacities based on modeling and material data*
- *Subscale prototype developed for* $NaAlH_4$
- *Full scale prototype developed for cryocompressed tank*



****Preliminary, based on initial analysis.***

Progress: Portfolio Down-select Decisions

Metal Hydrides-

- ~ More than 55 material systems assessed
- ~ 60% discontinued
- ~ 40% still being investigated

Chemical Hydrogen Storage-

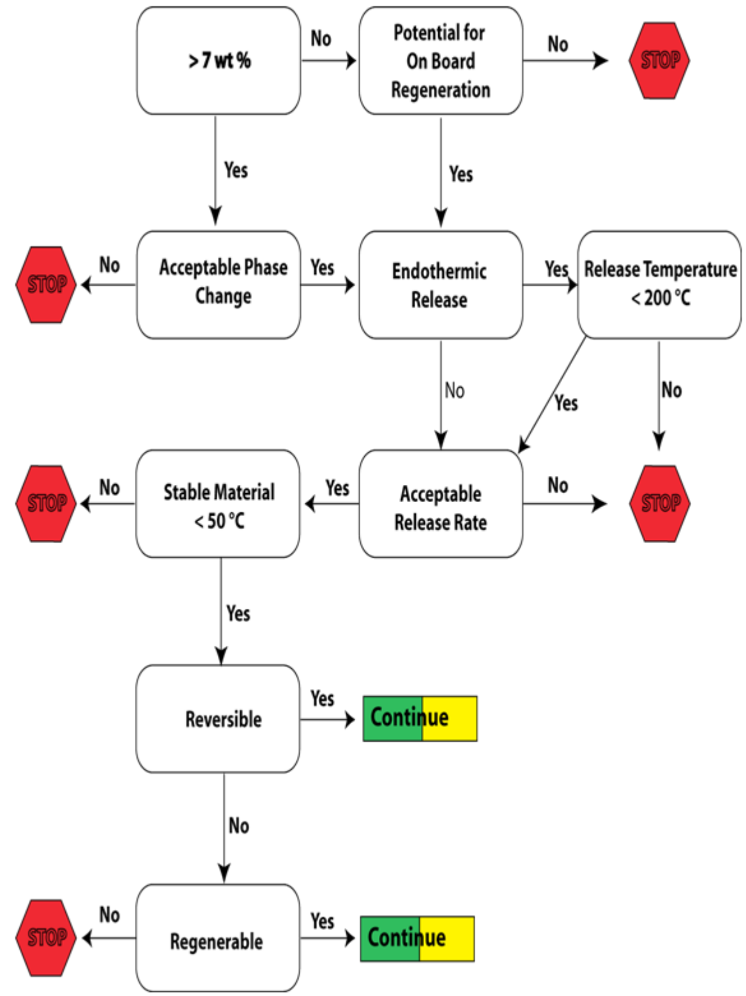
- ~ 120 materials/combinations have been examined
- ~ 85% discontinued
- ~ 15% still being investigated – many derivatives of AB, or mixture of AB with additives

Hydrogen Sorption-

- ~ 60 materials investigated
- ~ 40 discontinued
- ~ 20 still being investigated

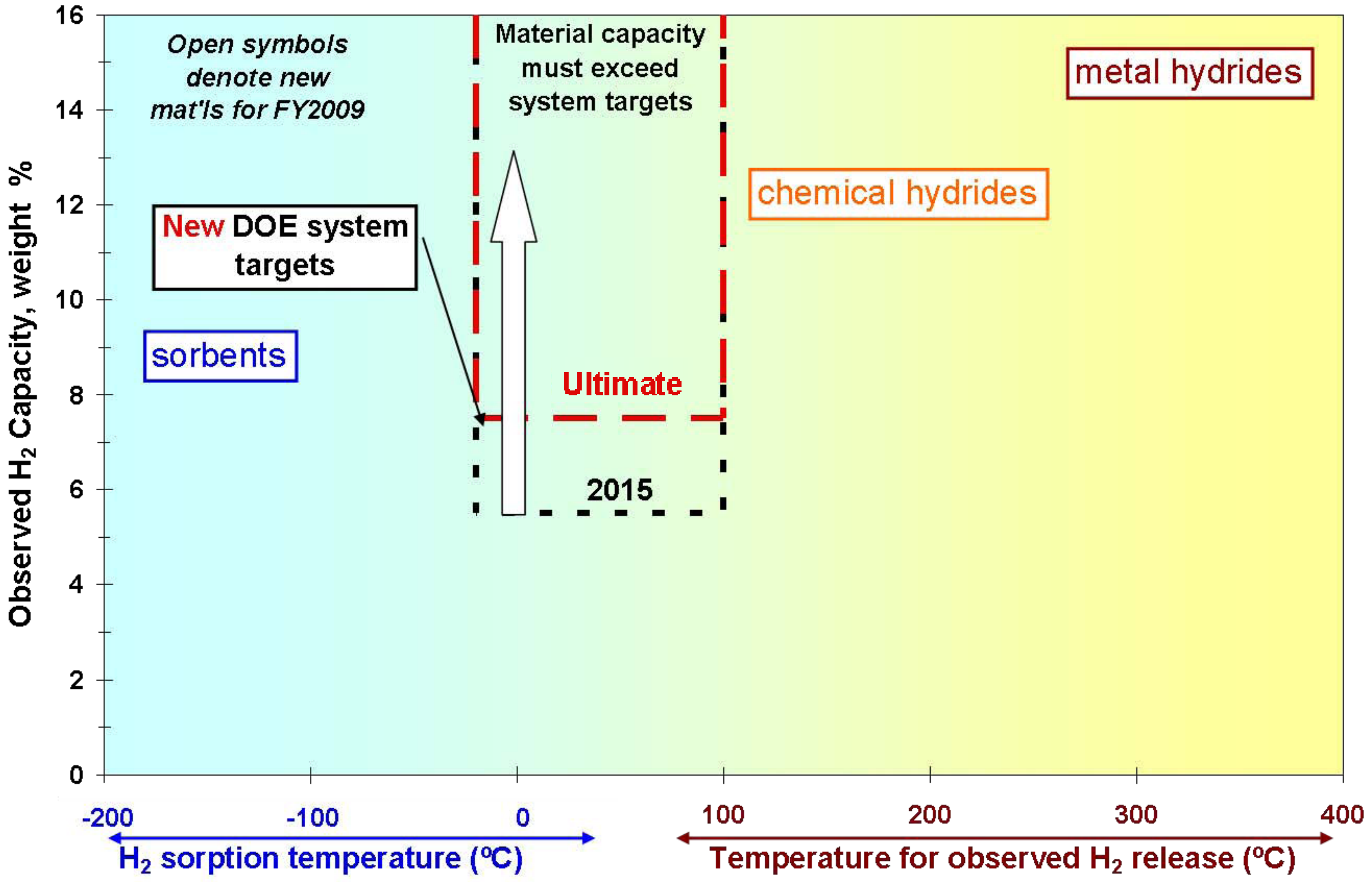
Down-select report in preparation

CHSCoE Materials Decision Tree



http://www1.eere.energy.gov/hydrogenandfuelcells/hydrogen_publications.html#h2_storage

Progress: Material Capacity vs. Temperature



DOE: G. Thomas (2007), G. Sandrock (2008), B. Bowman (2009)

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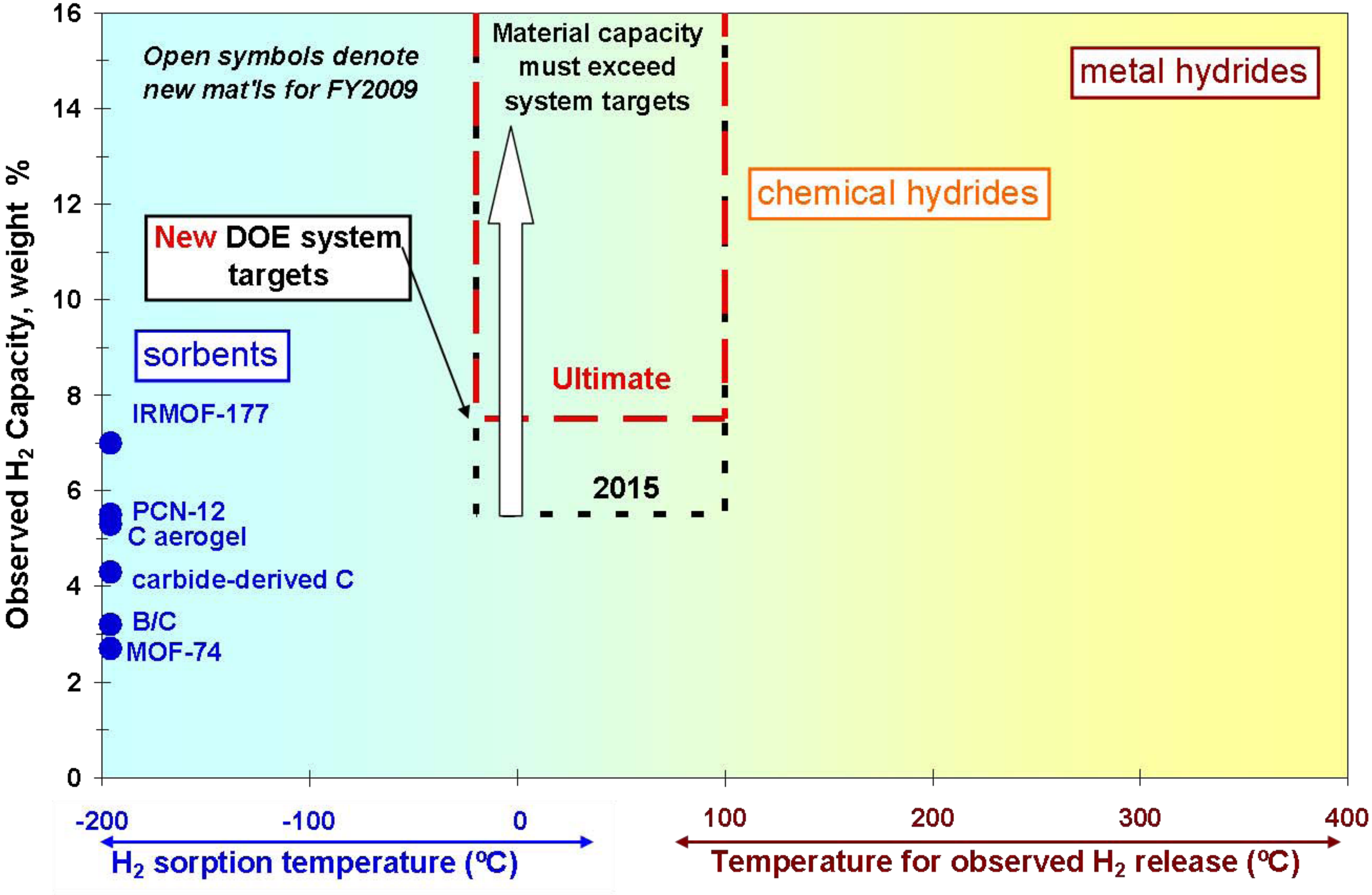

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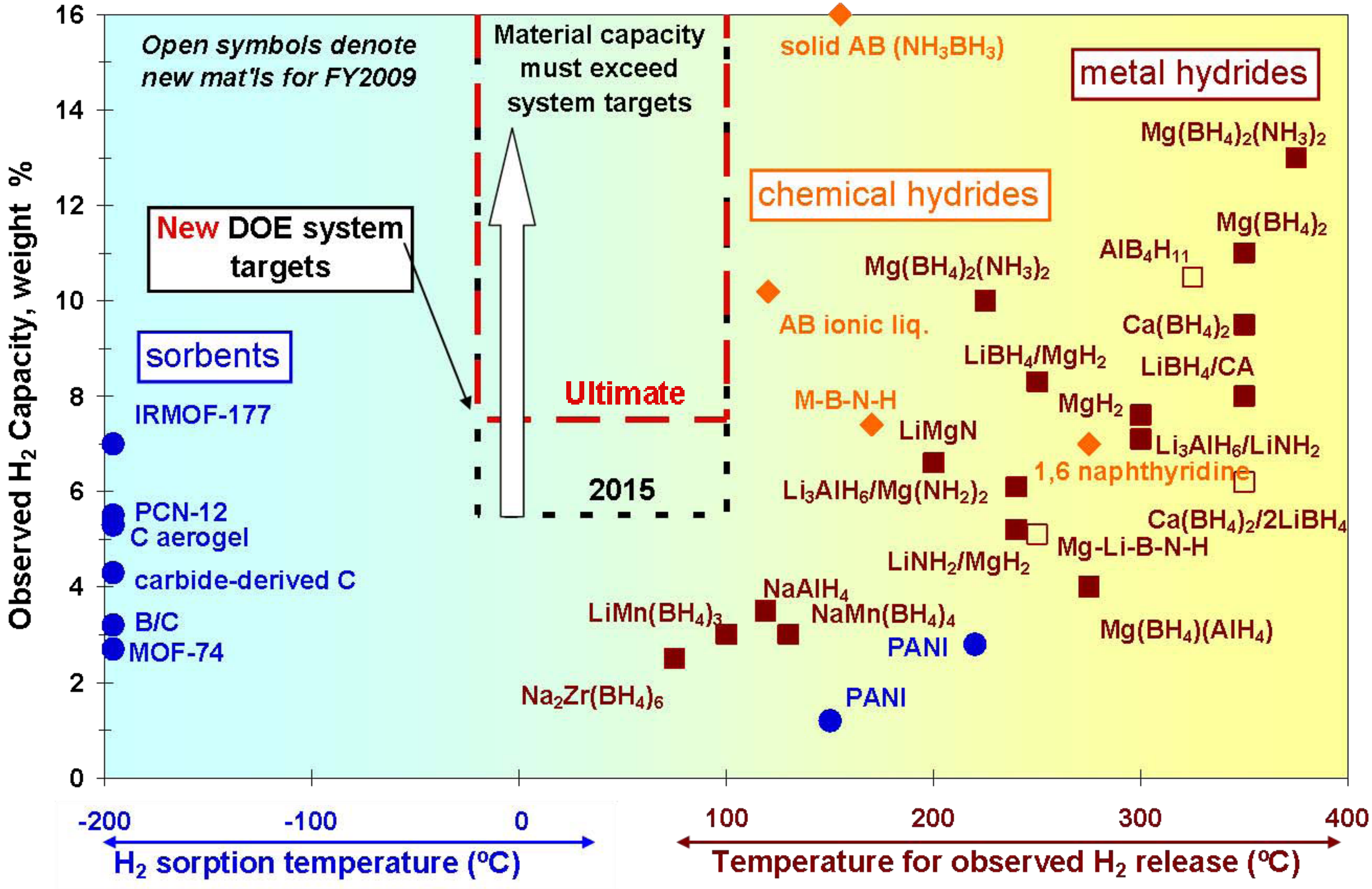

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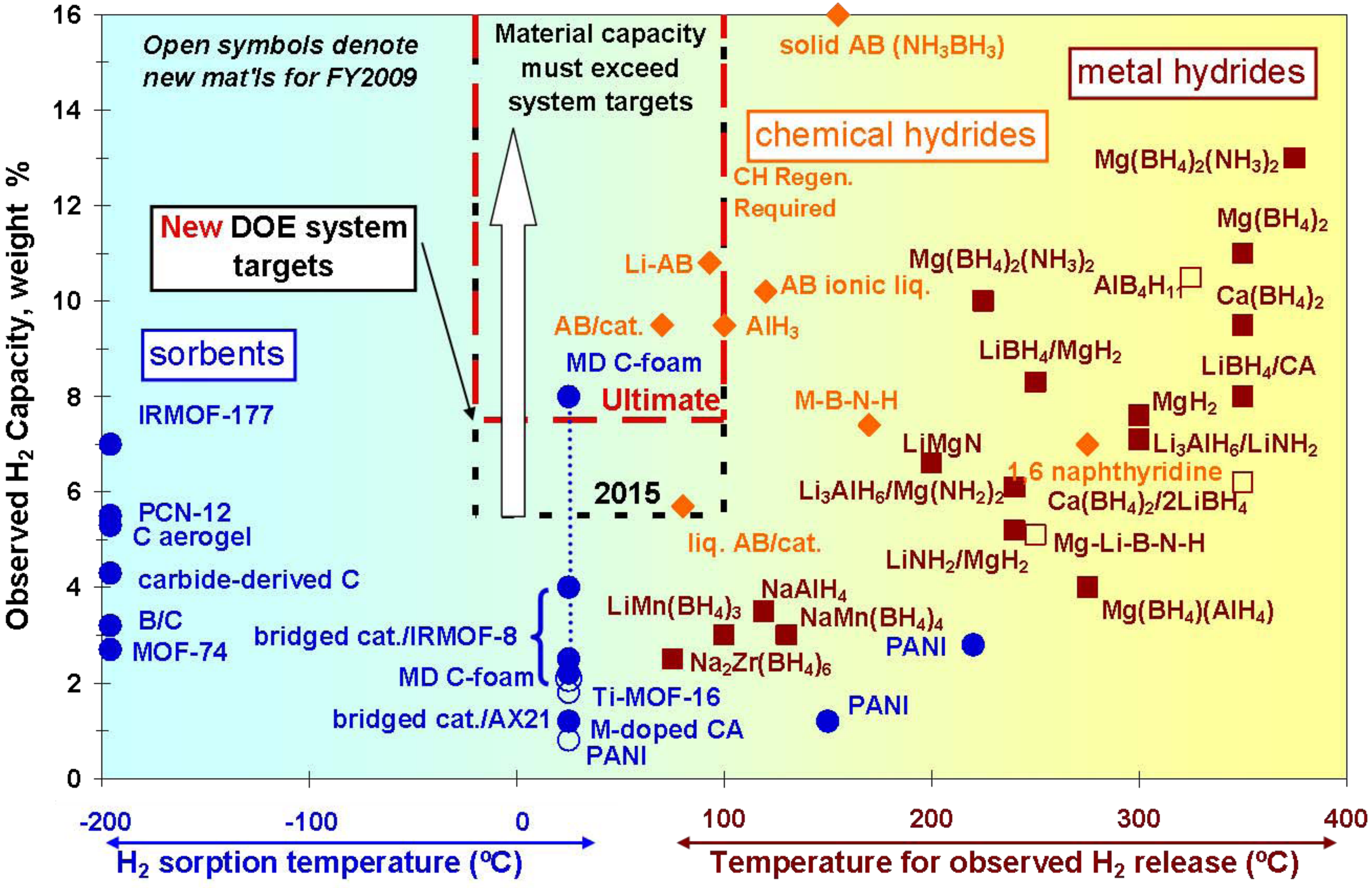

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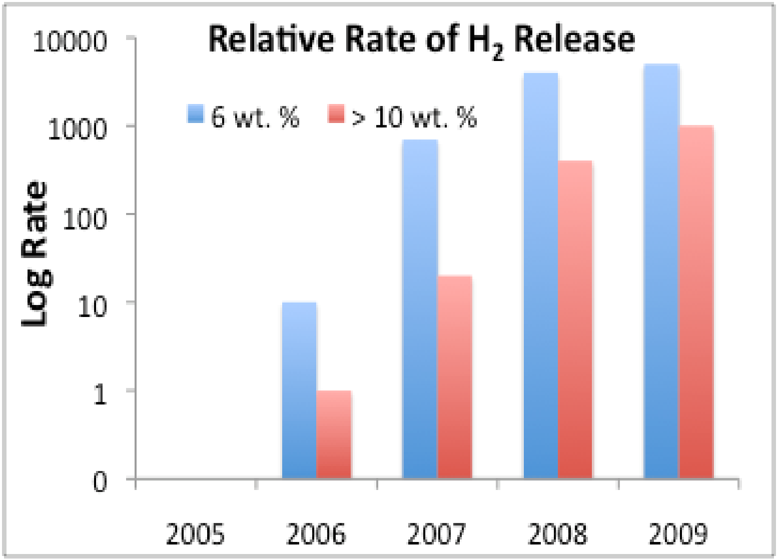
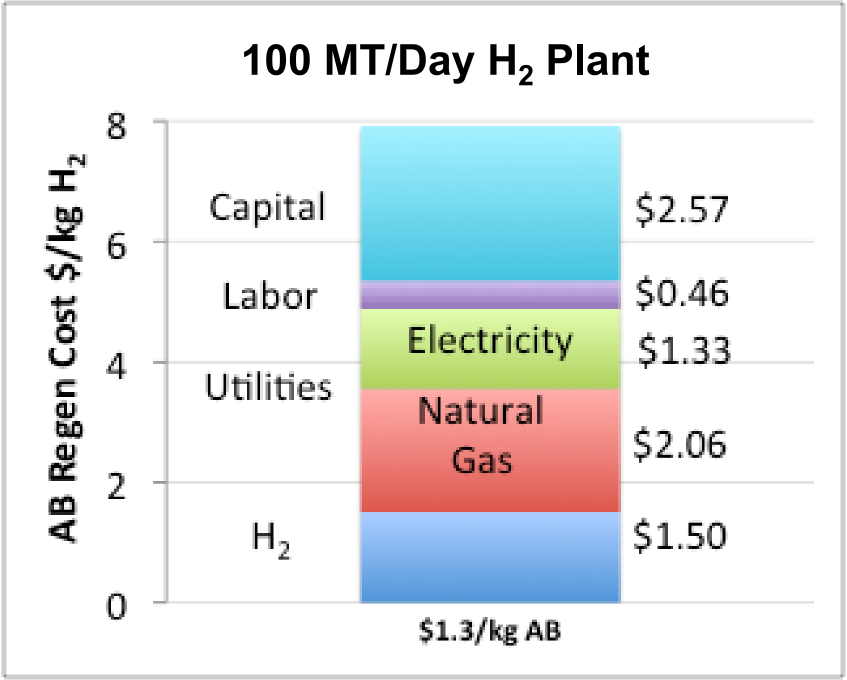
Progress: Chemical Storage Materials

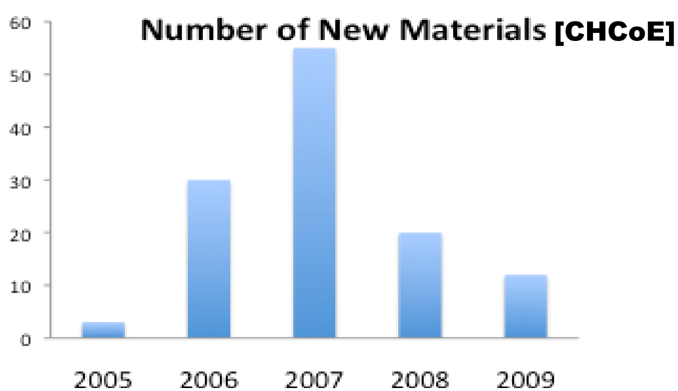
Ammonia Borane H_2 release rates increased by factor $10^2 – 10^3$ [CHCoE]



Cost analysis completed [Rohm&Haas]

- Baseline cost of AB regeneration: $7-8/kg H_2
- Separations are key to improvements





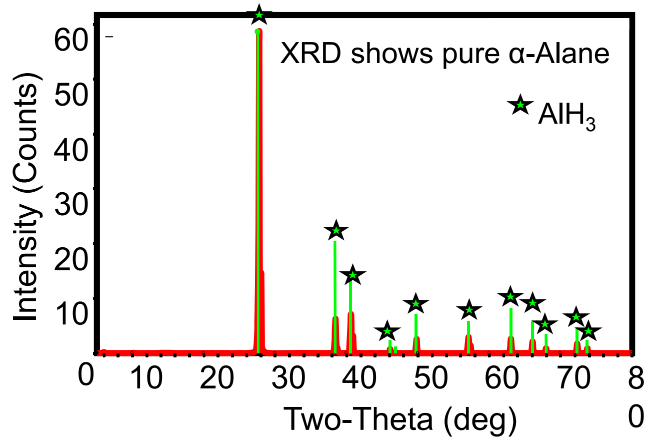
New materials include:

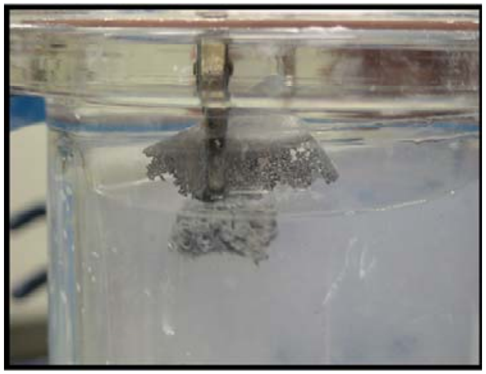
- **Diversity of metal amidoboranes (MABs)**
- **cyclo CBNs**
- **Novel compositions of AB with additives**

Progress: Metal Hydride Storage Materials

Electrochemical Regeneration of Alane (AlH_3)

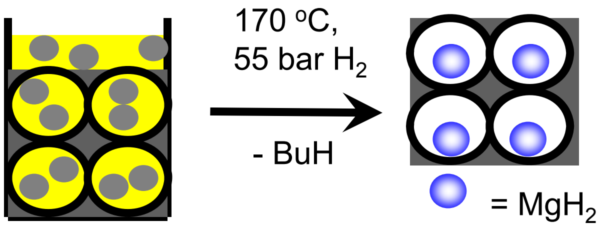
High yields of gram quantities of pure α-AlH_3 obtained under mild conditions.
[SRNL]



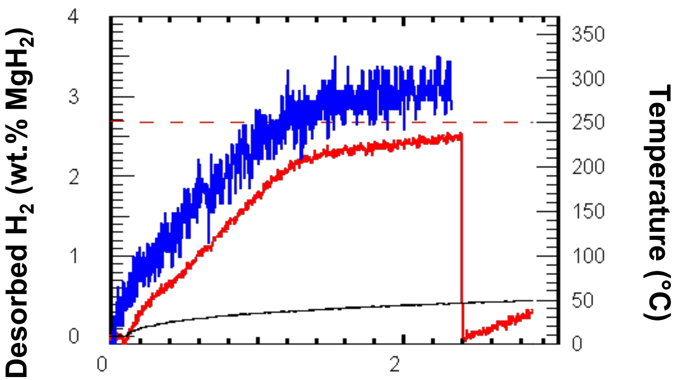


Consumed Al electrode after run

Incorporation of MgH_2 into Carbon Aerogel –
Key to enabling complete destabilized system infiltration



5x higher loading of MgH_2 into aerogel nanoscaffolds obtained by liquid phase route
[U. of HI]



Desorption kinetic comparable to melt infiltrated MgH_2 [U. of HI, HRL]

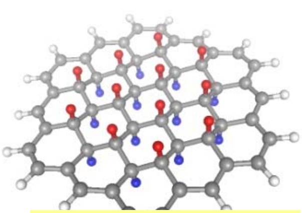
Progress: Sorbents

Goal: High volumetric capacity & kinetics at close to ambient T & nominal P

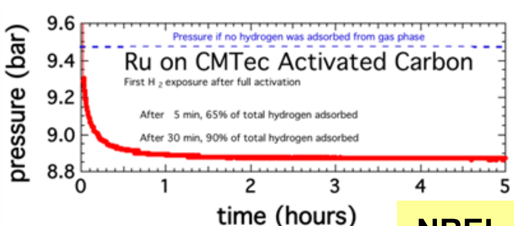
Chemisorption (Spillover)

Focus is on H_2 uptake kinetics & capacity [NREL, Rice, UM]

- Achieved synthesis process for catalyst deposition yielding enhanced rates; improved low pressure uptake rate by 5X
- Designed surface speciation that increased spillover capacity by ~20%
- Identified mechanisms through modeling that may facilitate increased H surface diffusion rates
- Identified surface species that can react with adsorbed hydrogen (e.g. for water formation) and may result in over -estimation of net capacity.



Rice-Yakobson

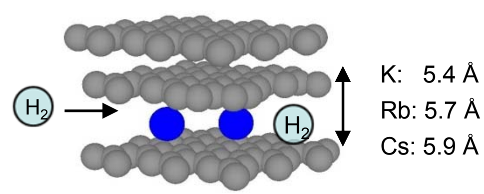


NREL

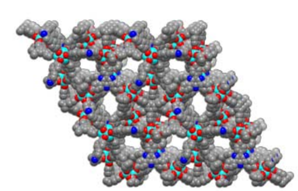
~77K Sorbents: Higher T goal

Increase volumetric capacity with narrow pore size distribution (pores 0.5 - 1 nm) & optimized ΔH_{ads} over wider coverage

- Achieved high SA polymers with 0.8 -1 nm micropores: ~1900 m^2/g, 1.4 g/ml bulk; 5 wt% at 77K and potential of 70 g/L H_2: 66% improvement over FY08 result [ANL/U. Chicago]
- Developed PCNs (MOFs) w uniform micropores ***and*** high SA (>4500 m^2/g), potential to surpass MOF177 [TAMU]
- Synthesized layered structures w uniform high ΔH_{ads}, retained 50% of 77K capacity at 195K [CalTech]



CalTech KC24

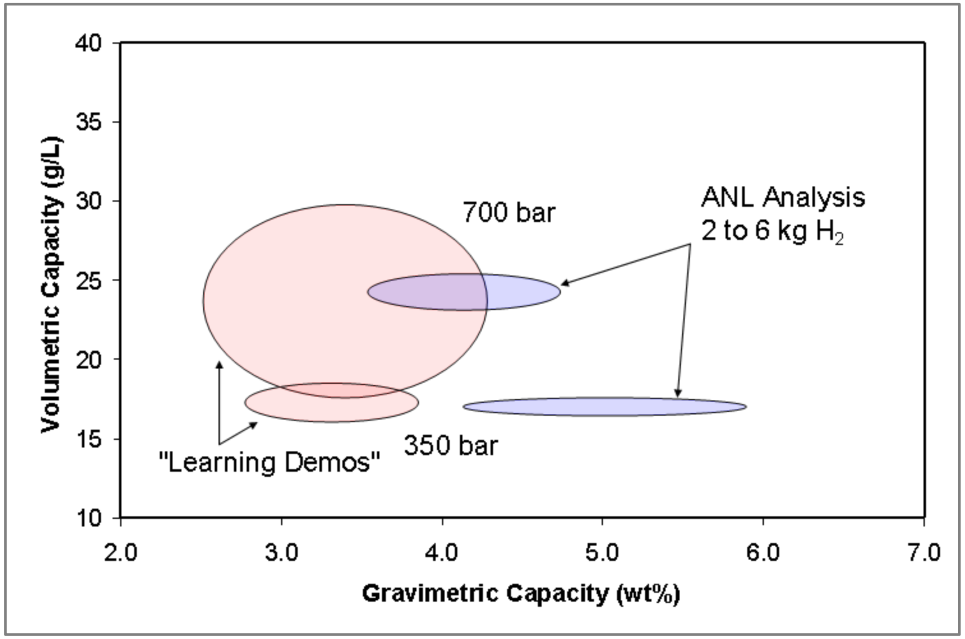


TAMU PCN103

Progress: Tanks

- Significant number of Gen 2 vehicles deployed with demonstrated range of 200 to 250 miles (up from 103 to 190)
- Currently 140 vehicles (33 vehicles with 700 bar and 75 with 350 bar) demonstrated through Technology Validation activity

Comparison of ANL Analysis with "Learning Demos"



System Gravimetric Capacity
350 bar: 2.8-3.8 wt.%
700 bar: 2.5-4.4 wt%

System Volumetric Capacity
350 bar: 17-18 g/L
700 bar: 18-25 g/L

New TIAX estimate (at 500,000 units)
$23/kWh (700 bar, -13% from '08)
$15.5/kWh (350 bar, -9% from '08)

Reduced cost due to revised design pressure requirements.

Progress: Systems Analyses, Testing

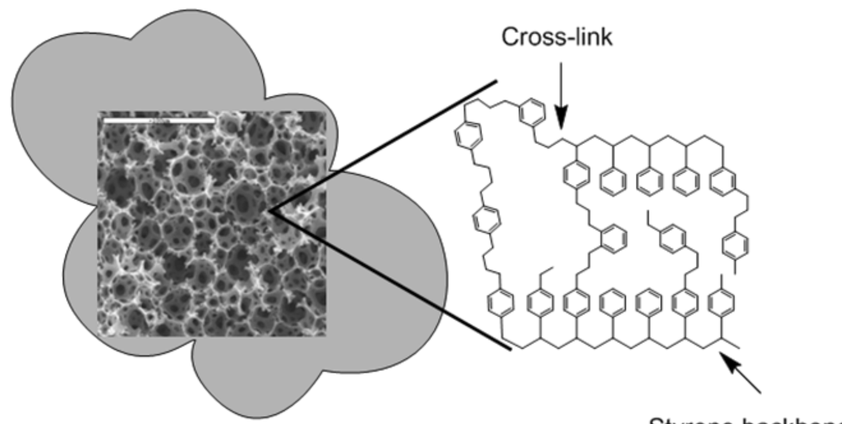
New Technical Reports Available:

- Completed "Technical Assessment: Cryocompressed Hydrogen Storage for Vehicular Applications"
  - -Summary of 2nd generation system and suggested approach for 3rd generation system (recently finished)
- Completed "Analysis of Compressed Hydrogen Storage Systems (350 bar and 700 bar) "*
  - -Weight, volume and cost updated based on industry feedback
- Completed "H_2 Storage using a Liquid Carrier: Off-board and On-board System Cost Assessments"*****
  - -Based on N-ethylcarbazole
- *Argonne, TIAX*

* **Available on-line next month.**

- **Reactivity of hydrogen storage materials assessed under various exposures** – *An IPHE Collaboration*
  - Developed a Failure Modes and Effects Analysis (FMEA) for materials-based hydrogen storage systems
  - Developed potential mitigation strategies in case of tank failures

U.S. (Savannah River, Sandia, UTRC), Japan, Germany, & Canada



Hazard risk mitigation strategy: Use low-cost, light-weight polymeric matrix for hydrogen storage material immobilization; reaction catalysts and/or fire suppressants could also be incorporated. [SNL]

See: http://www1.eere.energy.gov/hydrogenandfuelcells/hydrogen_publications.html#h2_storage

Hydrogen Storage H-Prize

- **Goal:** Demonstrate advancement for an on-board storage material exceeding performance targets
- **Administering Entity:** Pilot administered by Hydrogen Education Foundation, in partnership with SCRA
- **Announcement:** H-Prize criteria, eligibility requirements and registration procedures announced in the Federal Register **Spring, 2009.** ***Registration to submit a proposal must occur within 6 months of Federal Register posting.***
- **Award:** The pilot award of $1 Million Prize expected in **September 2010**
  - Administering entity is raising cost share to augments funds for future prizes

(Opens w/Federal Register Notice)

Summary

High Energy Density Storage for Fuel Cells

- Significant progress in hydrogen storage materials
  - Materials systems developed for on-board and off-board fuel storage; on-board and off-board regeneration of hydrogen
  - Performance targets updated
- Storage needs and performance targets for early market applications need to be defined

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For More Information

Hydrogen Storage Team

Sara Dillich
Hydrogen Storage Team Leader
202-586-7925
sara.dillich@ee.doe.gov

Carole Read
Sorbents & New Materials, Hydrogen Sorption Center of Excellence/FreedomCar Tech Team
202-586-3152
carole.read@ee.doe.gov

Grace Ordaz
Chemical Hydrides, Chemical Hydrogen Storage Center of Excellence
202-586-8350
Grace.Ordaz@ee.doe.gov

Monterey R. Gardiner
Tanks, Sorbents, Delivery, Engineering Center of Excellence
202-586-1758
monterey.gardiner@ee.doe.gov

Ned Stetson
Metal Hydrides, Metal Hydride Center of Excellence, SC&C Interface
202-586-9995
ned.stetson@ee.doe.gov

Announcing our newest team member:
Dr. Robert (Bob) Bowman Jr. (ORNL)
Technical Support Hydrogen Storage Team
robert.bowman@ee.doe.gov

Field Office Project Officers:
Jesse Adams
James Alkire
Paul Bakke
Katie Randolph

Support:
Anita Messick (BCS, Inc.)