



U.S. DEPARTMENT OF
ENERGY

Hydrogen Storage

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**2009 DOE Hydrogen Program & Vehicle
Technologies Program**

Merit Review and Peer Evaluation Meeting

May 19, 2009

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.

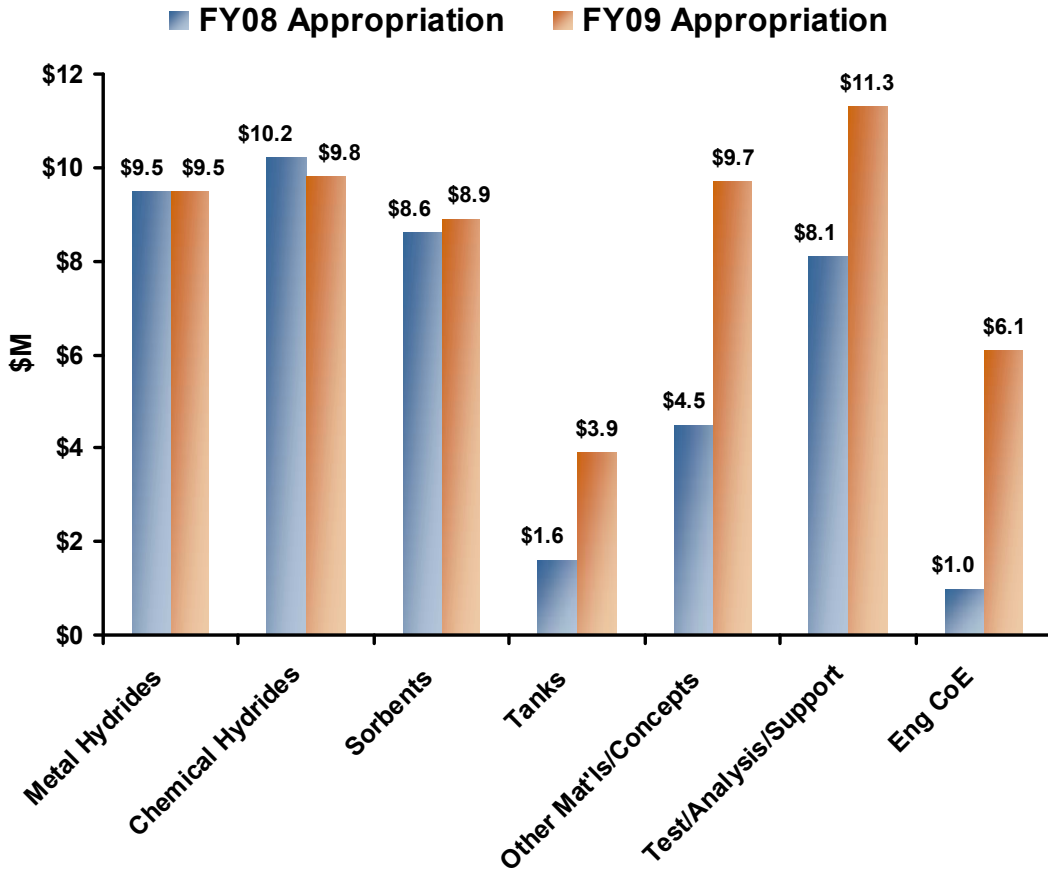
Goal: Develop storage options to facilitate deployment and market growth of fuel cell power systems for early market applications; define role of hydrogen for utility storage.

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



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.**



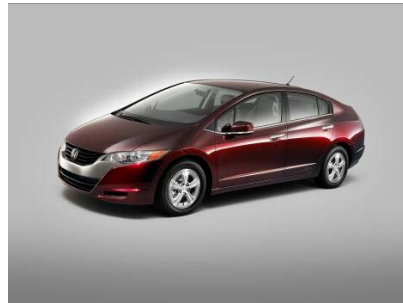
Storage for Early Market Applications As Well As for Light-Duty Vehicles

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.





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

Target	2015	2015	Ultimate*
	<i>new</i>	<i>old</i>	<i>new</i>
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

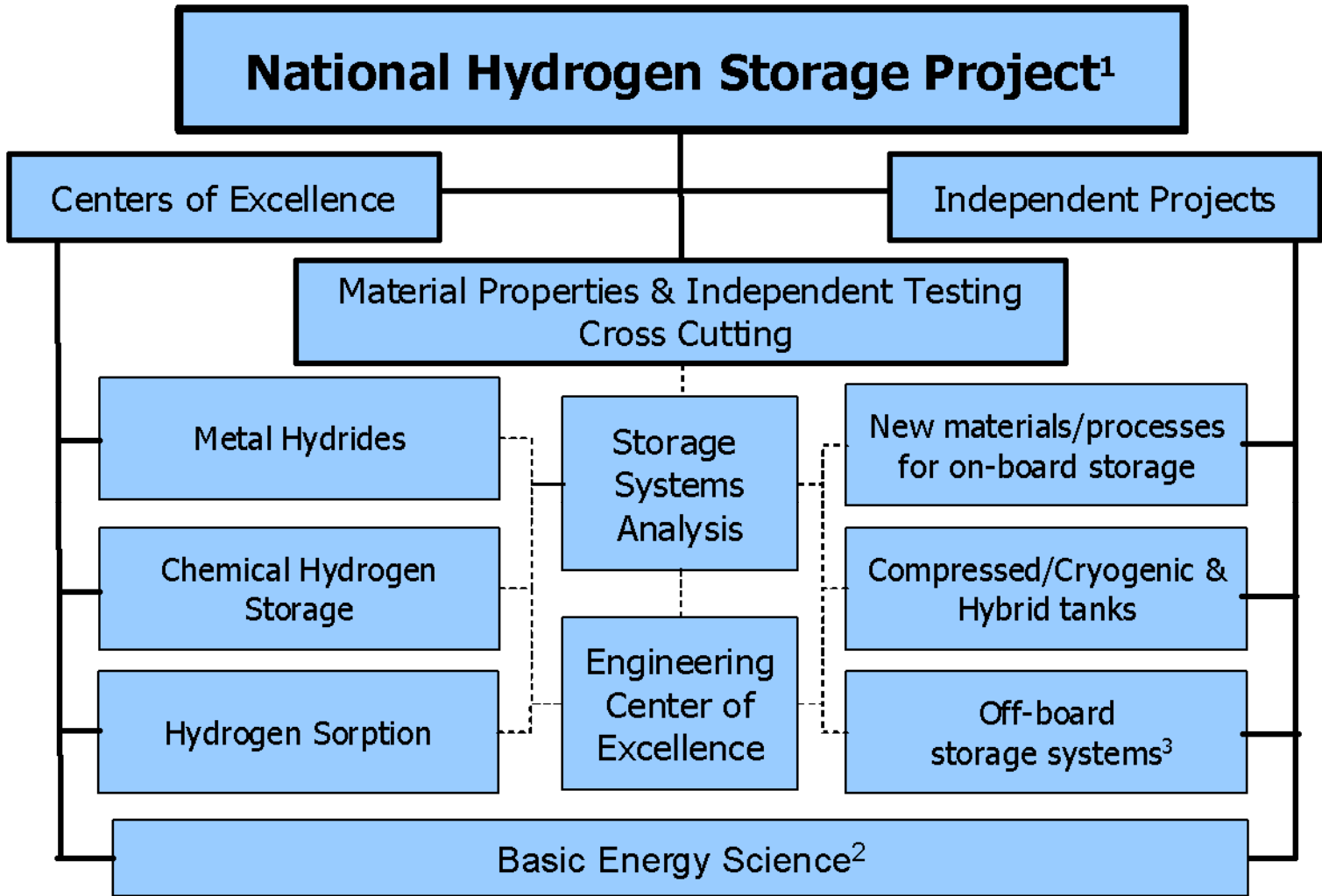
***Ultimate** targets are intended to facilitate the introduction of hydrogen-fueled propulsion systems across the majority of vehicle classes and models



*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 H₂ FCs
 - Revised – Vehicle architecture will change between gasoline ICE and H₂ FCs; Current targets based on packaging and design of current FC vehicle fleets
 - Fuel Economy –
 - Original – 2.5 to 3 times improvement for H₂ FCs over ICE
 - Fuel economy based on current FC vehicle fleet data

Diverse, Highly Integrated Program



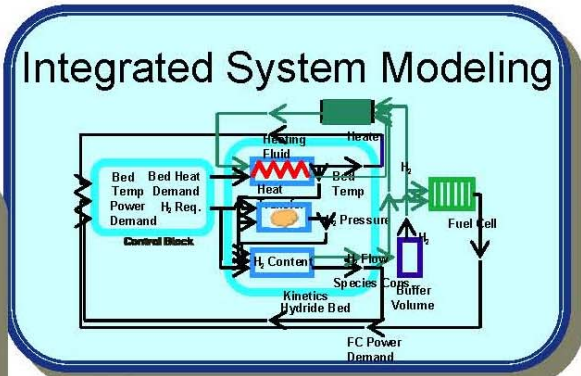
1. Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program element



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

Performance Analysis

The diagram illustrates a performance analysis workflow. It starts with a car icon, followed by a graph showing a peak. Below the graph is a box labeled 'DIRECT'. A circular arrow indicates a feedback loop between the car and the graph.



Balance of Plant Parameters from System Models

Storage System

Forecourt Parameters from Models and External Input

Enabling Technologies

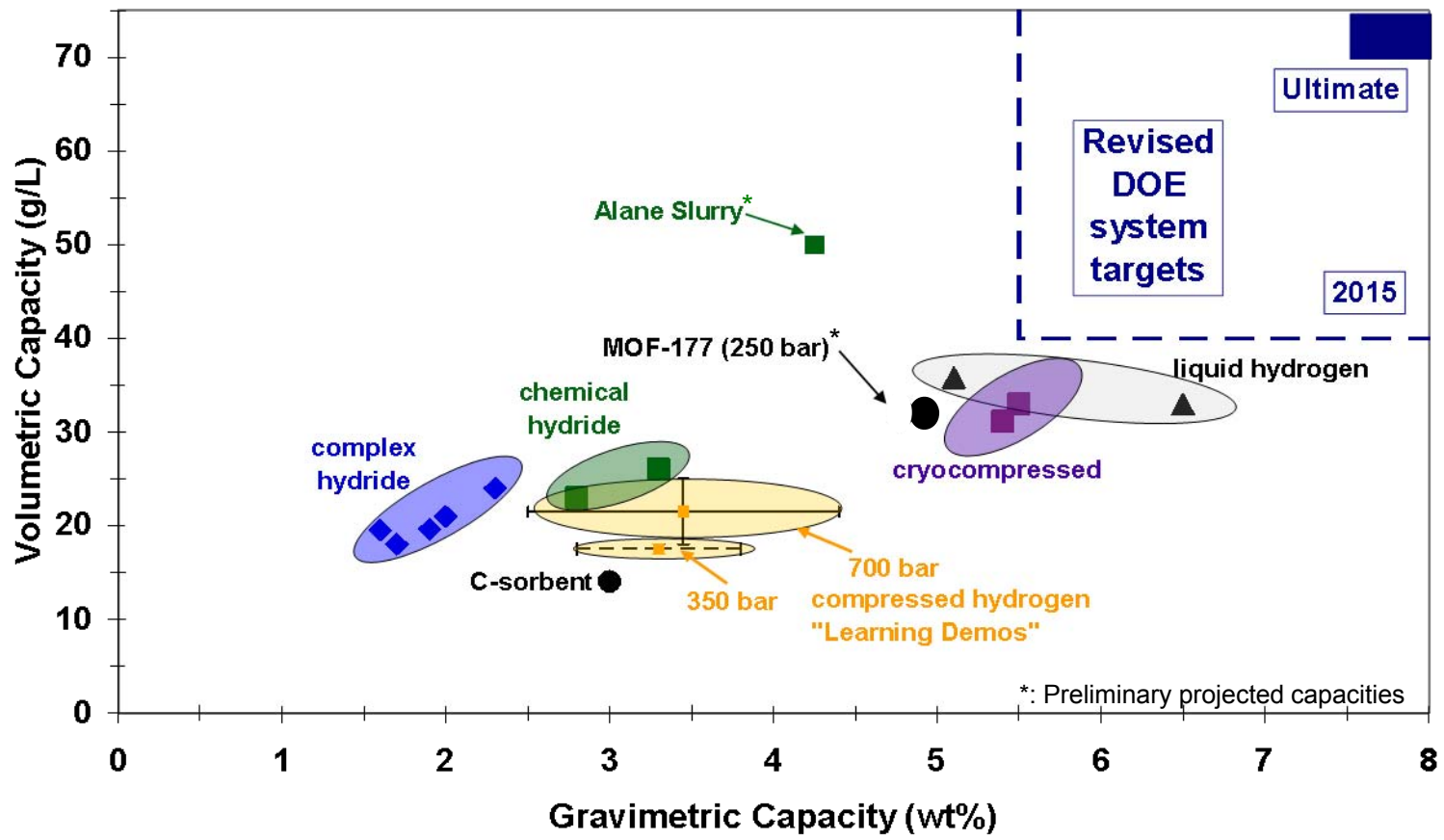
The image shows several mechanical parts: a black cylindrical component, a brass-colored multi-port valve, and a smaller brass component with a blue pen for scale.

Transport Phenomenon

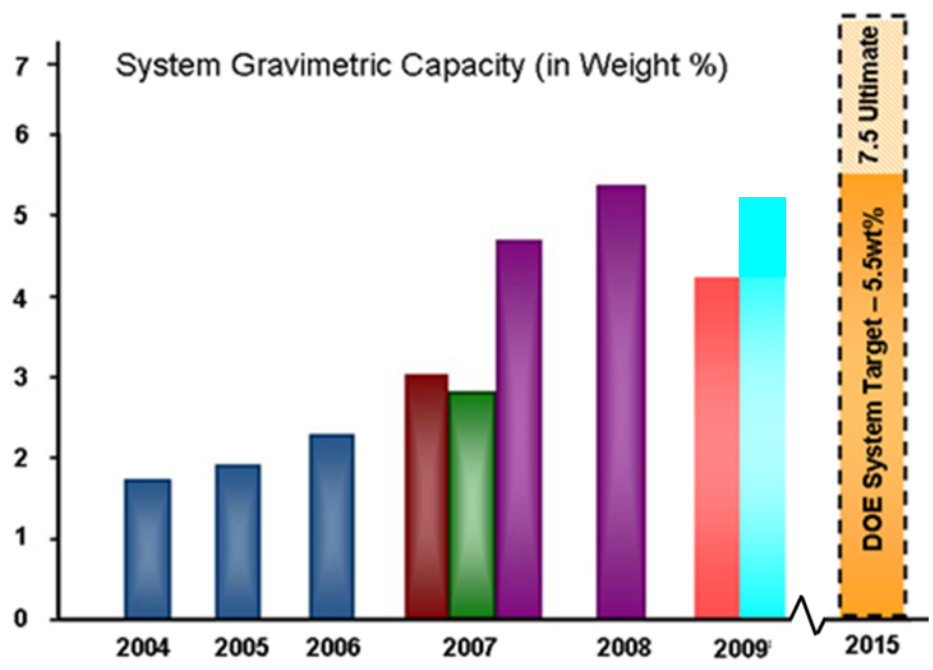
The image shows four circular heat maps with color gradients from blue (low) to red (high), representing temperature distribution. To the right is a photograph of a cylindrical metal component with a mesh-like structure.

Prototype Testing

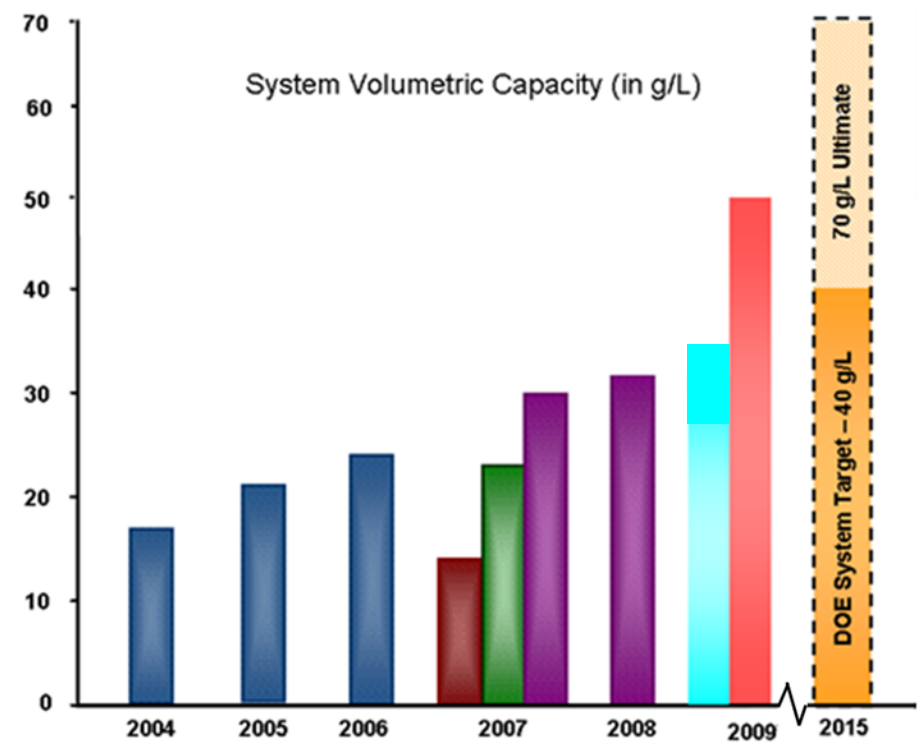
The image shows a laboratory environment with various pieces of equipment, including a large cylindrical vessel, and several people working at computer workstations.



- 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



- *Projected system capacities based on modeling and material data*
- *Subscale prototype developed for NaAlH₄*
- *Full scale prototype developed for cryocompressed tank*



**Preliminary, based on initial analysis.*

Metal Hydrides-

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

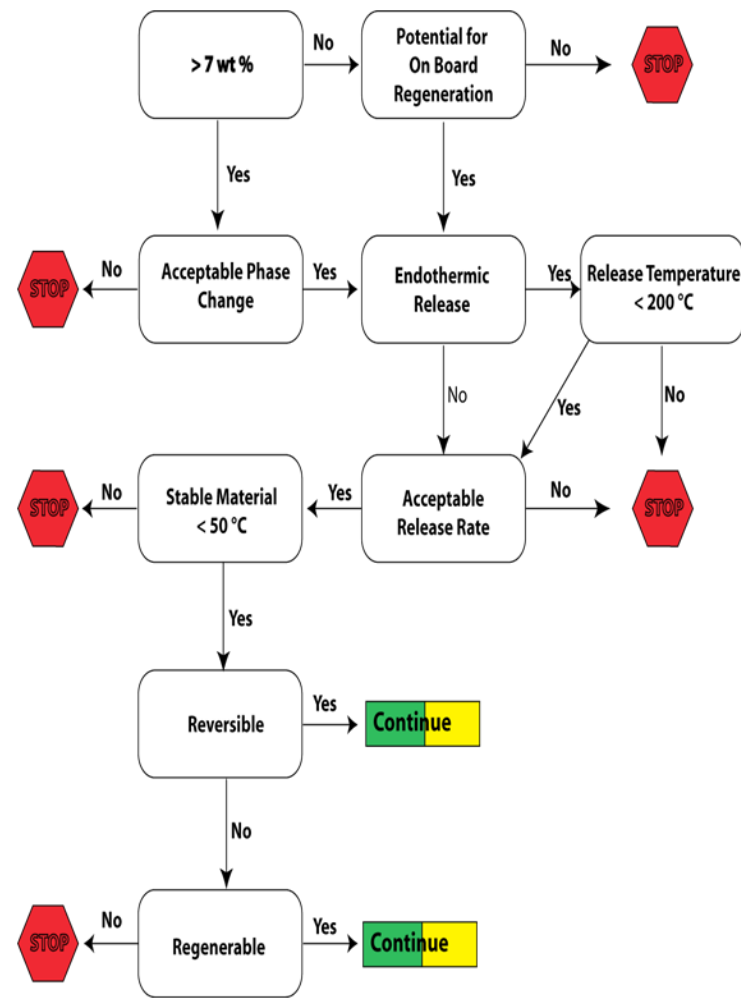
Chemical Hydrogen Storage-

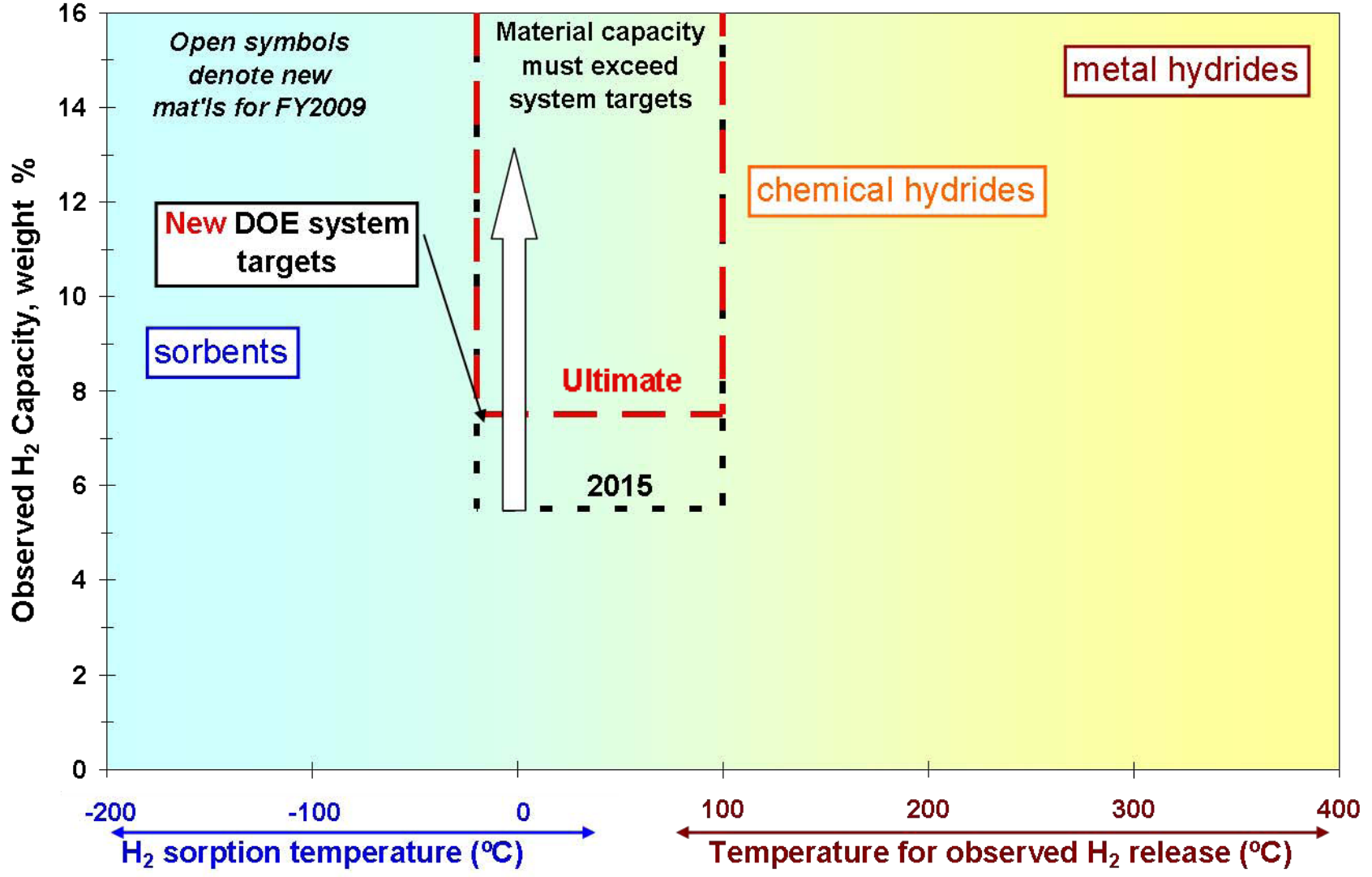
- ~ 120 materials/combinations have been examined
- ~ 85% discontinued
- ~ 15% still being investigated – many derivatives of AB, or mixture of AB with additives

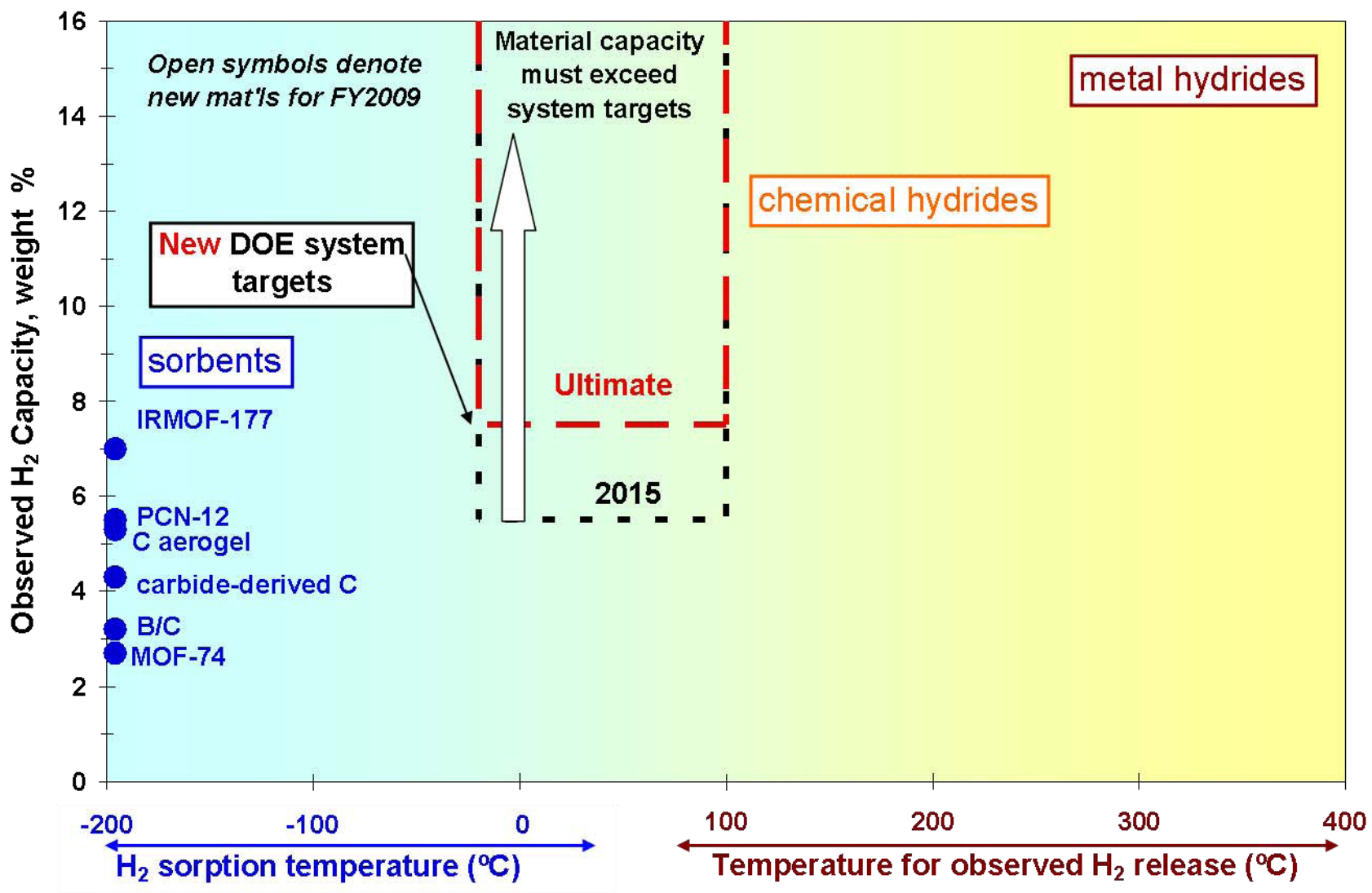
Hydrogen Sorption-

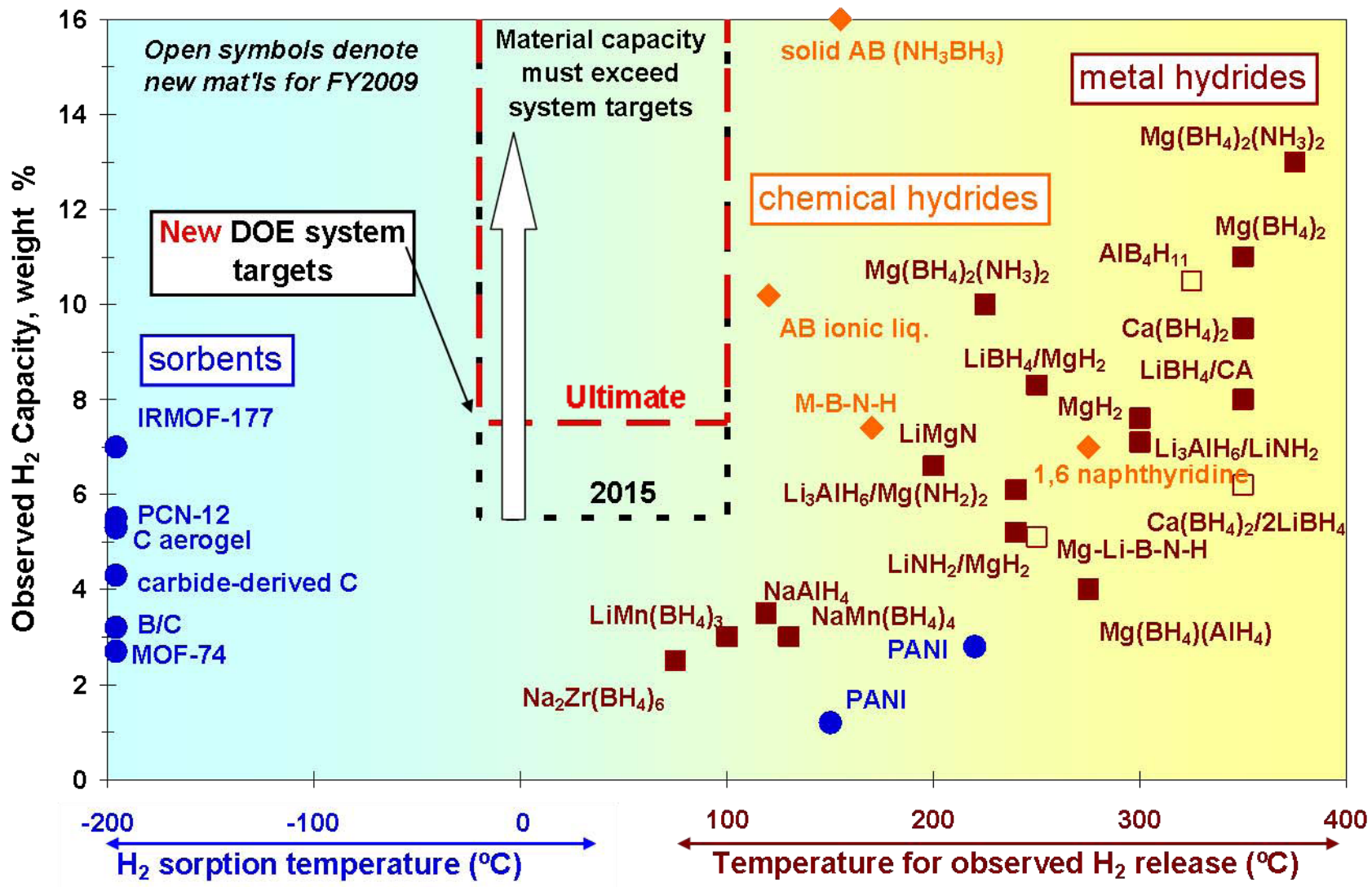
- ~ 60 materials investigated
 - ~ 40 discontinued
 - ~ 20 still being investigated
- Down-select report in preparation

CHSCoE Materials Decision Tree



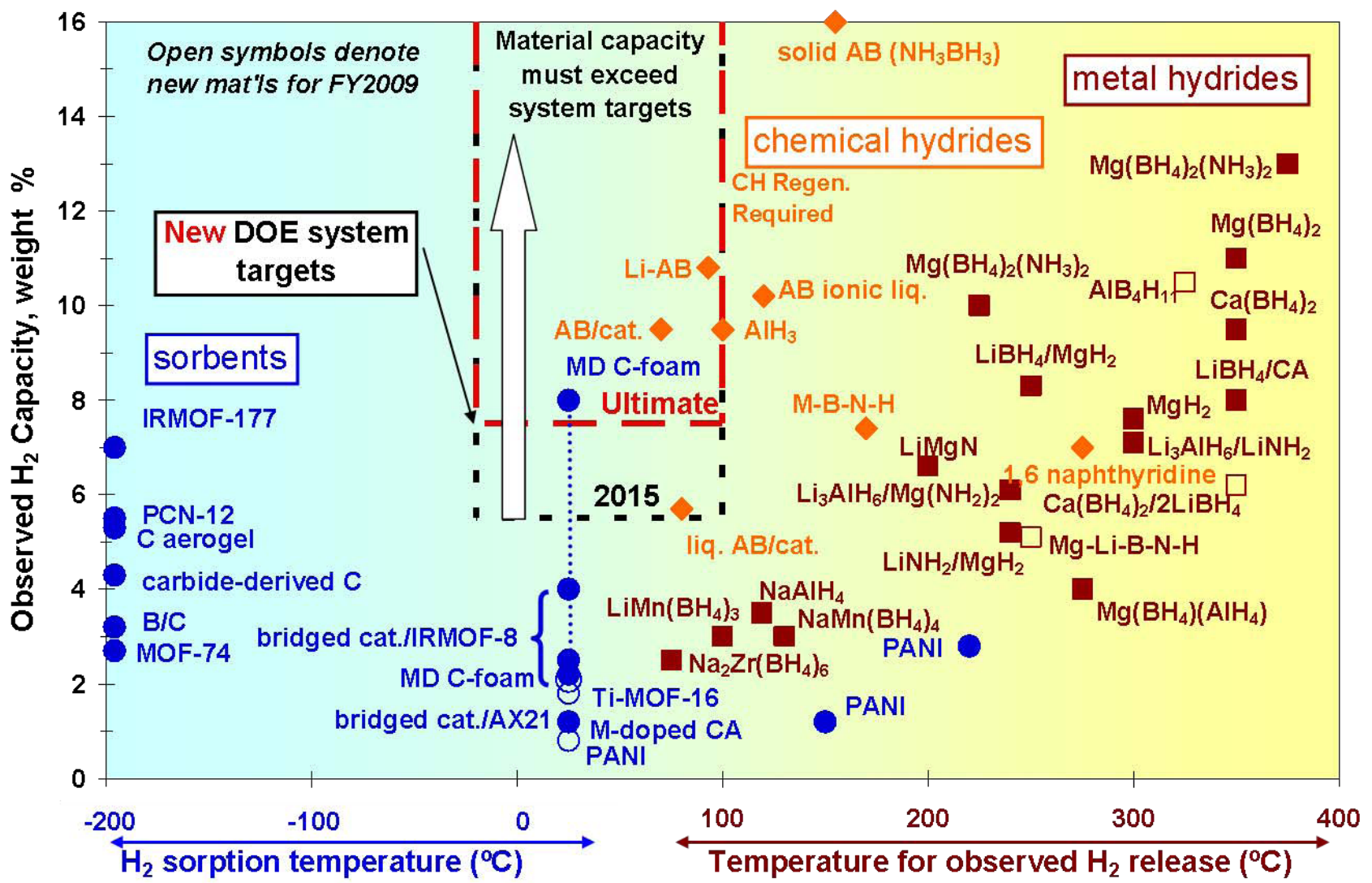






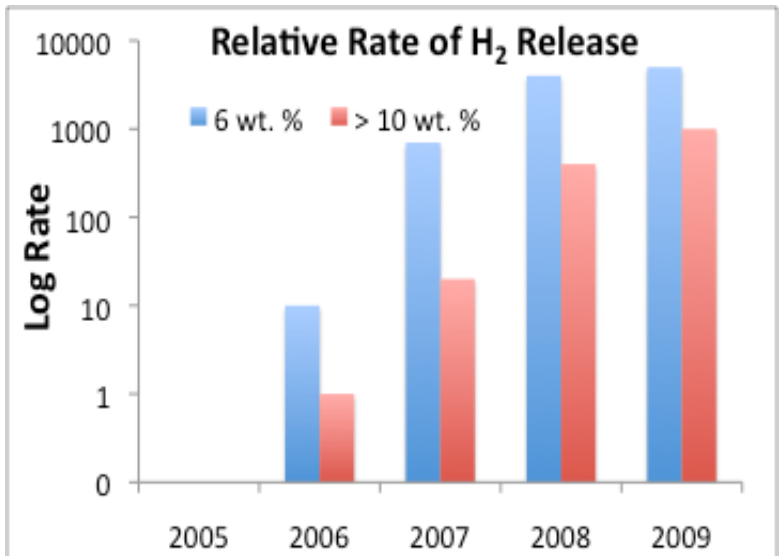


Progress: Material Capacity vs. Temperature



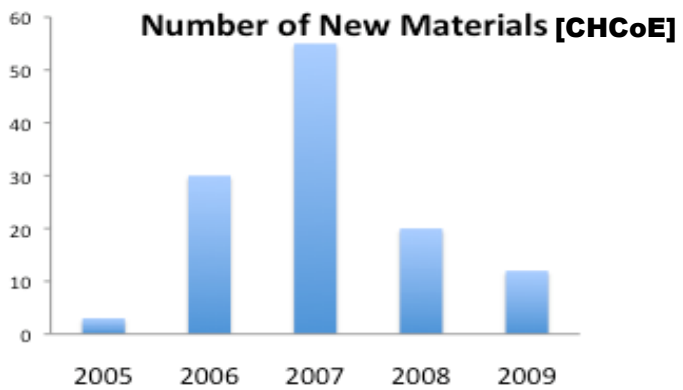
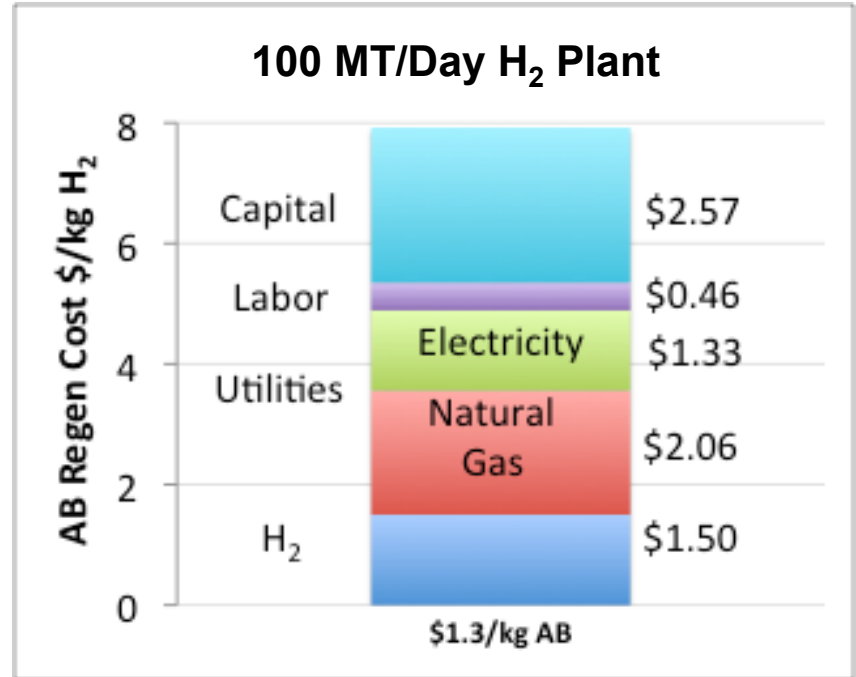


Ammonia Borane H₂ release rates increased by factor 10² – 10³ [CHCoE]



Cost analysis completed [Rohm&Haas]

- Baseline cost of AB regeneration: \$7-8/kg H₂
- Separations are key to improvements

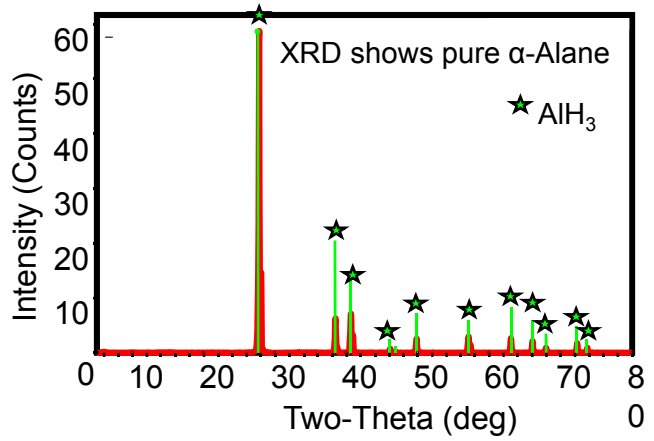


New materials include:

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

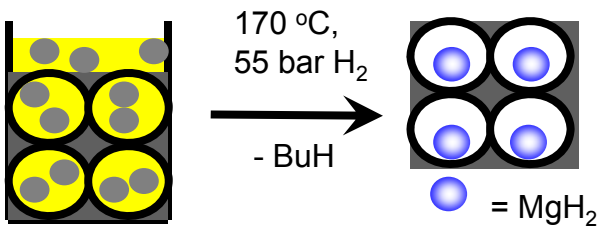
Electrochemical Regeneration of Alane (AlH₃)

High yields of gram quantities of pure α -AlH₃ obtained under mild conditions.
[SRNL]

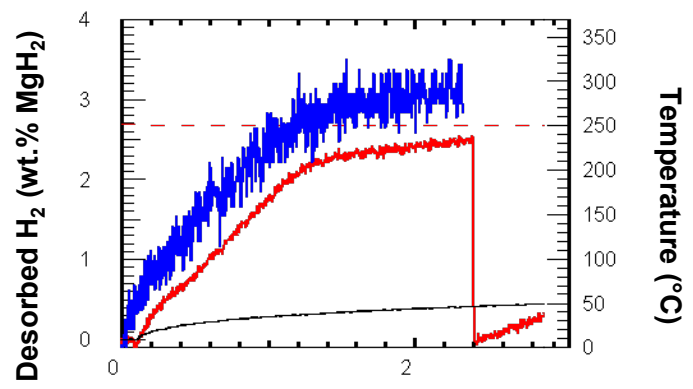


Consumed Al electrode after run

Incorporation of MgH₂ into Carbon Aerogel – Key to enabling complete destabilized system infiltration



5x higher loading of MgH₂ into aerogel nanoscaffolds obtained by liquid phase route
[U. of HI]



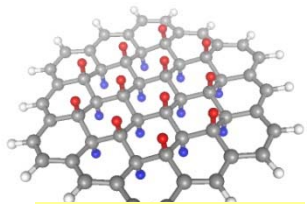
Desorption kinetic comparable to melt infiltrated MgH₂ [U. of HI, HRL]

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

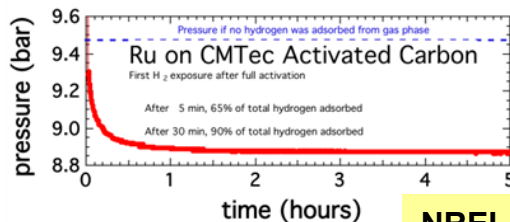
Chemisorption (Spillover)

Focus is on H₂ 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

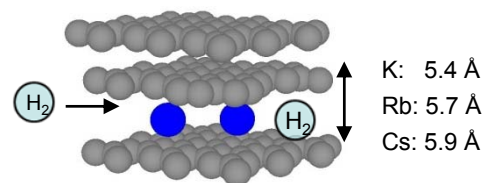


NREL

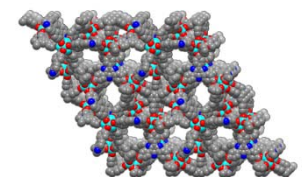
~77K Sorbents: Higher T goal

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 m²/g, 1.4 g/ml bulk; 5 wt% at 77K and potential of 70 g/L H₂: 66% improvement over FY08 result [ANL/U. Chicago]
- Developed PCNs (MOFs) w uniform micropores **and** high SA (>4500 m²/g), potential to surpass MOF177 [TAMU]
- Synthesized layered structures w uniform high ΔH_{ads} , retained 50% of 77K capacity at 195K [CalTech]



CalTech KC24

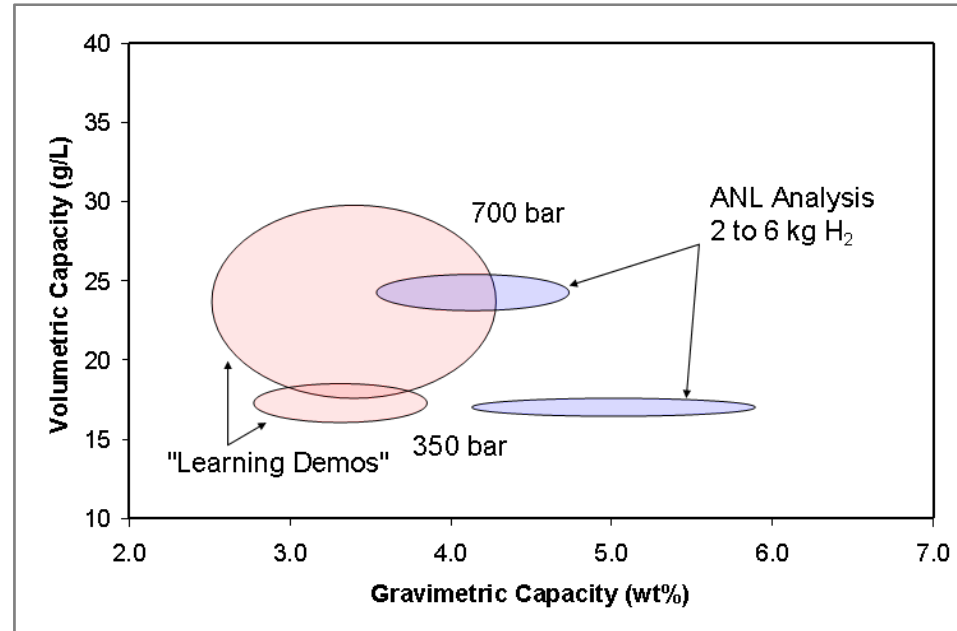


TAMU PCN103



- 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.

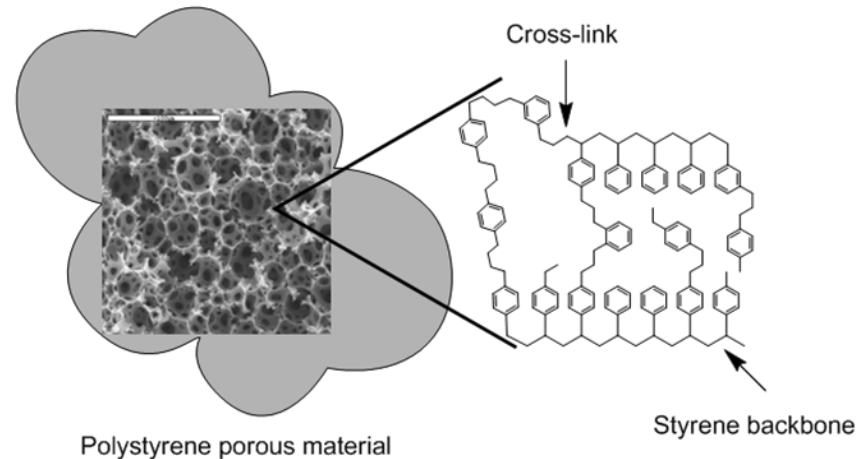
New Technical Reports Available:

- 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 “H₂ 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]



- **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 augment funds for future prizes

(Opens w/Federal Register Notice)



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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Announcing our newest team member:

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