U.S. Department of Energy
Hydrogen Program

Hydrogen Storage

Sunita Satyapal

2008 DOE Hydrogen Program
Merit Review and Peer Evaluation Meeting

June 9, 2008

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.) or cost

Develop on-board storage systems to meet DOE targets, including:

- Capacity
- Operating temperature range (-40 to +85^{o}C)
- Hydrogen supply rate/refueling rate
  - 0.02 g H_2 per sec. per kW of power
  - Refueling time <3 min. for 5 kg H_2
- System cost
- Fuel cost
- Safety, C&S, reliability, cycle life, efficiency, etc.

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

Challenges

- **Vehicles are being designed by OEMs that can achieve > 300 miles**
  - **350 or 700 bar**
  - **1 to 4 tanks**
  - **Specified range from ~200 to > 350 miles**

- **But performance, space on-board and cost are still challenges for mass market penetration…**

- **Is there a low pressure alternative?**

Strategy – Diverse, Balanced Portfolio

National Hydrogen Storage Project[1]

- Centers of Excellence
  - Metal Hydrides
  - Chemical Hydrogen Storage
  - Hydrogen Sorption
  - Engineering Center of Excellence
- Testing, Material Properties & Analysis Cross Cutting
- Basic Science[2]
- Independent Projects
  - New materials/processes for on-board storage
  - Compressed/Cryogenic & Hybrid tanks
  - Off-board storage systems[3]

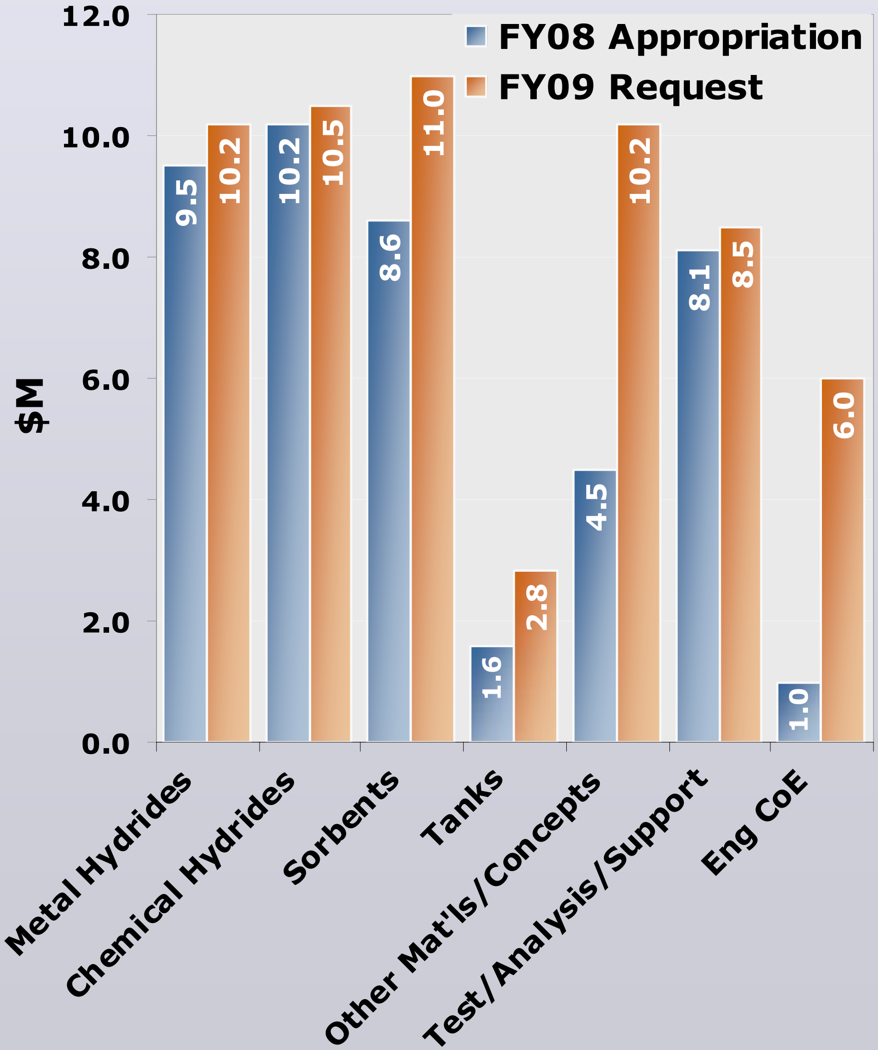
1. Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program element

~40 Universities, ~20 Companies, ~15 Federal Laboratories

Hydrogen Storage Budget

FY 2009 REQUEST = $59.2M

FY 2008 APPROPRIATION = $43.5M

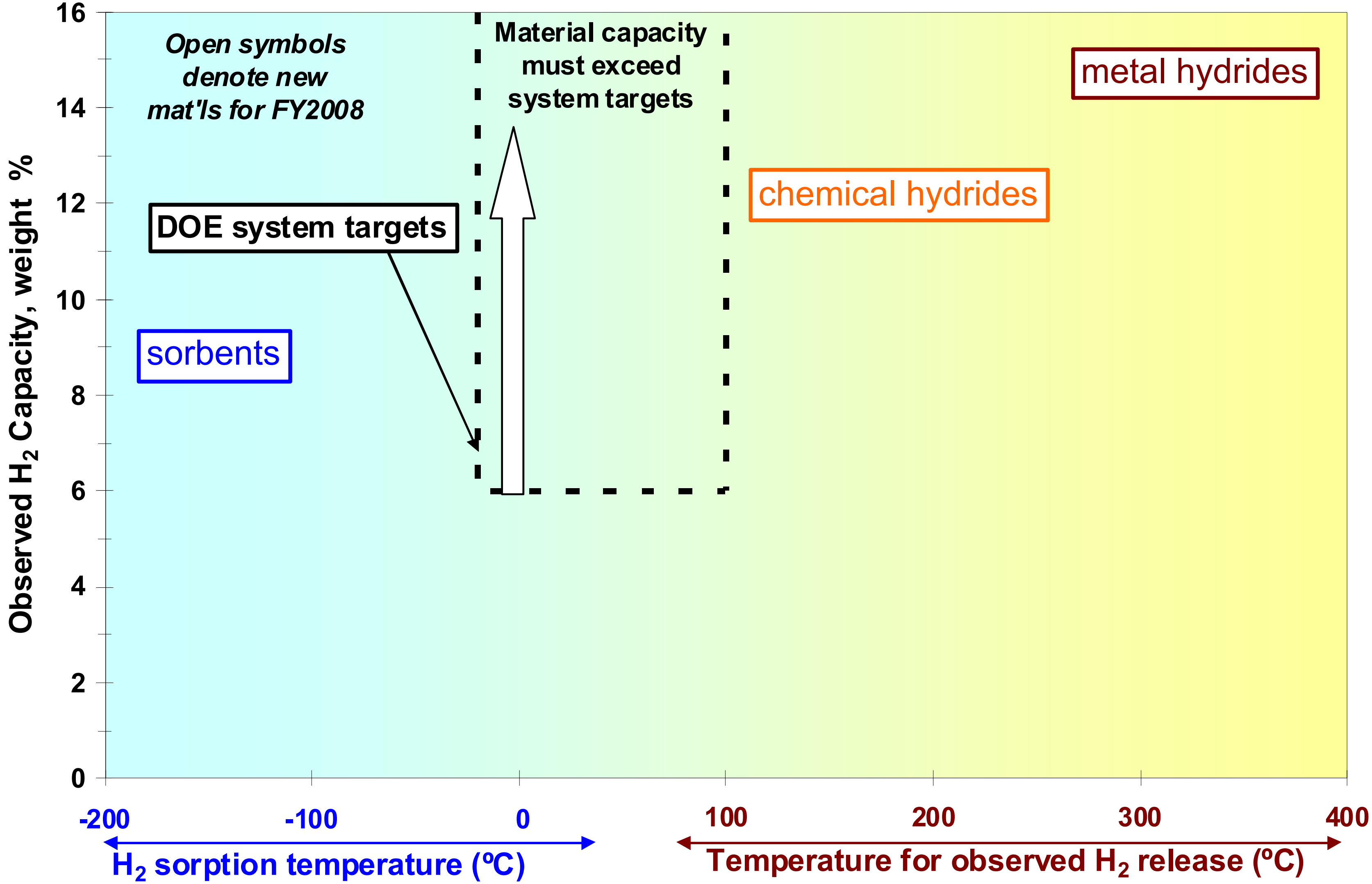


FY2009 Emphasis

- Increase engineering in addition to materials R&D through Centers of Excellence and independent projects to enable system targets.
- Focus on kinetics, temperature, pressure, cycle life, spent fuel regeneration, etc. *in addition* to capacity
- Strengthen tank R&D to address NAS recommendations. Focus on cost reduction and advanced concepts. Also applicable to materials-based approaches.
- Continue close coordination with Basic Science

Progress

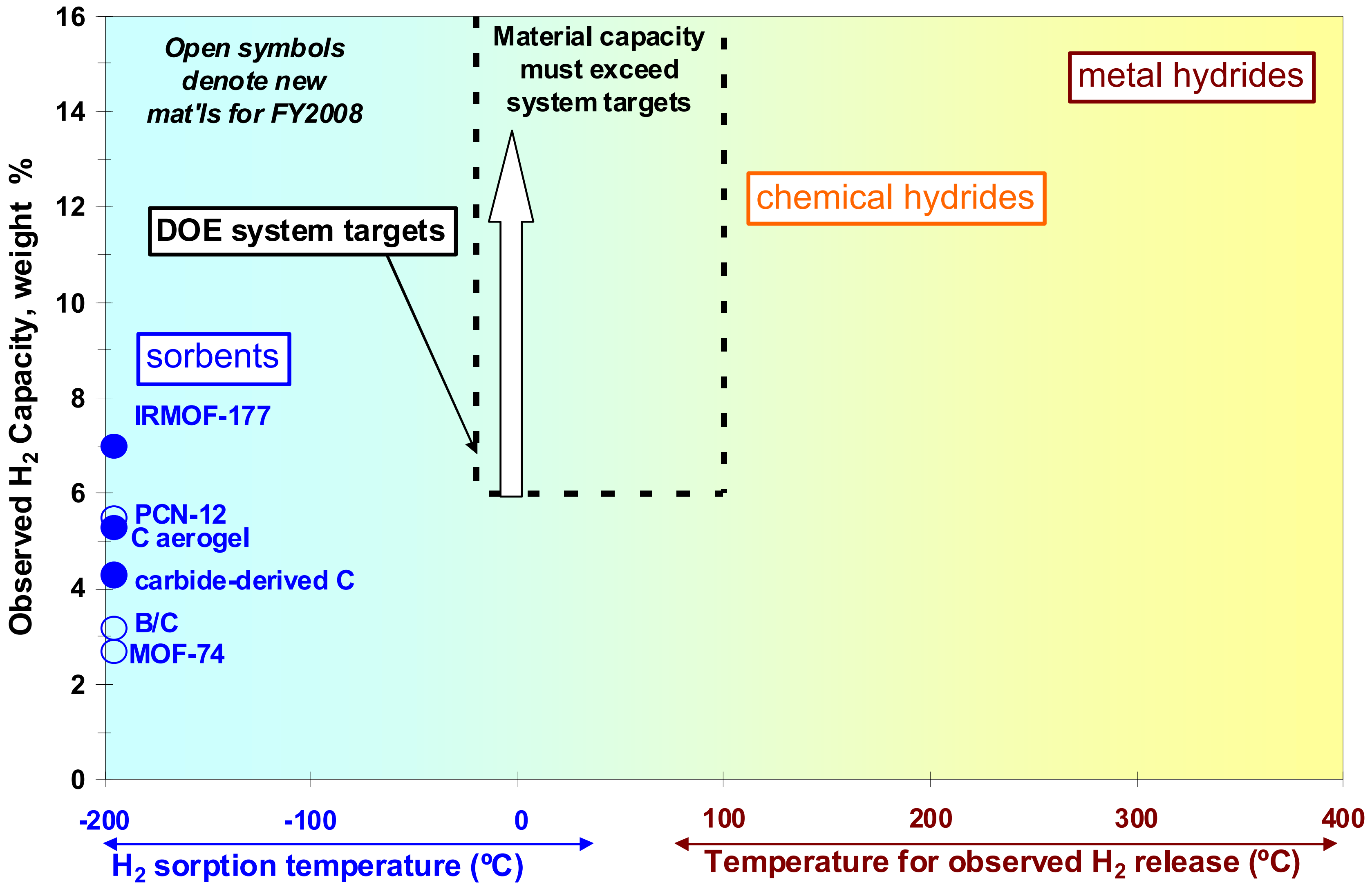
Material Capacity vs. Temperature



DOE: G. Thomas (2007), G. Sandrock (2008)

Progress

Material Capacity vs. Temperature



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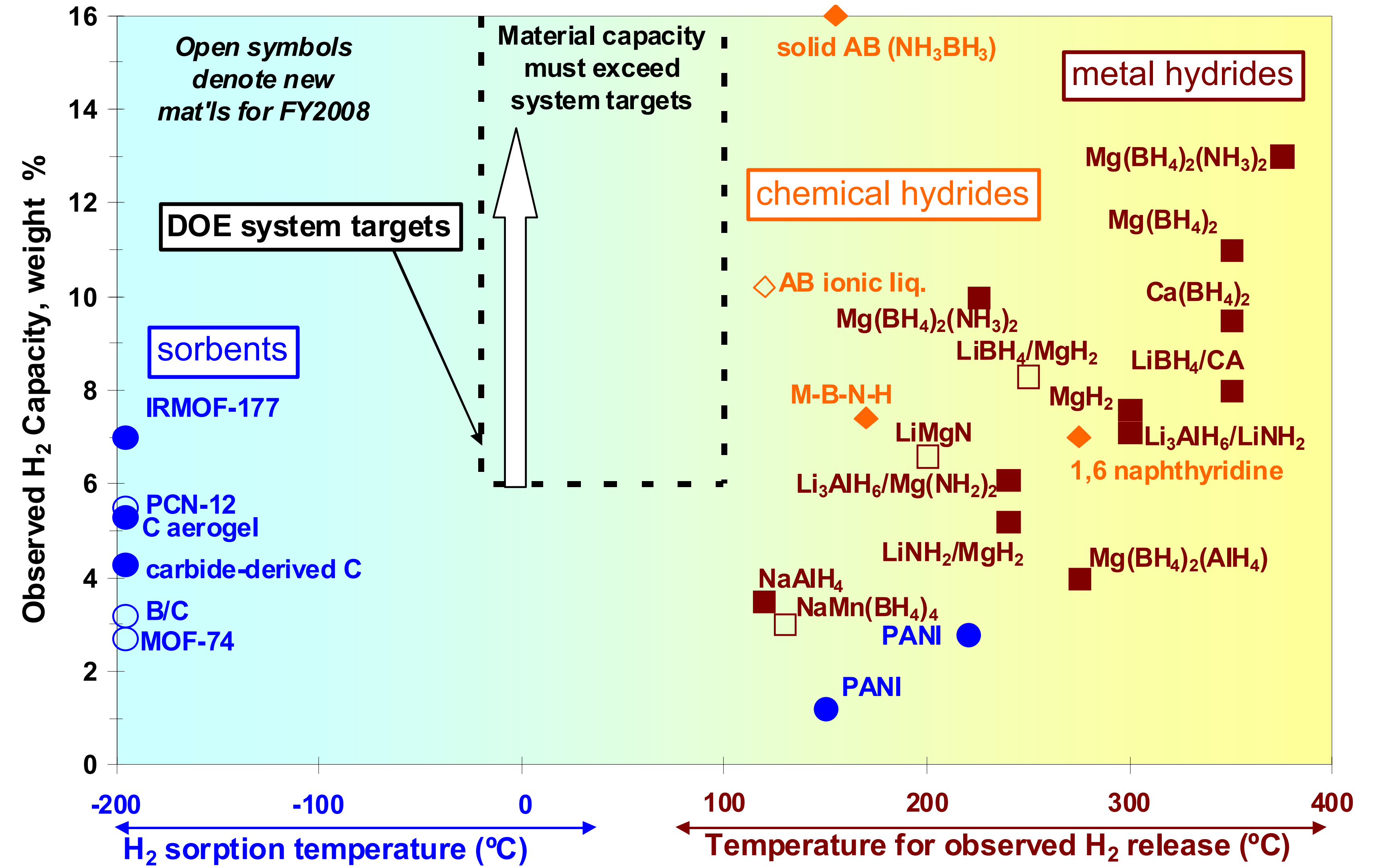
Progress

Material Capacity vs. Temperature



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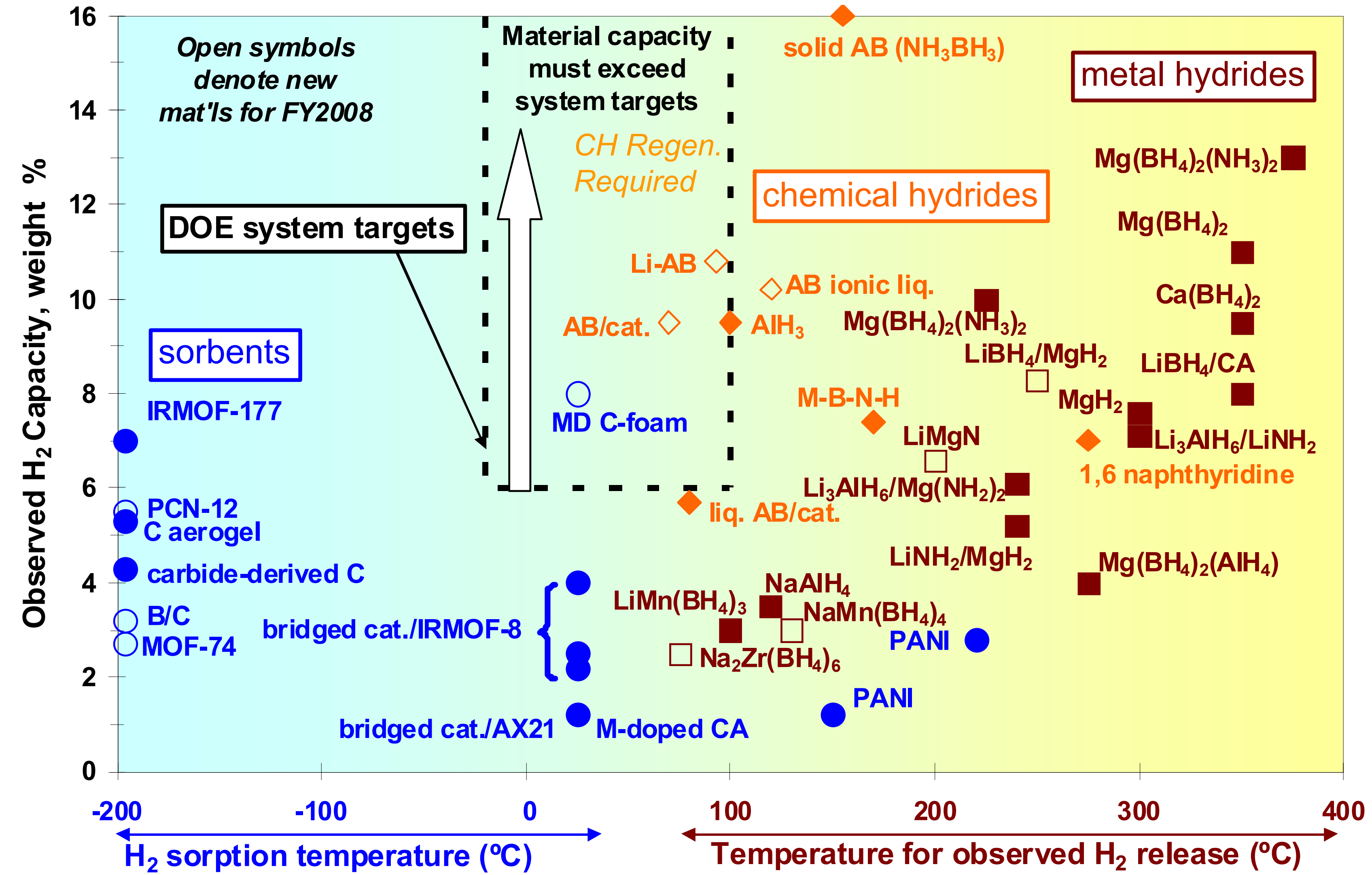
Progress

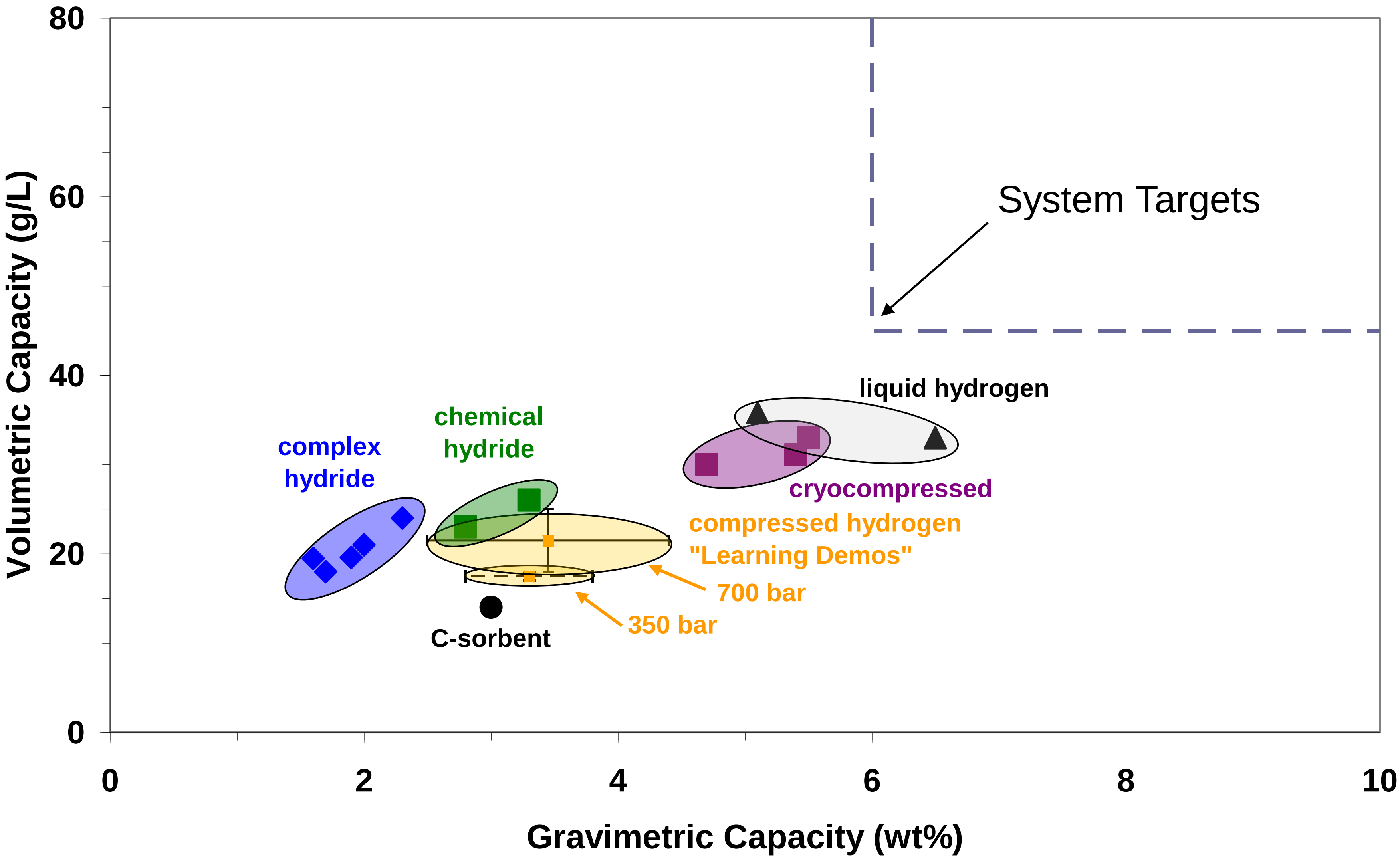
Material Capacity vs. Temperature



DOE: G. Thomas (2007), G. Sandrock (2008)

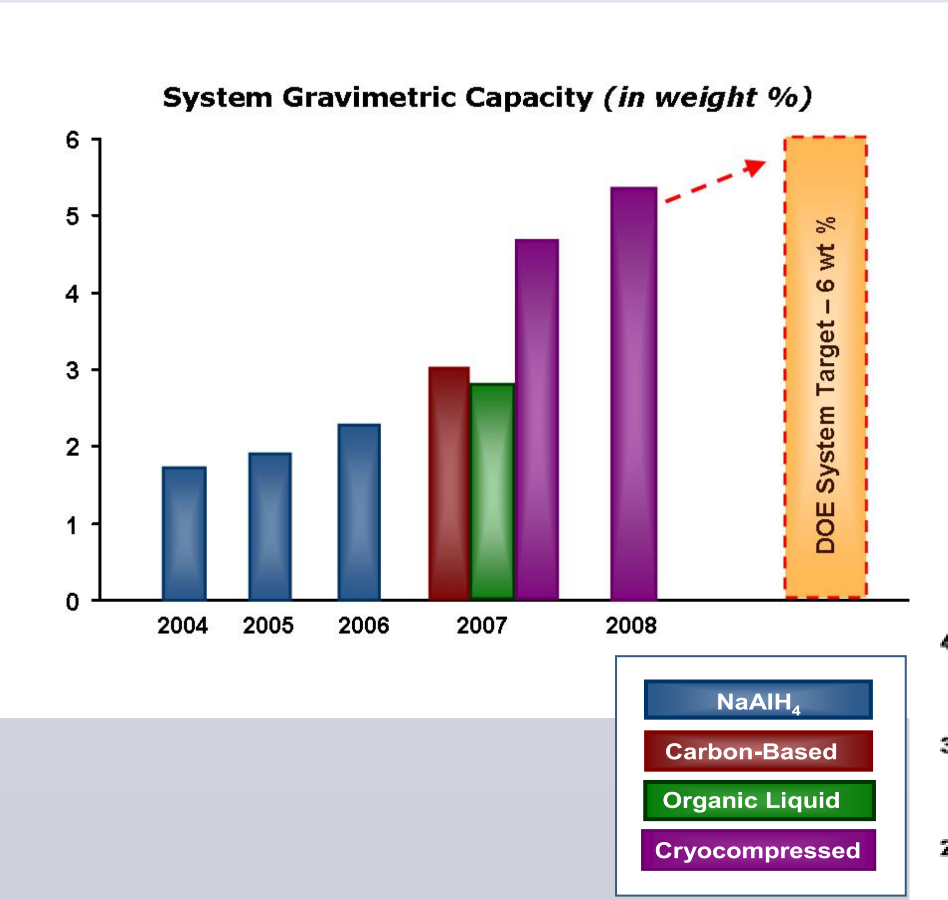
Current Status

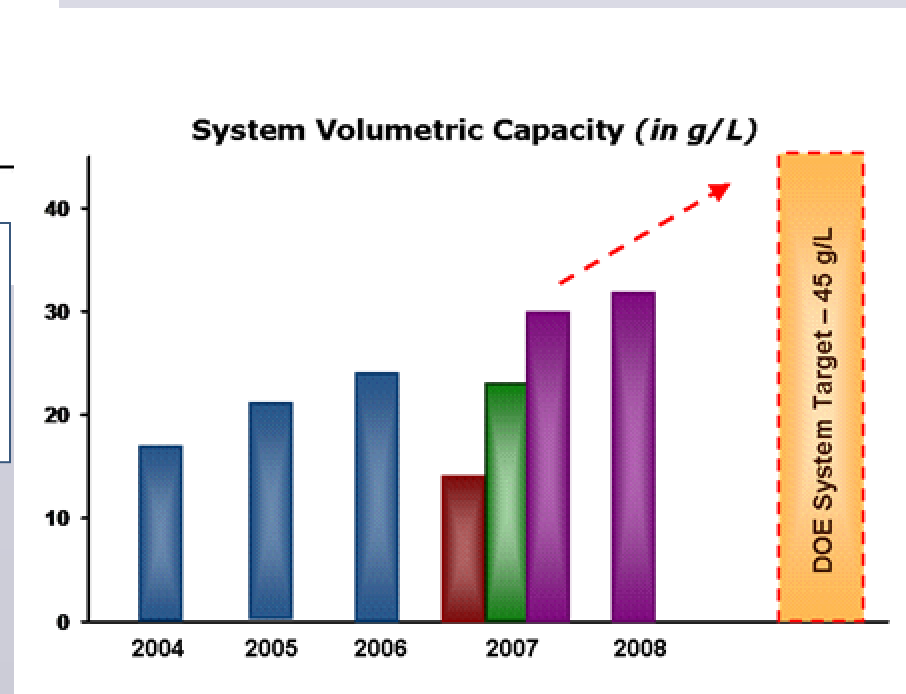
No technology meets targets



Hydrogen Storage System Progress

- Preliminary designs developed and improvements made
- But no technology meets targets
- Need to focus on volumetric capacities





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

Progress

Metal Hydride Down-Selects

More than 50 Metal Hydride Approaches Assessed

- **~ 50% discontinued**
- **~ 50% show some promise**

Examples of Approaches Discontinued:

- MgH_2/Si: not reversible X
- $2LiNH_2 + MgH_2$: wt. % limited X
- $Li_2Zn(BH_4)_4$: high diborane X

Examples of Approaches Continued:

- $LiBH_4/MgH_2$ in aerogels ✓
- LiMgN, $Li_3AlH_6/3LiNH_2$ ✓
- $A_xMn(BH_4)_y$ [A=Li, Na, K] ✓
- AlH_3 , and 22 other systems ✓

In fulfillment of materials down-select milestone

Materials Go/No-Go Decisions Made Within the Department of Energy Metal Hydride Center of Excellence (MHCoE)

In fulfillment of the end of Fiscal Year 2007 Project Milestone on Materials Down-selection

Lennie Klebanoff, Director
Sandia National Laboratories
Livermore, CA 94551

September/October 2007

METAL HYDRIDE CENTER OF EXCELLENCE

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

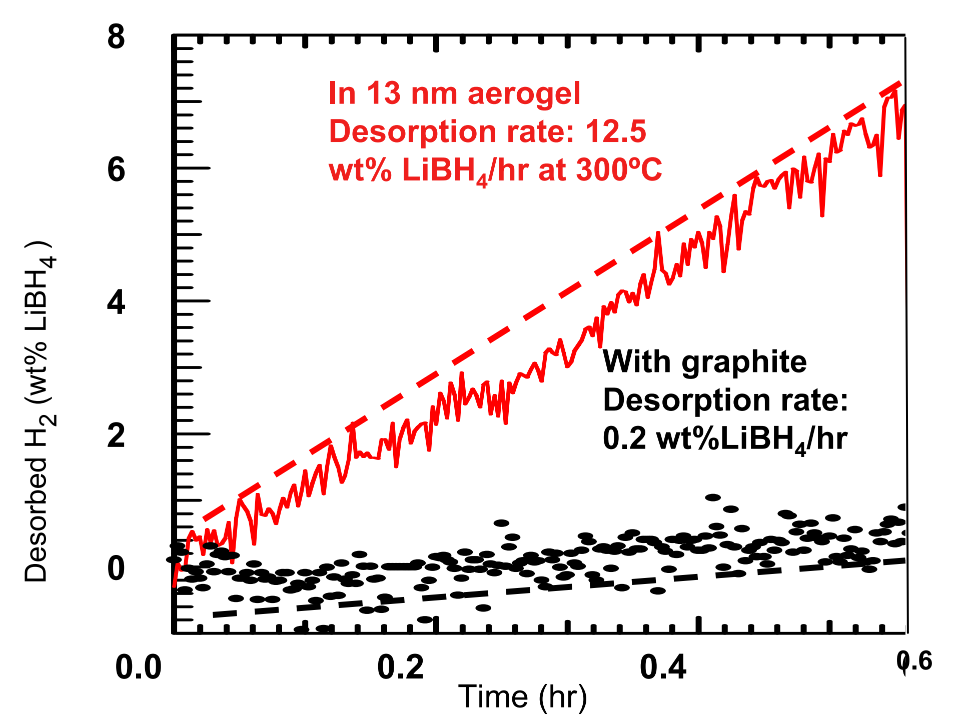
Accomplishments
Metal Hydride Examples

- Developed theory tool and screened > 16 million compositions
- Identified > 40 single step reactions as promising so far (with > 6 wt% H_2 and 15 < ΔU_0 < 75 kJ/mol H_2)

Alapati, Johnson and Sholl,
J. Phys. Chem. C, **112**, 5258 (2008)

Increased kinetics *60-fold* using $LiBH_4$ in aerogel

$LiBH_4 \rightarrow LiH + B + 1.5H_2$



Vajo, et al, HRL & Baumann, et al, LLNL

2008 Progress

Chemical Hydrogen Storage Down-Selects

More than 60 Materials Assessed

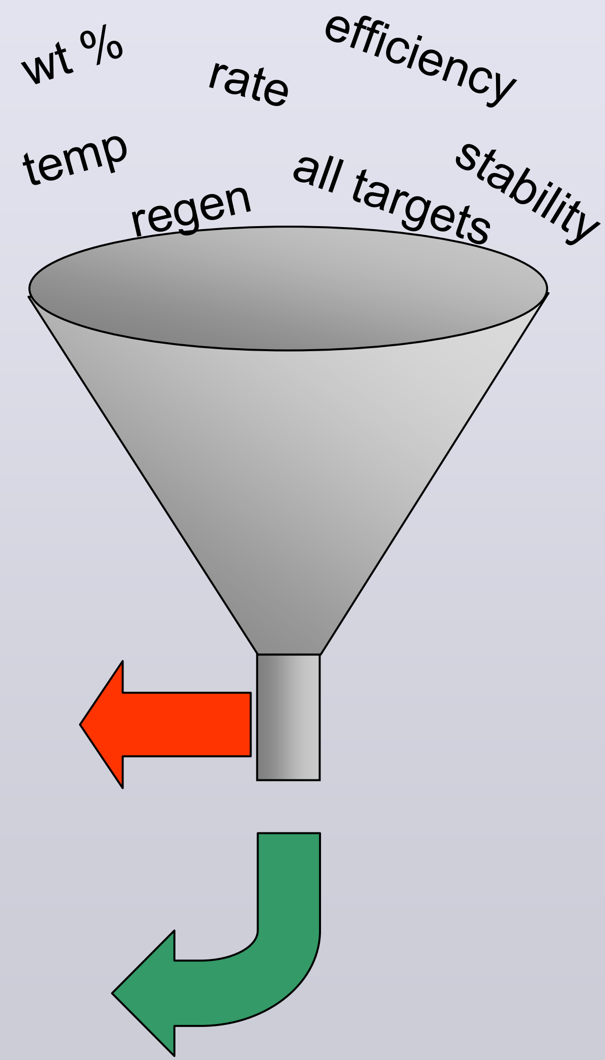
- **~ 50% discontinued**
- **~ 30% show some promise but have issues**
- **~ 20% show some potential to meet targets**

Examples of Approaches Discontinued:

- Hydrolysis of polyhedral boranes, & $NaBH_4$: inefficient spent fuel regen **X**
- $Mg(OMe)_2/H_2O$: >200C release T **X**

Examples of Approaches Continued:

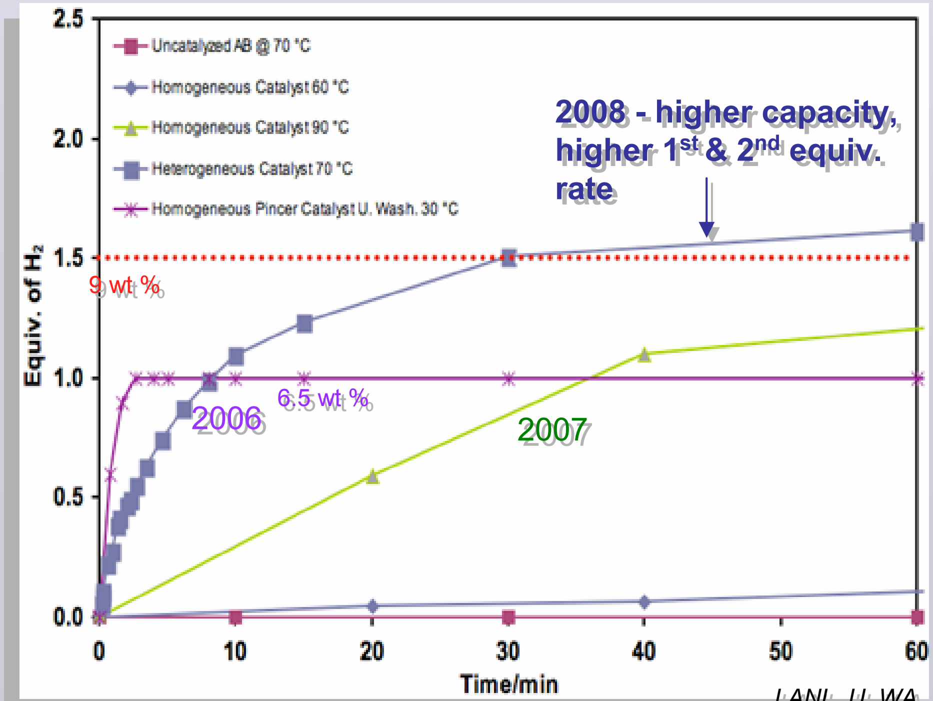
- **Exothermic release:** e.g. Ammonia borane (AB), AB-scaffolds, AB - ionic liquid mixtures, liquid amine boranes ✓
- **New materials, thermoneutral or coupled release:** E.g., Metal-boron-nitrogen materials ✓



Accomplishments
Ammonia borane

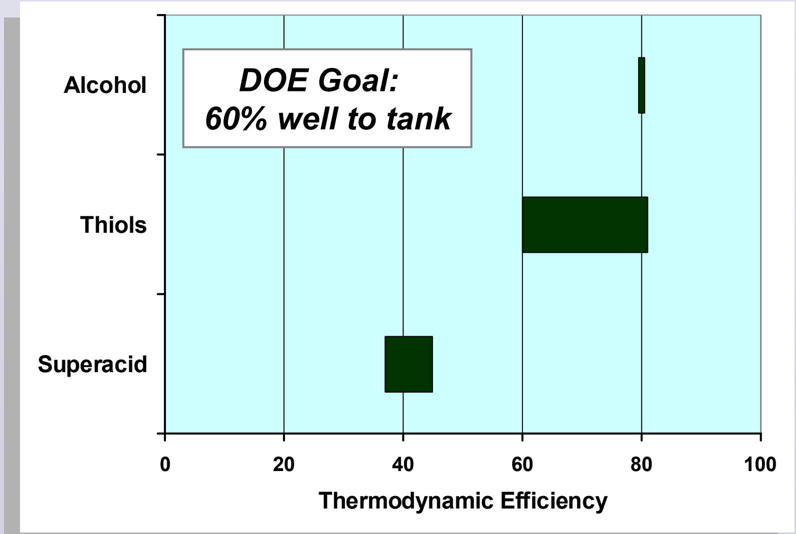
$NH_3BH_3 \rightarrow BNH_x + 3H_2$ **19.4 wt.%, 160 g/L** (theoretical material capacity)

- **Increased H_2 release rates by 4X compared to 2007. Can meet DOE rate targets**
- **Improved H_2 capacity by > 50% since 2006**



LANL, U. WA

- **Improved regeneration efficiencies by 22-35%**



- **Increased efficiency via design of optimum digesting agent and reduction strategy**
- **Improved yields for all steps in the 3 regen schemes**

LANL, PNNL, U. AL, U.C.-Davis, UPenn

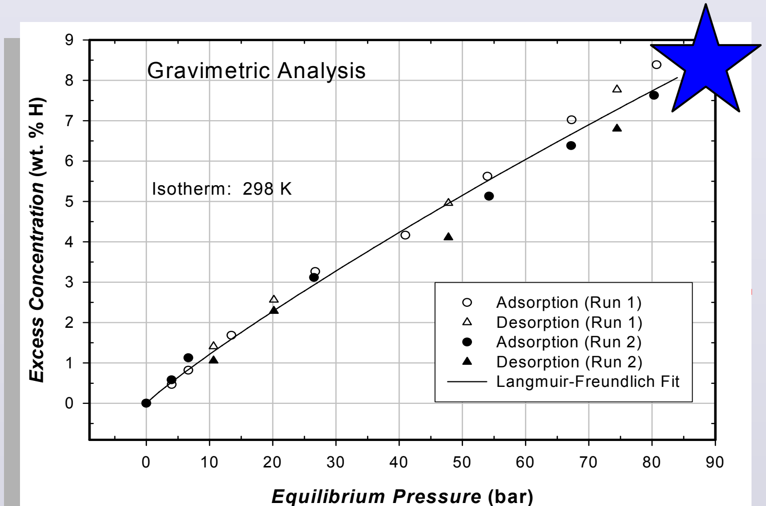
Progress

Hydrogen Sorption Examples

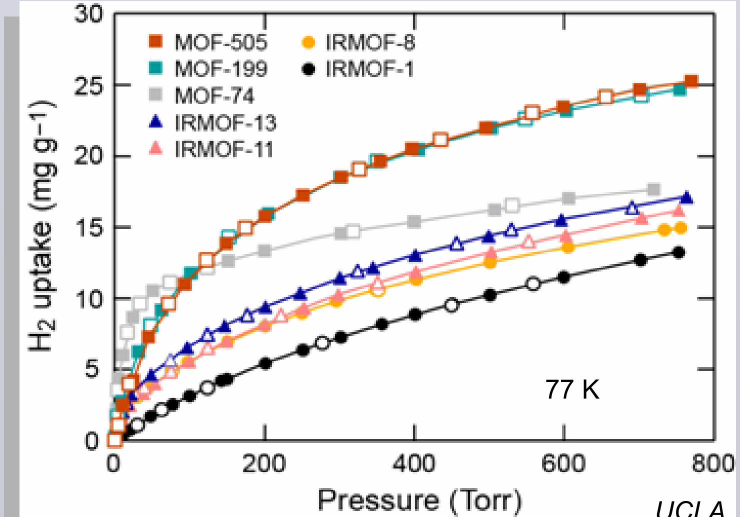
- **DOE work on "spillover" catalyzed worldwide R&D**
- **Led to 8 wt.% at room temp**

- **Tailored binding energies**
  - ✓ **PCN-12 ΔH_i ~ 12 kJ/mol**
  - ✓ **MOF-74 ~ 8 kJ/mol**
  - ✓ **Activated C-fiber ~10 kJ/mol**

  (compared to <6 kJ/mol)
- **Increased H_2 uptake by 75% using open metal sites**
- **Modeling of sorbents and spillover identified thermodynamically favorable approaches**



National Center of Scientific Research "Demokritos" (NESSHY, EC) and SwRI (DOE)



Hydrogen Sorption Center of Excellence, SwRI and UCLA

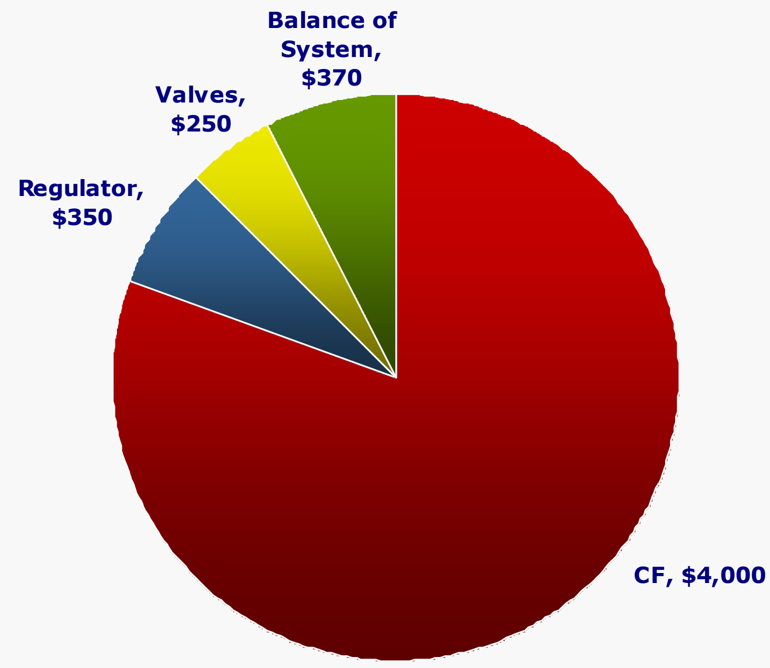
Progress

Tanks

- Demonstrated 103 to 190 mile range across 92 vehicles (Gen 1) through Technology Validation activity
- Demonstrated ~ 2X increase in dormancy using cryocompressed tanks (LLNL)
- Assessed high P tank cost (TIAX)
  - High volume cost projections:
    - ~ $27/kWh (700 bar)
  - Assessed cryo-compressed tank cost & sensitivity analysis

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



700 bar, 5.6 kg net, $5,000 (500,000 units)

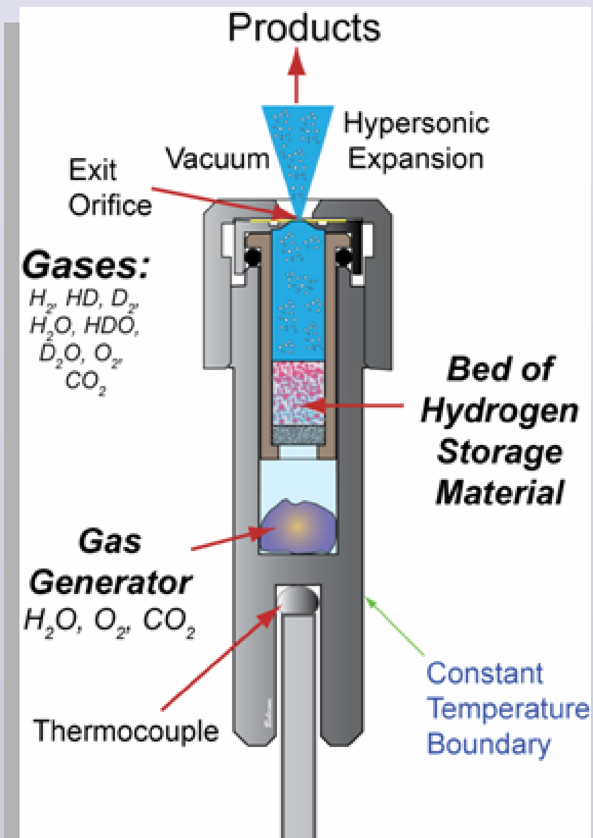
Progress

Materials Properties, Testing & Analyses

- **Best Practices developed for hydrogen storage equilibrium & kinetics measurements**
  - **Draft online for public comment**

K. Gross, H2 Technology Solutions/HyEnergy, LLC/NREL

- **Reactivity of hydrogen storage materials assessed under various exposures –** *An IPHE Collaboration*



Savannah River, Sandia, UTRC (US) & Japan, Germany, Canada

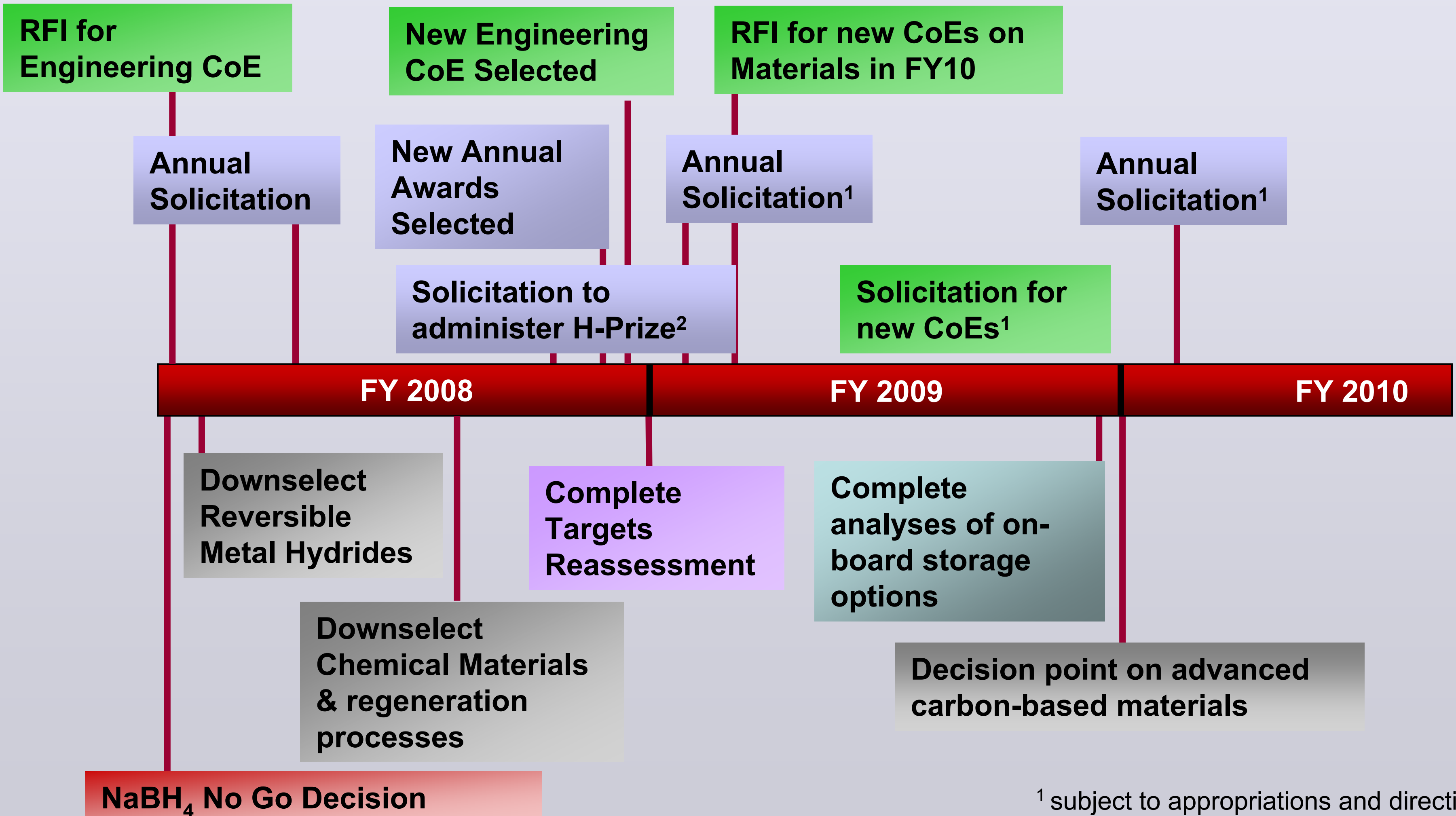
Systems Analysis

- **Preliminary well to tank efficiency analysis conducted**
- **System capacity and cost analysis conducted for multiple approaches**

Argonne, TIAX

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

Key Hydrogen Storage Milestones & Future Plans



[1] subject to appropriations and direction
[2] In accordance with EISA (2007)

Hydrogen Storage Collaborations

Applied R&D under the President's Hydrogen Fuel and Advanced Energy Initiatives is coordinated among national and international organizations

INTERNATIONAL ACTIVITIES

Examples

- IEA HIA Task 22

  ~ 15 countries

  ~ 50 projects

- IPHE

  5 projects

  (EU, Russia, Canada, US, New Zealand, Singapore, China)

DOE

(Energy Efficiency & Renewable Energy- EERE)

National Hydrogen Storage Project

H_2 Storage Applied R&D

- 3 Centers of Excellence
- Independent projects
- Total of ~80 projects

INDUSTRY

- FreedomCAR & Fuel Partnership

  Tech teams:
  - H_2 Storage
  - Fuel Cells, Delivery
  - Fuel Pathways
  - Vehicle Systems
- Codes & Standards Organizations

TECHNOLOGY VALIDATION (DOE EERE)

~92 vehicles & 15 stations

National Collaboration *(inter- and intra-agency efforts)*

DOE – Basic Energy Sciences
~30 Projects

NSF
New projects in basic science

NIST
- Neutron scattering
- Measurements

DOT
Material handling/transport

DOD – Defense Logistics Agency
6 projects & prototypes

For More Information

Hydrogen Storage Team

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James Alkire
Paul Bakke

Support:
Kristin Deason (Sentech)

Applied R&D Hydrogen Storage "Grand Challenge" Partners

Diverse Portfolio with University, Industry & National Labs

Centers of Excellence

Metal Hydride Center

National Laboratory:
Sandia-Livermore

Industrial partners:
General Electric
HRL Laboratories
Intematix Corp.

Universities:
CalTech
Stanford
Pitt / GATech
Hawai'i / UNB
Illinois
Ohio State
Nevada-Reno
Utah

Federal Lab Partners:
Brookhaven
JPL, NIST
Oak Ridge
Savannah River

Hydrogen Sorption Center

National Laboratory:
NREL

Industrial partners:
Air Products & Chemicals

Universities:
CalTech
Duke
Miami Univ.-OH
Michigan
North Carolina
Penn State
Rice
Univ. of Chicago

Federal Lab Partners:
Argonne
Lawrence Livermore
NIST
Oak Ridge

Chemical Hydrogen Storage Center

National Laboratories:
Los Alamos
Pacific Northwest

Industrial partners:
Intematix Corp.
Millennium Cell
Rohm & Haas
US Borax

Universities:
Northern Arizona
Penn State
Alabama
California-Davis
Univ. of Missouri
Pennsylvania
Washington

Federal Lab Partners:
INL

Coordination with: Basic Science (Office of Science, BES)

MIT, U.WA, U. Penn., CO School of Mines, Georgia Tech, Louisiana Tech, U.Georgia, Missouri-Rolla, Tulane, Southern Illinois, Rutgers, Stonybrook, UC Davis, UC Santa Barbara, Sth Florida, Missouri-Columbia; Labs: Ames, BNL, LBNL, ORNL, PNNL, SRNL

Independent Projects

Advanced Metal Hydrides
UOP
Univ. of Connecticut
Delaware State

Sorbent/Carbon-based Materials
UCLA
State University of New York
Gas Technology Institute
UPenn & Drexel Univ.

Chemical Hydrogen Storage
Air Products & Chemicals
RTI
Millennium Cell
Safe Hydrogen LLC

Other New Materials & Concepts
Alfred University
Michigan Technological University
UC-Berkeley/LBL
UC-Santa Barbara
Univ. of Arkansas
Purdue
UNLV

Tanks, Safety, Analysis & Testing
Lawrence Livermore Nat'l Lab
Quantum
Argonne Nat'l Lab, TIAX LLC
SwRI, UTRC, Sandia Nat'l Lab
Savannah River Nat'l Lab