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

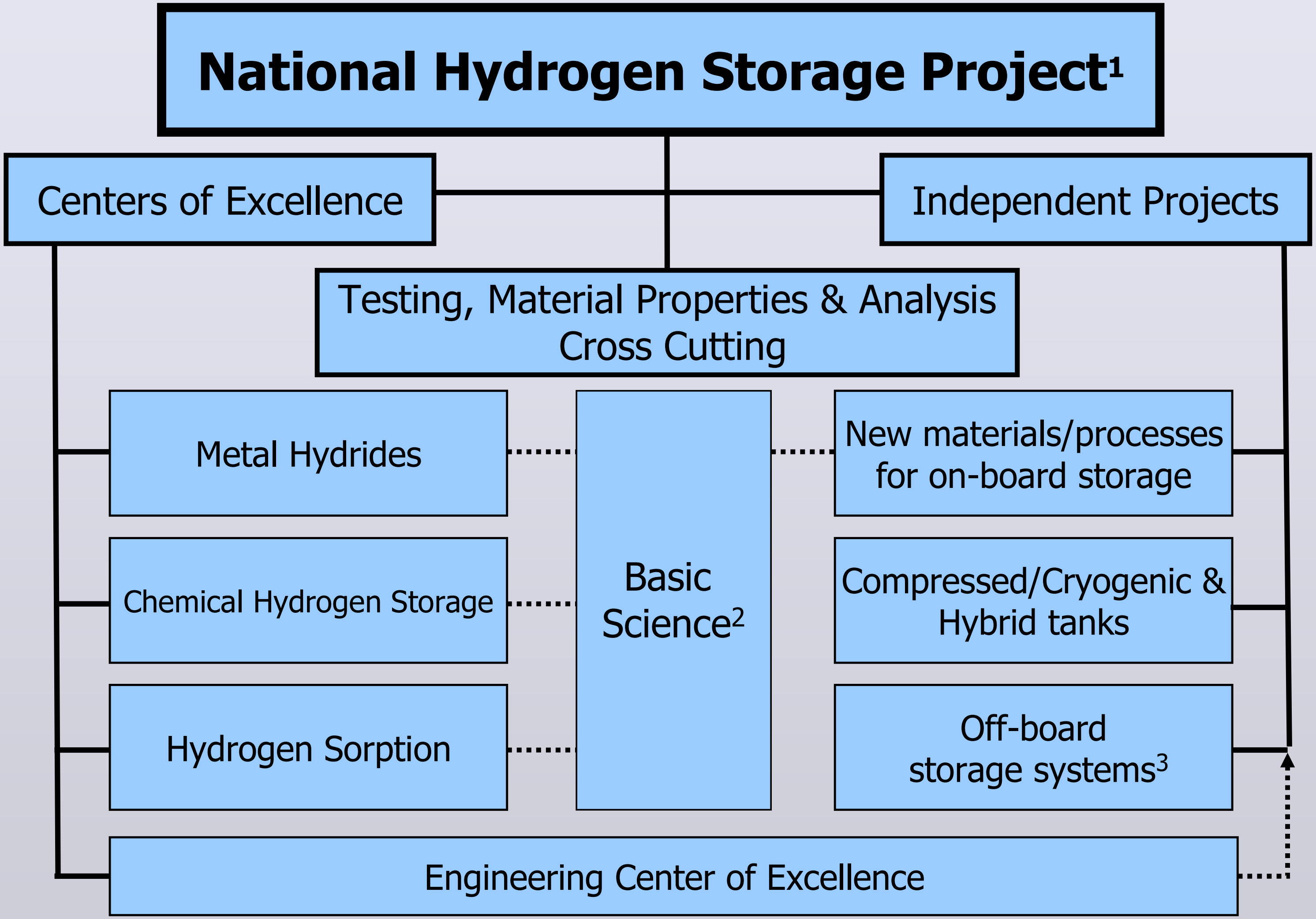
Challenges

- **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



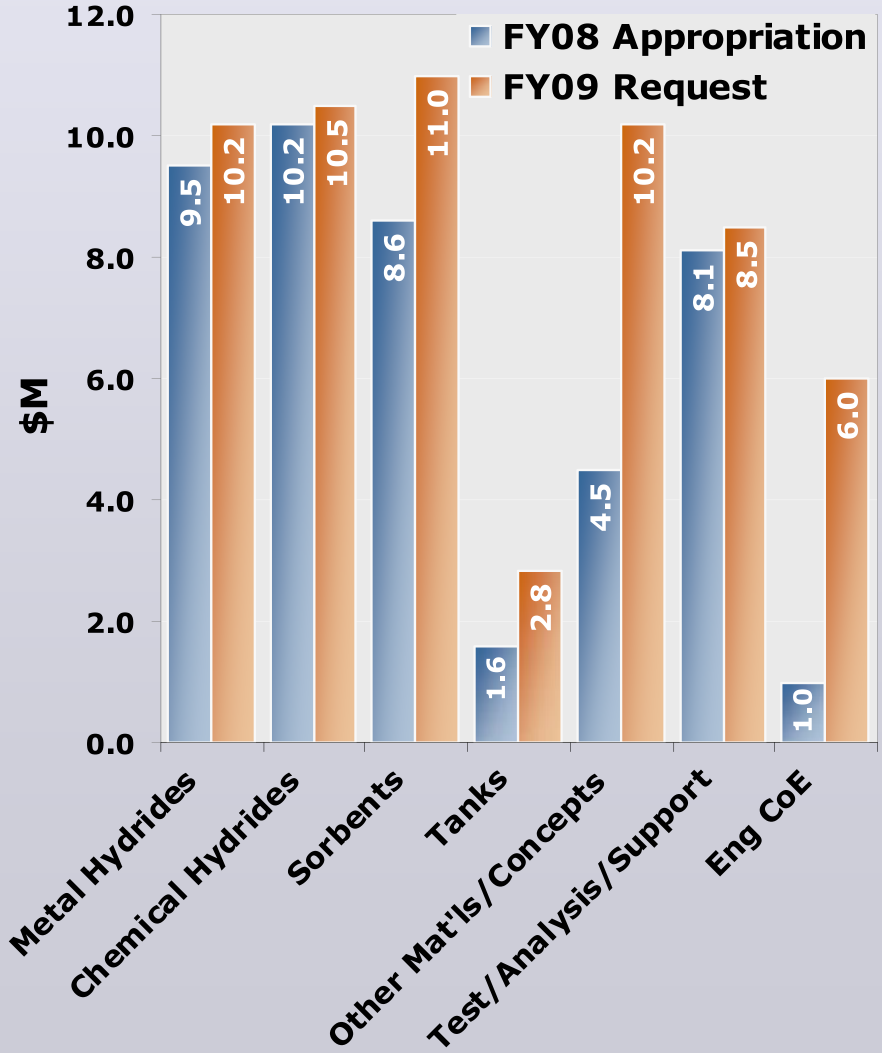
1. Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies
2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
3. Coordinated with Delivery Program element

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

Hydrogen Storage Budget

FY 2009 REQUEST = $59.2M

FY 2008 APPROPRIATION = $43.5M

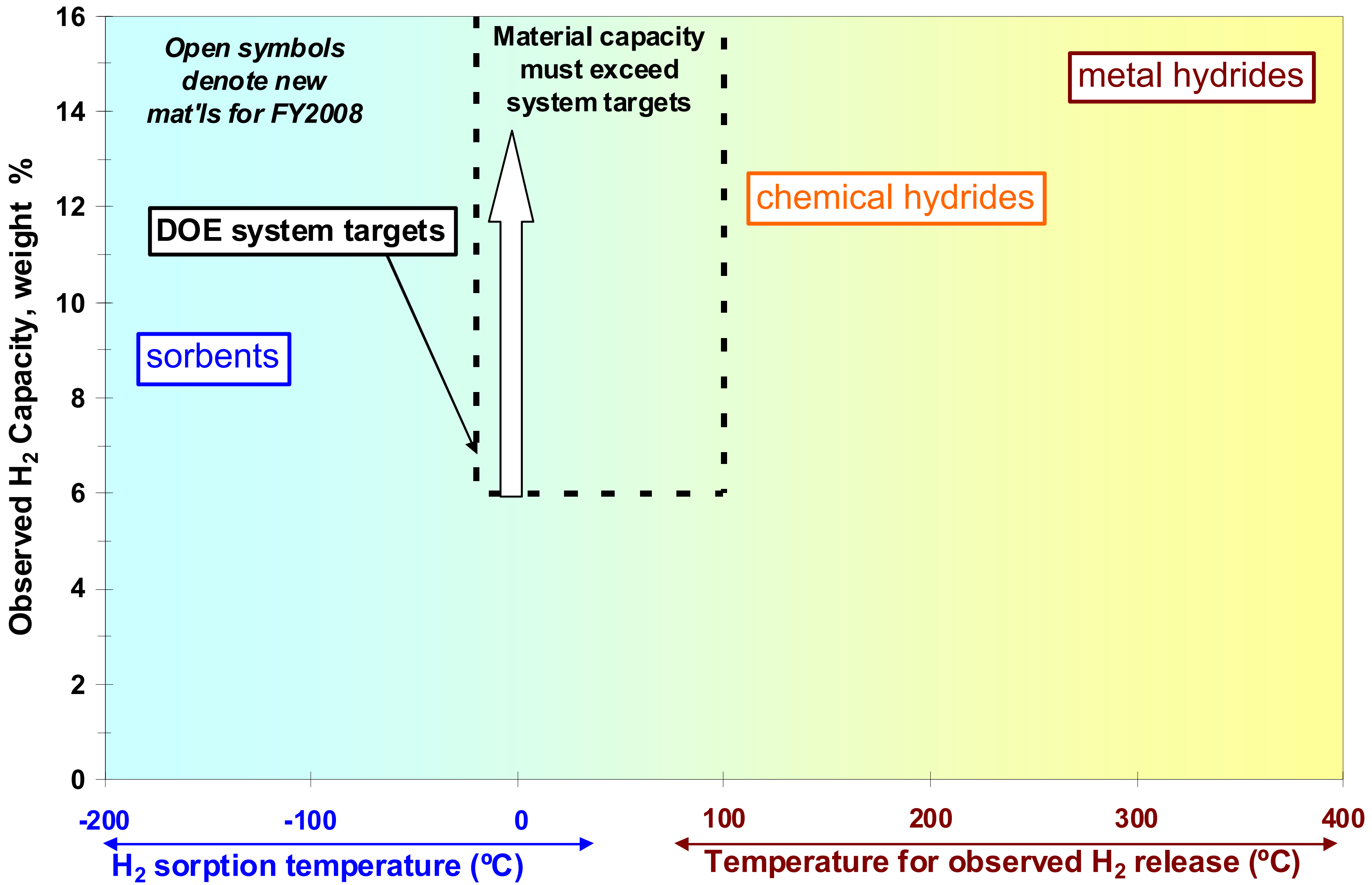


FY2009 Emphasis

- 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

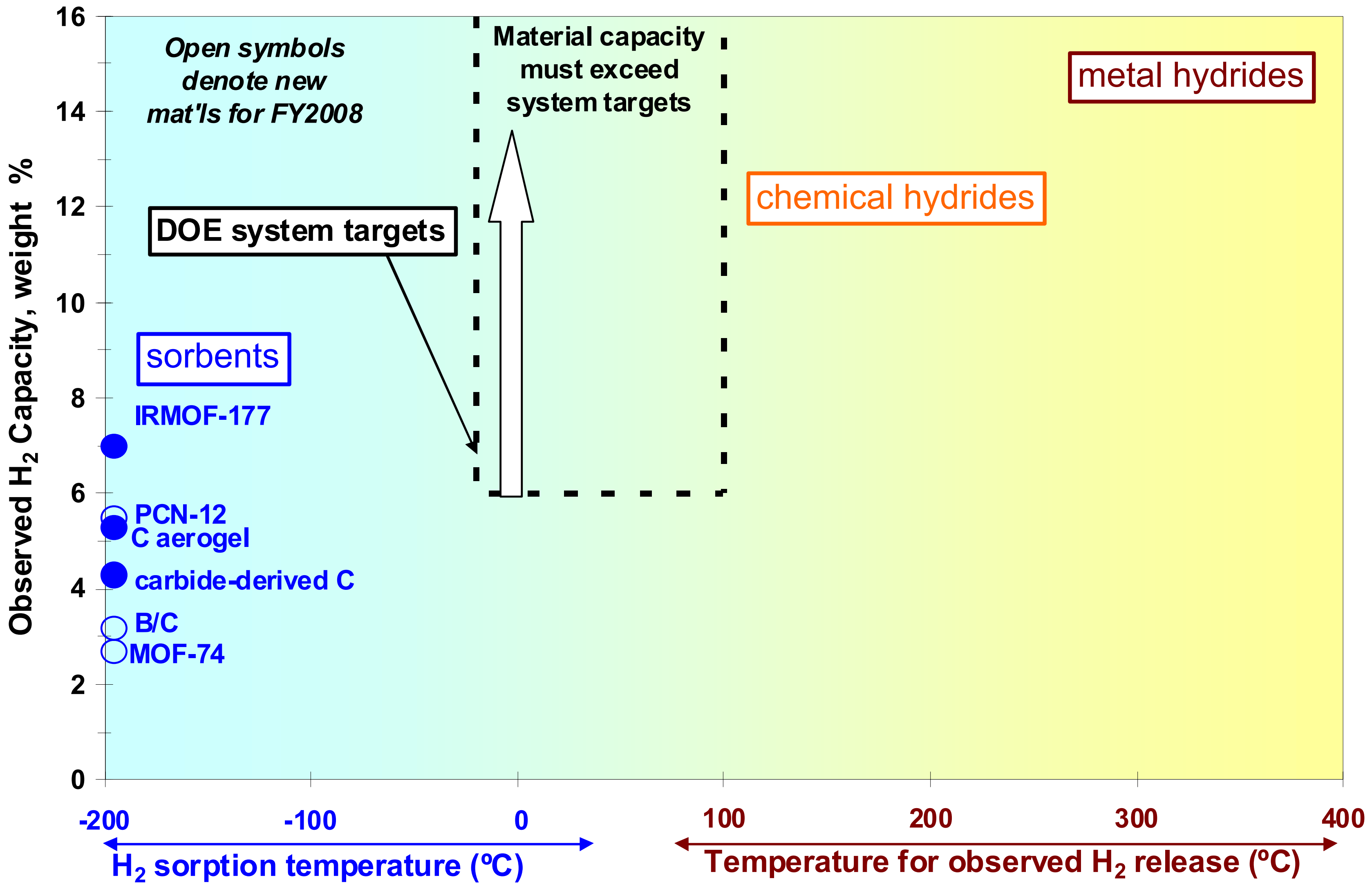
Material Capacity vs. Temperature



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

Progress

Material Capacity vs. Temperature



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Progress

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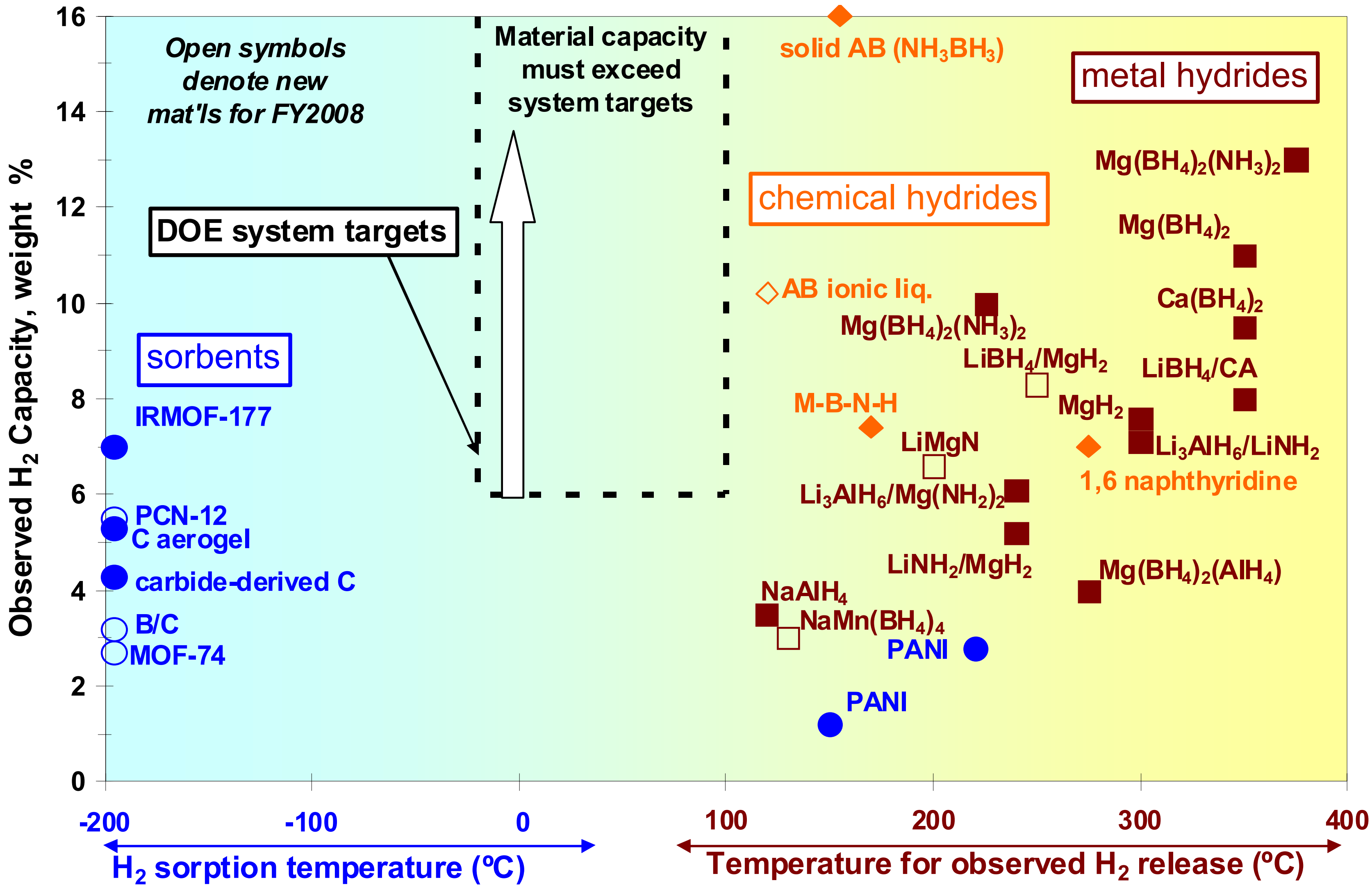

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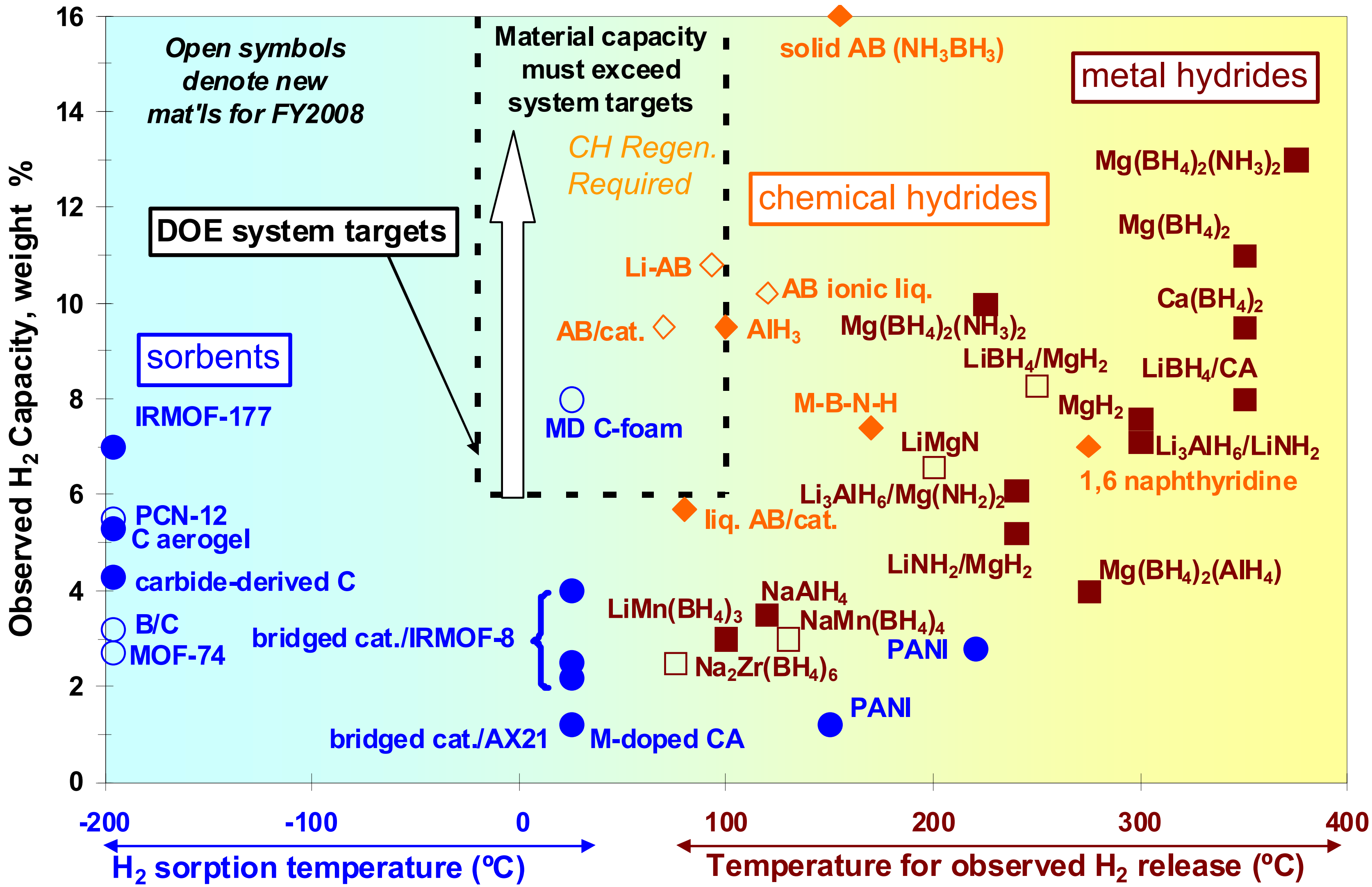
Progress

Material Capacity vs. Temperature



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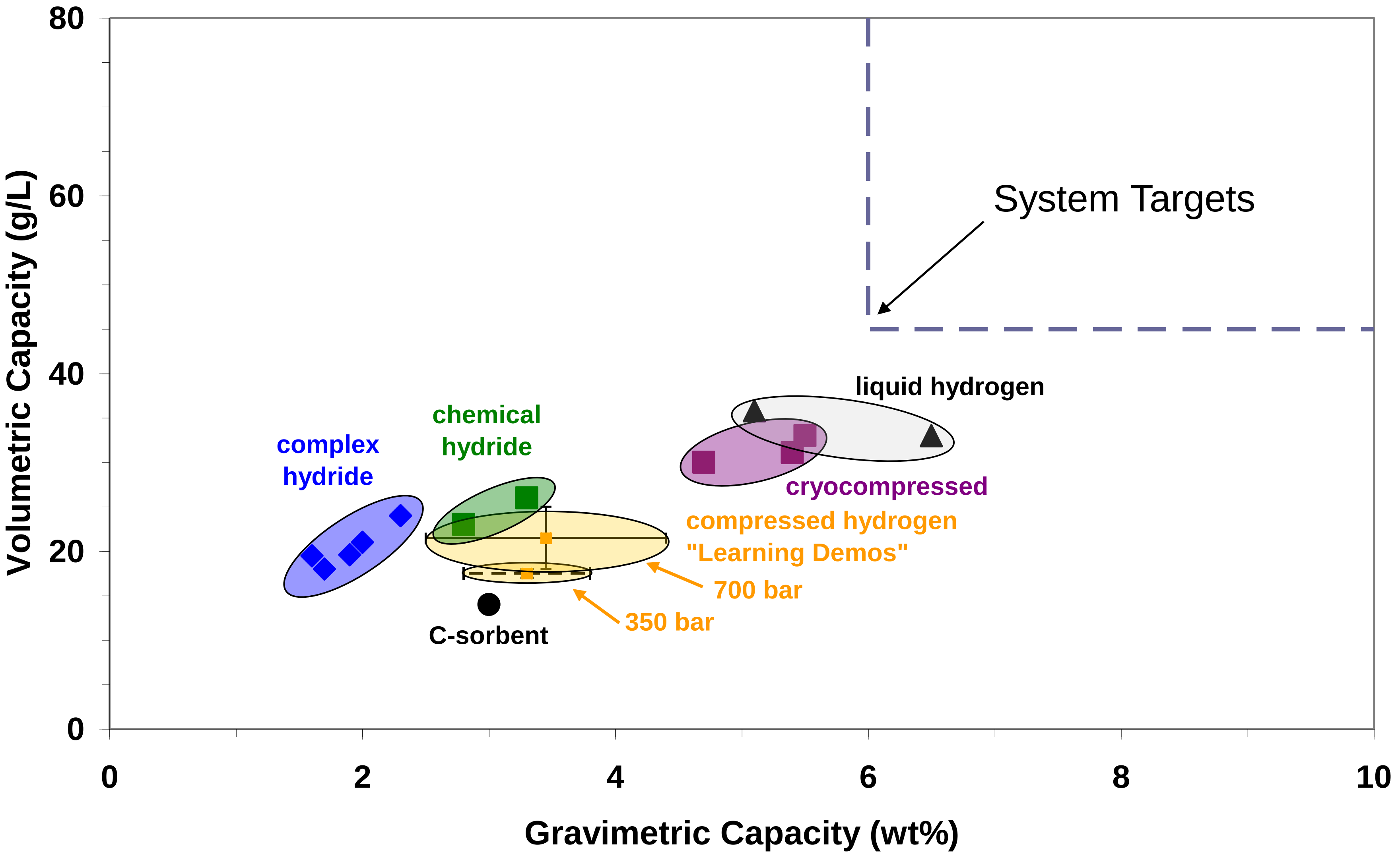
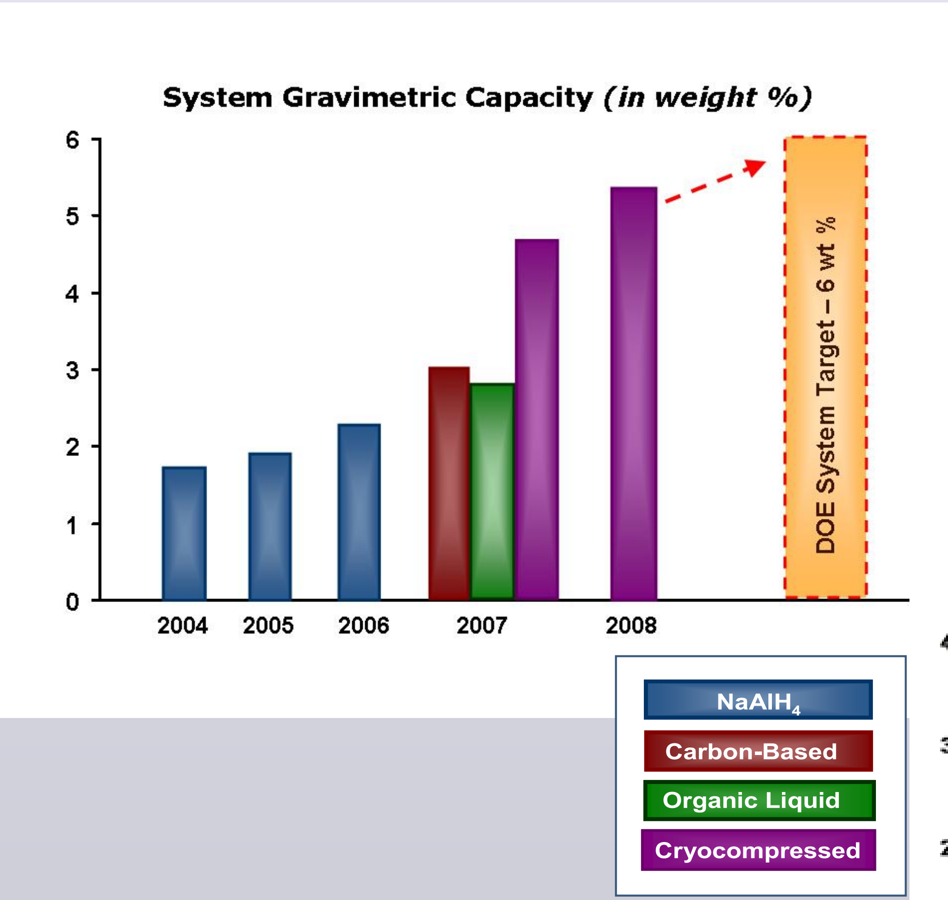
Current Status

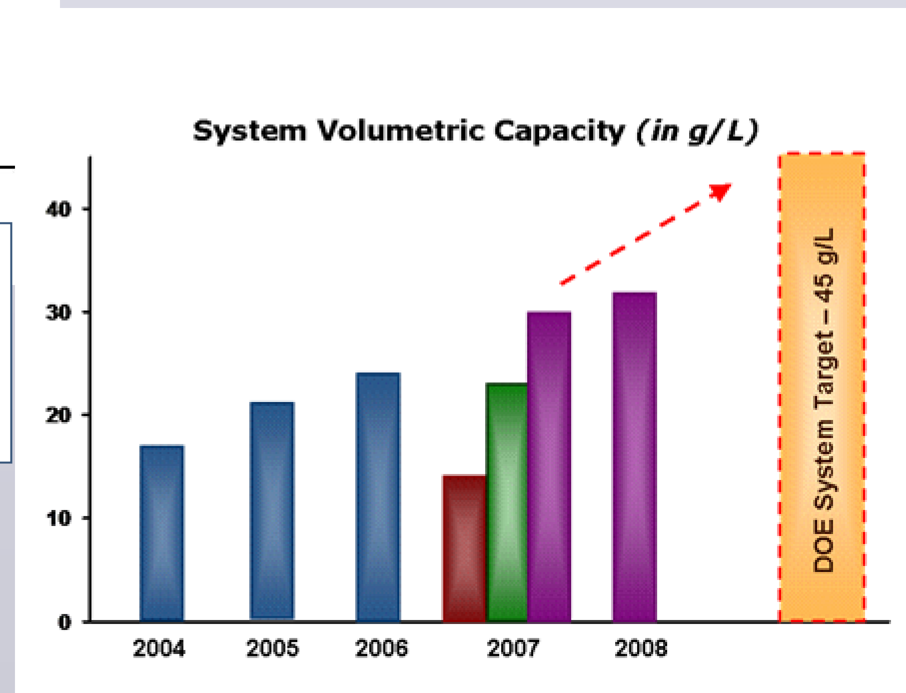
No technology meets targets



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 Hydrides-

More than 50 Approaches Assessed

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

Chemical Hydrogen Storage-

More than 60 Approaches Assessed

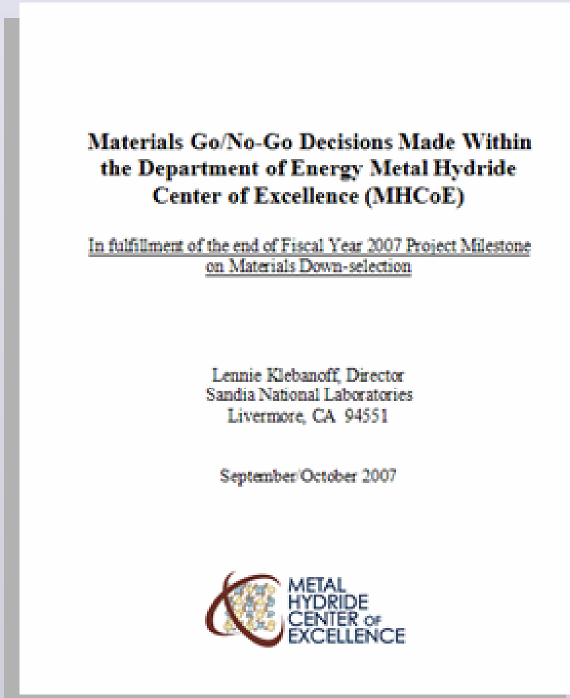
- **~ 50% discontinued**
- **~ 30% show some promise but have issues**
- **~ 20% show some potential to meet targets**

Hydrogen Sorption-

No go on pure SWNT resulted in expanded work scope

Led to H_2 storage at room T

Example of down-select report on metal hydrides


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

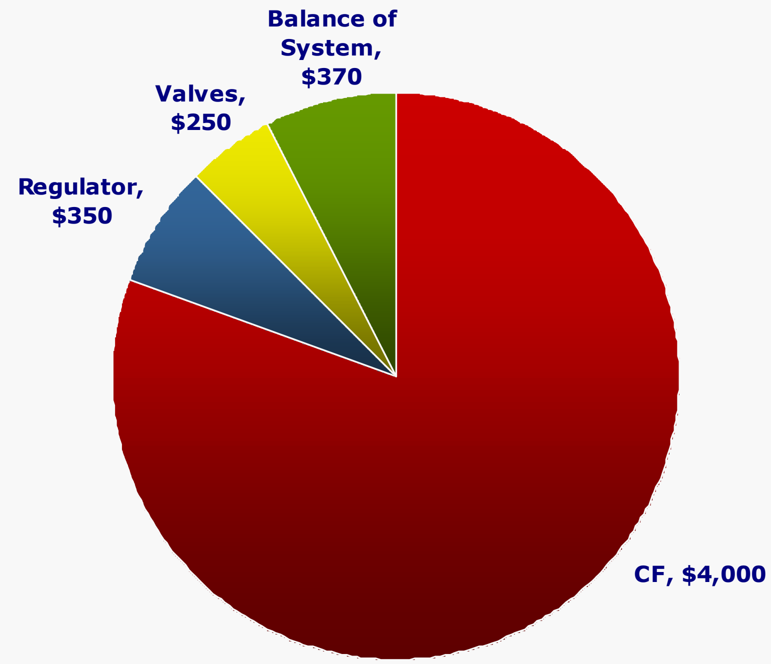
http://www1.eere.energy.gov/hydrogenandfuelcells/hydrogen_publications.html#h2_storage

Progress and Status- Tanks

- **Demonstrated 103 to 190 mile range across 92 vehicles (Gen 1) through Technology Validation activity**

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)

Tank cost is a significant challenge
TIAX estimate: $27/kWh (700 bar)
$17/kWh (300 bar)
(at 500,000 units)

Progress

Materials Properties, Testing & Analyses

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

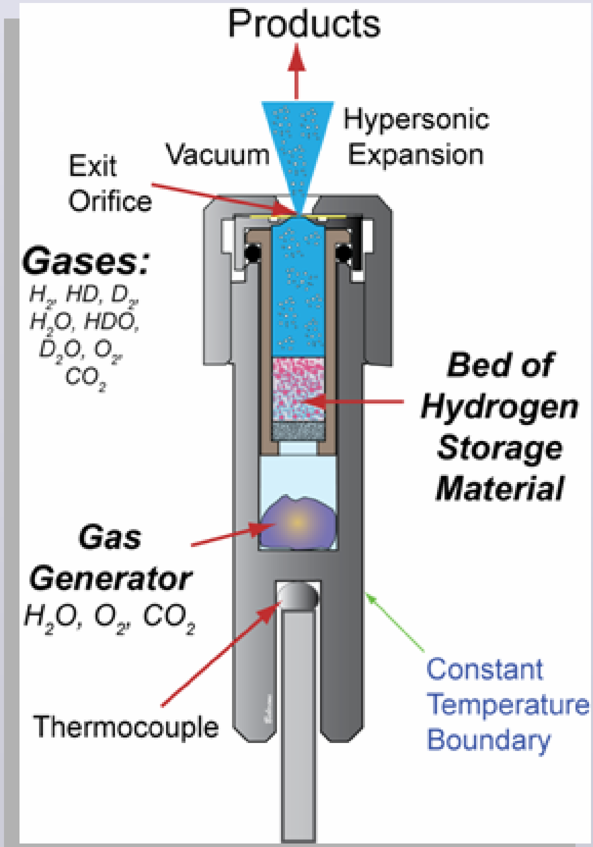
K. Gross, H2 Technology Solutions/HyEnergy, LLC/NREL

Systems Analysis

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

Argonne, TIAX

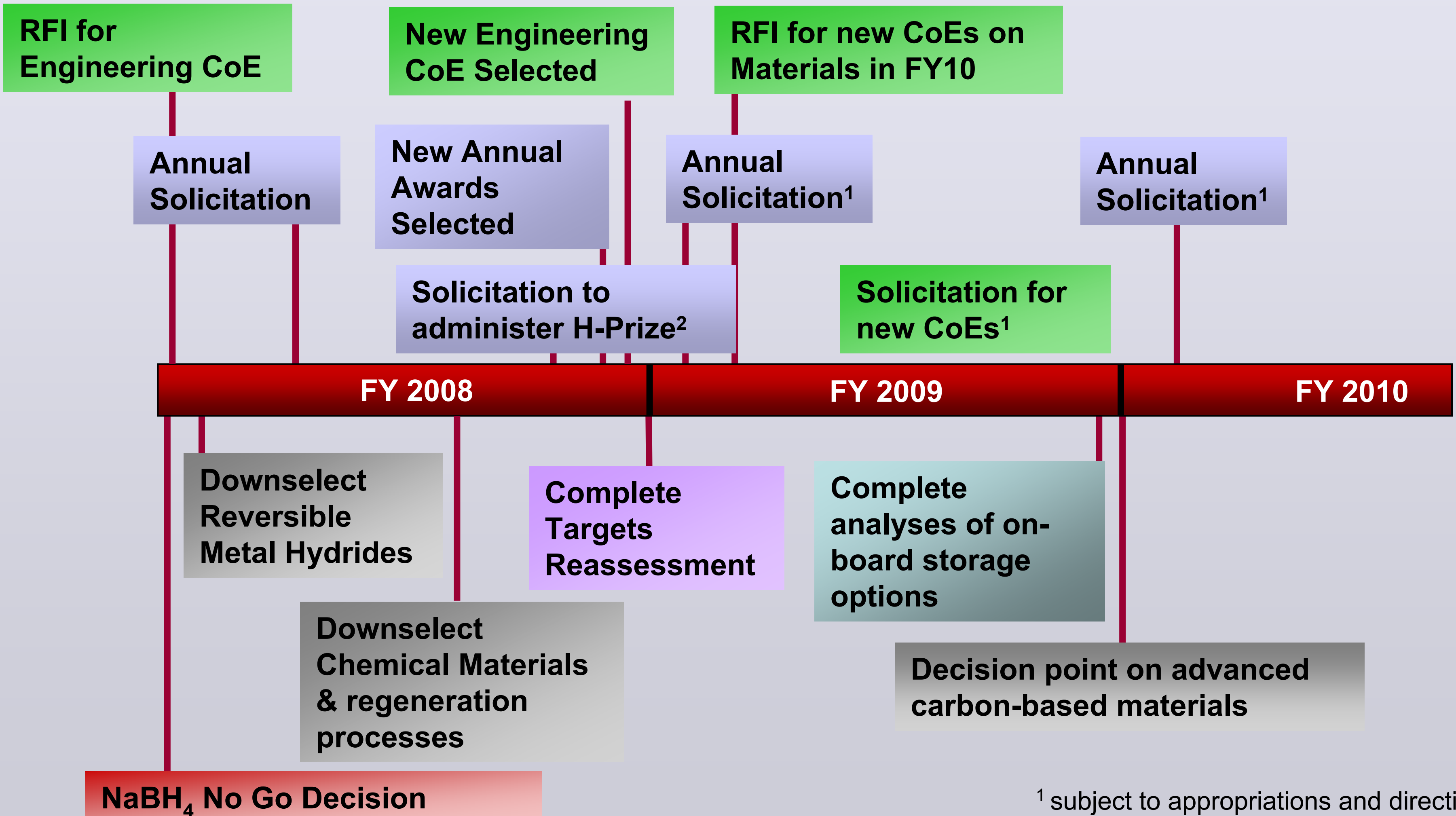
- **Reactivity of hydrogen storage materials assessed under various exposures –** *An IPHE Collaboration*



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

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

Session Instructions

- Presentations will begin precisely at the scheduled times.
- Talks will be ~20 minutes, 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.

Reviewer Reminders

- Reviews should be submitted at the end of the day.
- Reviews must be submitted before departure from the Annual Merit Review & Peer Evaluation meeting.
- On Thursday, there will be a brief reviewer feedback session following the last presentation.
- Friday, June 13- 10:45 am to 1:15:DOD-Defense Logistics Agency Storage Projects will be presented

For More Information

Hydrogen Storage Team

Sunita Satyapal, Team Leader
Overall Storage/ FreedomCAR Tech Team/International
202-586-2336
sunita.satyapal@ee.doe.gov

Monterey Gardiner
Tanks, Sorbents, Delivery
202-586-1758
monterey.gardiner@ee.doe.gov

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

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

Gary Sandrock
On Assignment to DOE
Oak Ridge Nat'l Lab
202-586-8707
gary.sandrock@ee.doe.gov

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

Field Office Project Officers:
Jesse Adams
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

Reviewer Reminders

Mark your calendars-

Next Annual Review is week of

May 18, 2009

Thank you

Additional Details

Accomplishments

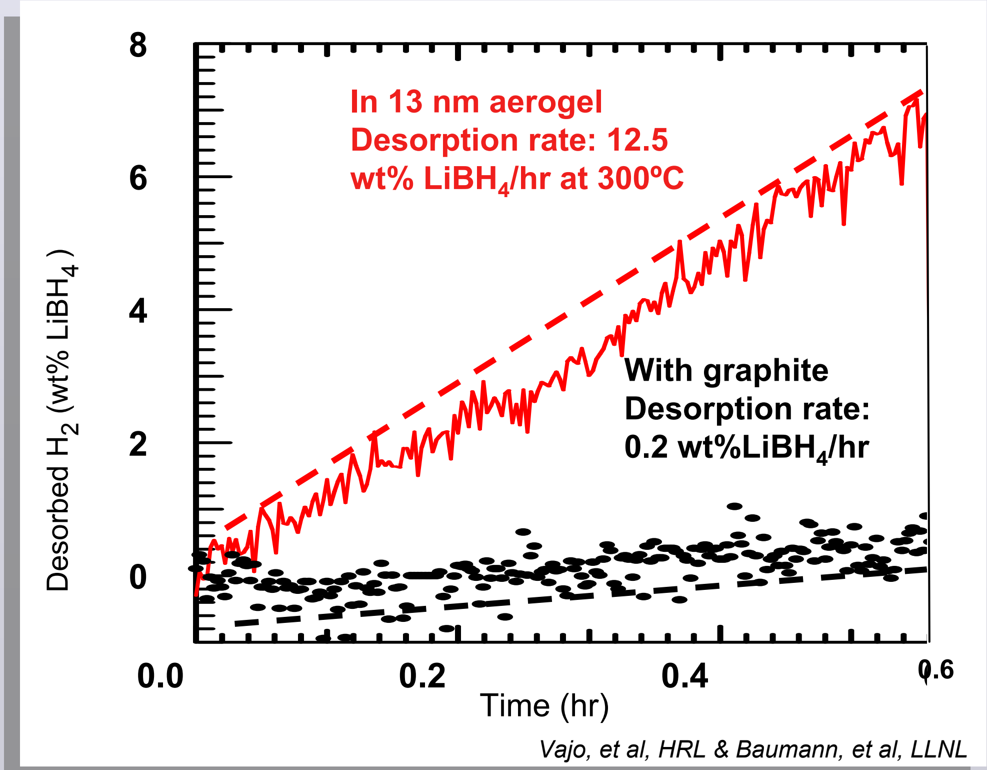
Metal Hydride Examples

- 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 *<u>60-fold</u>* using $LiBH_4$ in aerogel

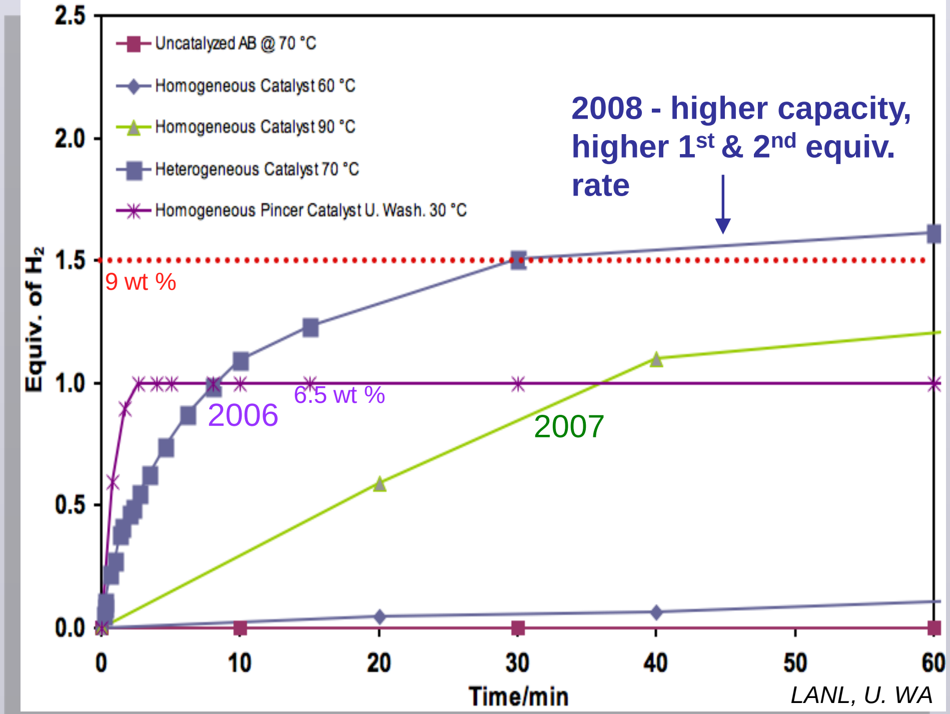
$$LiBH_4 \rightarrow LiH + B + 1.5H_2$$



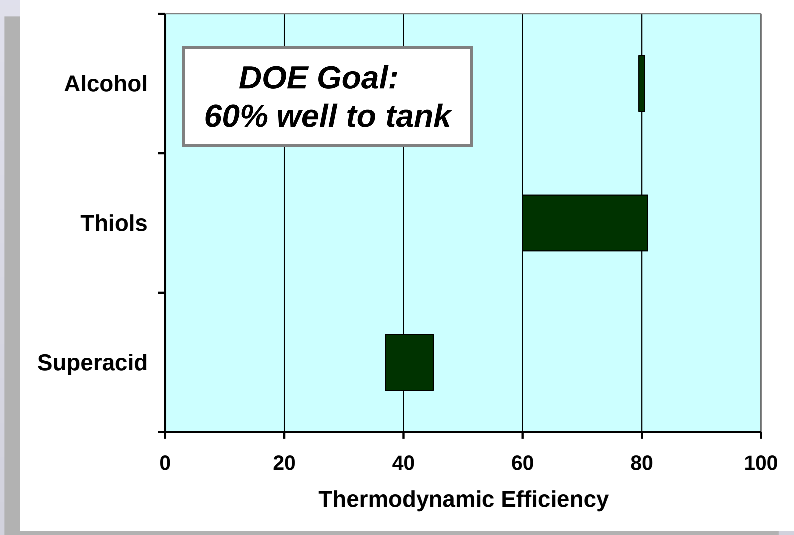
Accomplishments
Ammonia borane

$NH_3BH_3 \rightarrow BNH_x + 3H_2$ 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



- 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

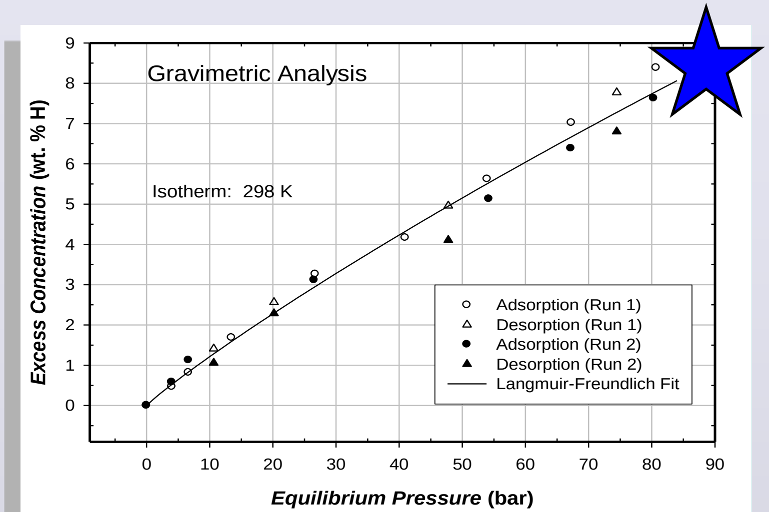
Progress

Hydrogen Sorption Examples

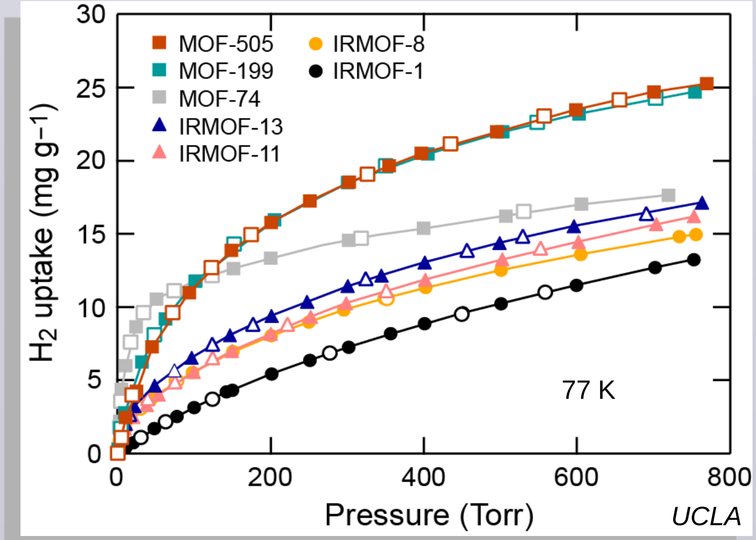
- **DOE work on "spillover" catalyzed worldwide R&D**
- **Led to 8 wt.% at room temp**

- **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