
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°C)
- Hydrogen supply rate/refueling rate
 - 0.02 g H₂ per sec. per kW of power
 - Refueling time <3 min. for 5 kg H₂
- System cost
- Fuel cost
- Safety, C&S, reliability, cycle life, efficiency, etc.



Challenges

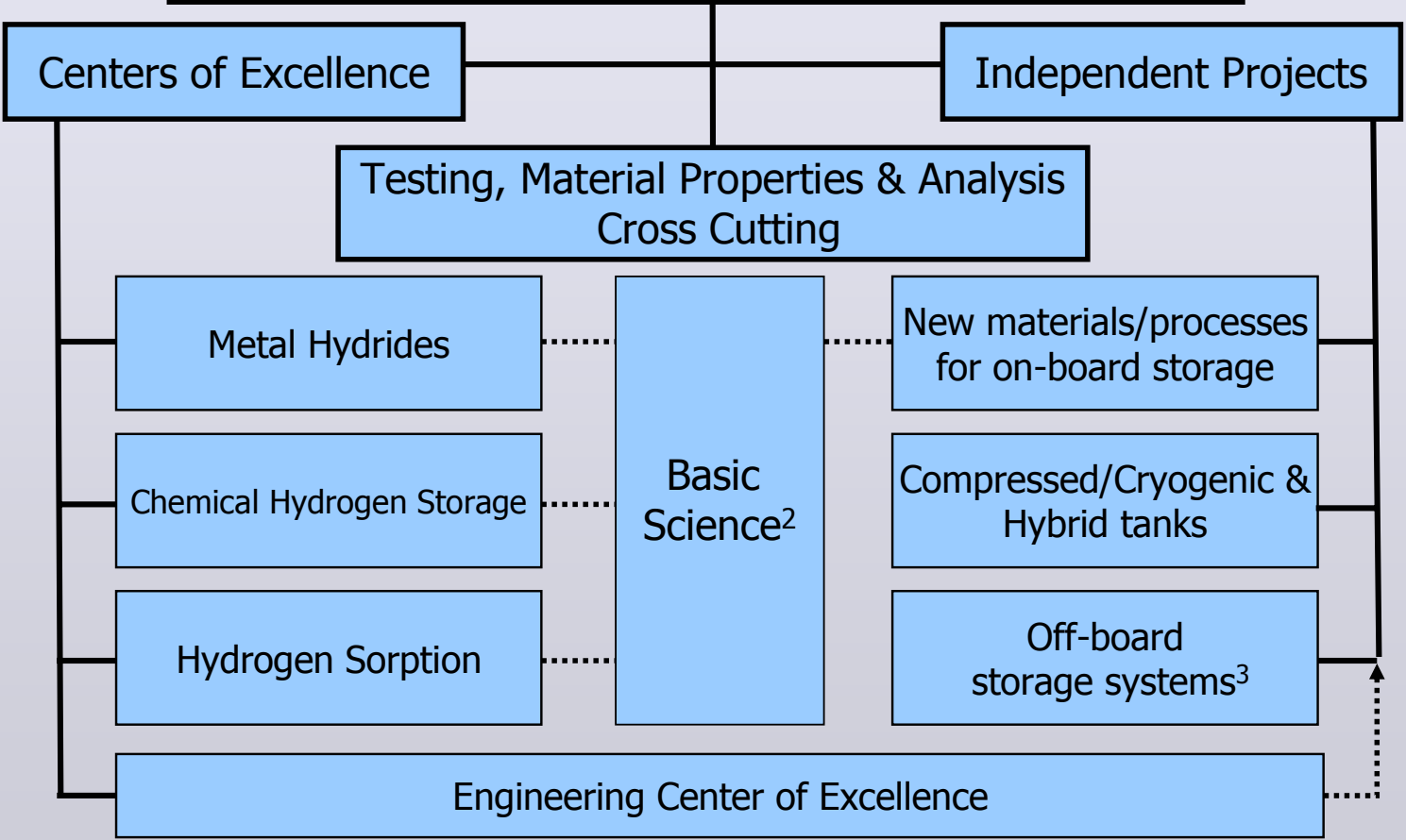
- **Vehicles are being designed by OEMs that can achieve > 300 miles**
 - 350 or 700 bar
 - 1 to 4 tanks
 - Specified range from ~200 to > 350 miles
- **But performance, space on-board and cost are still challenges for mass market penetration...**
- **Is there a low pressure alternative?**





Strategy – Diverse, Balanced Portfolio

National Hydrogen Storage Project¹



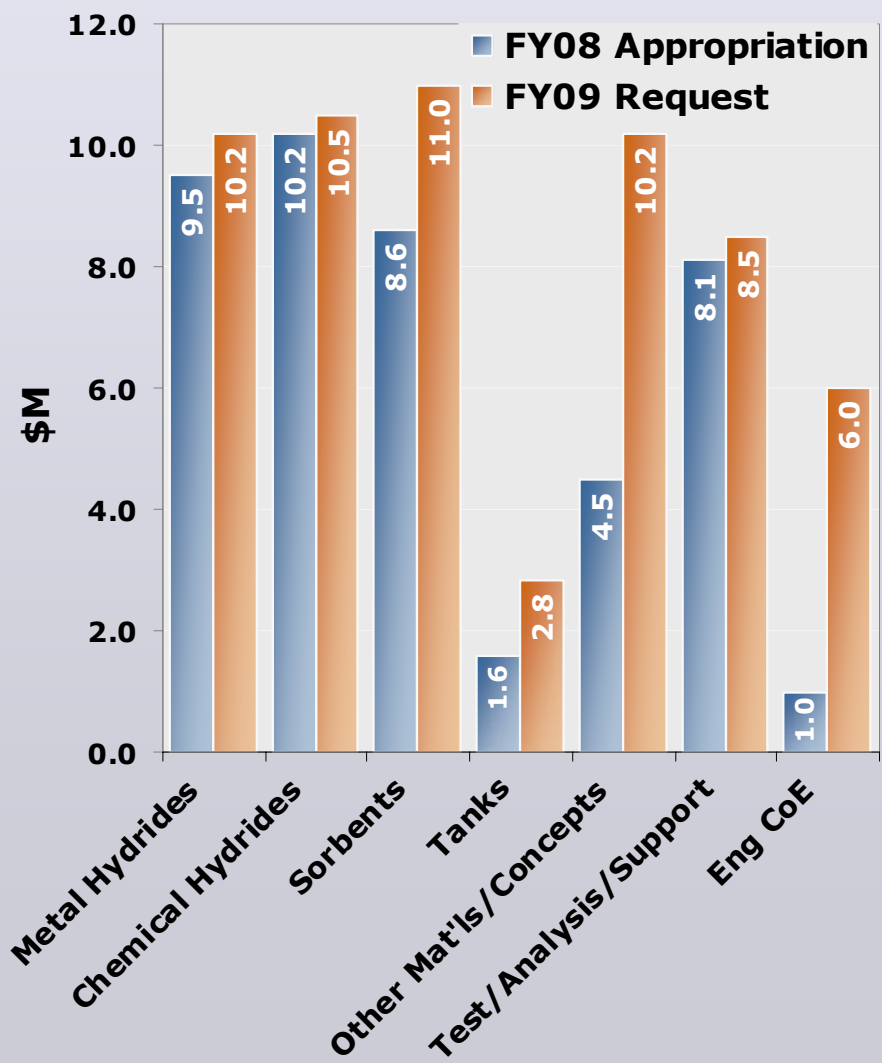
- 1. Coordinated by DOE Energy Efficiency and Renewable Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies
- 2. Basic science for hydrogen storage conducted through DOE Office of Science, Basic Energy Sciences
- 3. Coordinated with Delivery Program element

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



Hydrogen Storage Budget

FY 2009 REQUEST = \$59.2M
FY 2008 APPROPRIATION = \$43.5M

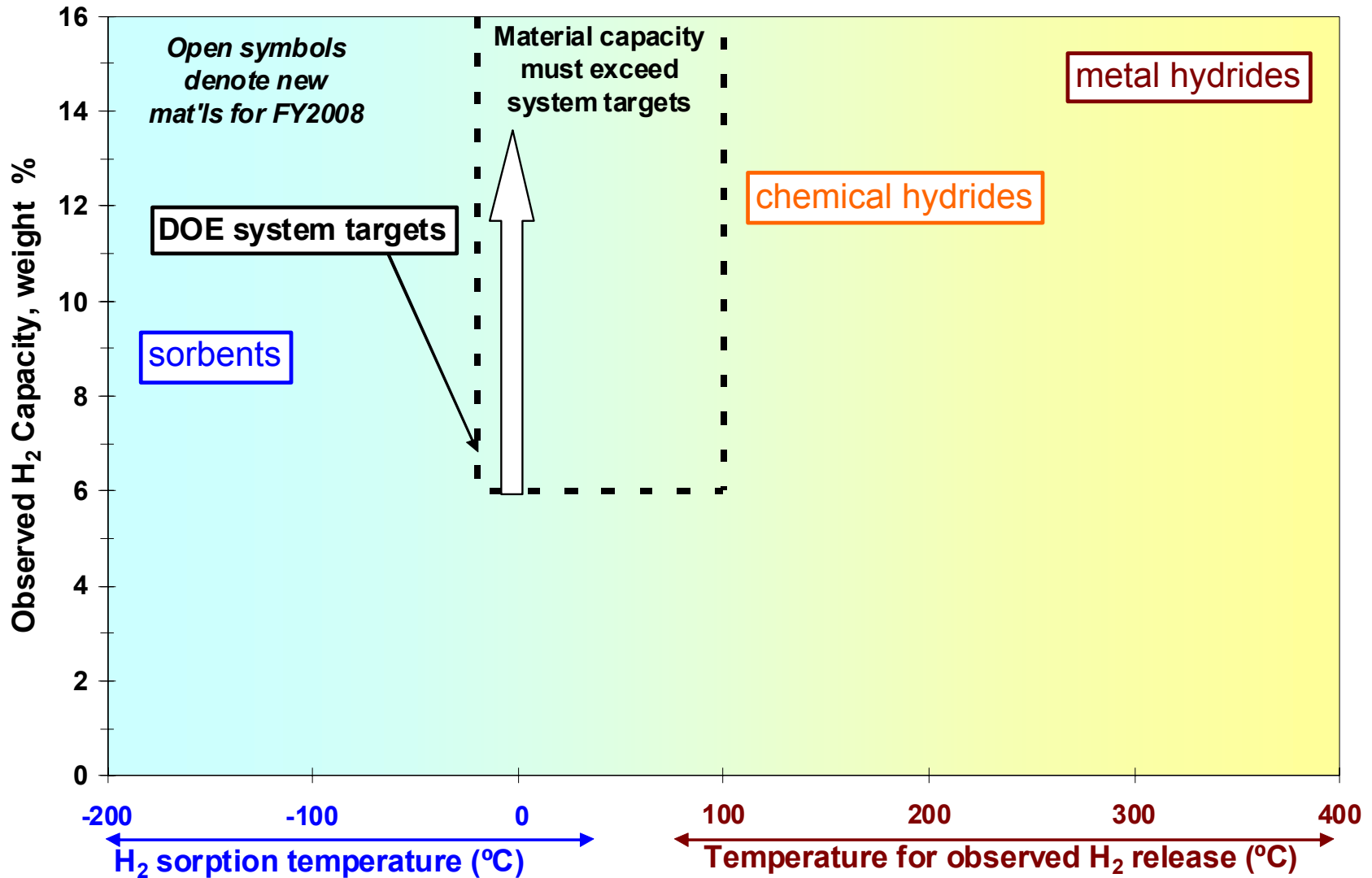


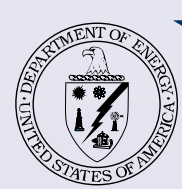
- ### FY2009 Emphasis
- Increase engineering in addition to materials R&D through Centers of Excellence and independent projects to enable system targets.
 - Focus on kinetics, temperature, pressure, cycle life, spent fuel regeneration, etc. *in addition* to capacity
 - Strengthen tank R&D to address NAS recommendations. Focus on cost reduction and advanced concepts. Also applicable to materials-based approaches.
 - Continue close coordination with Basic Science



Progress

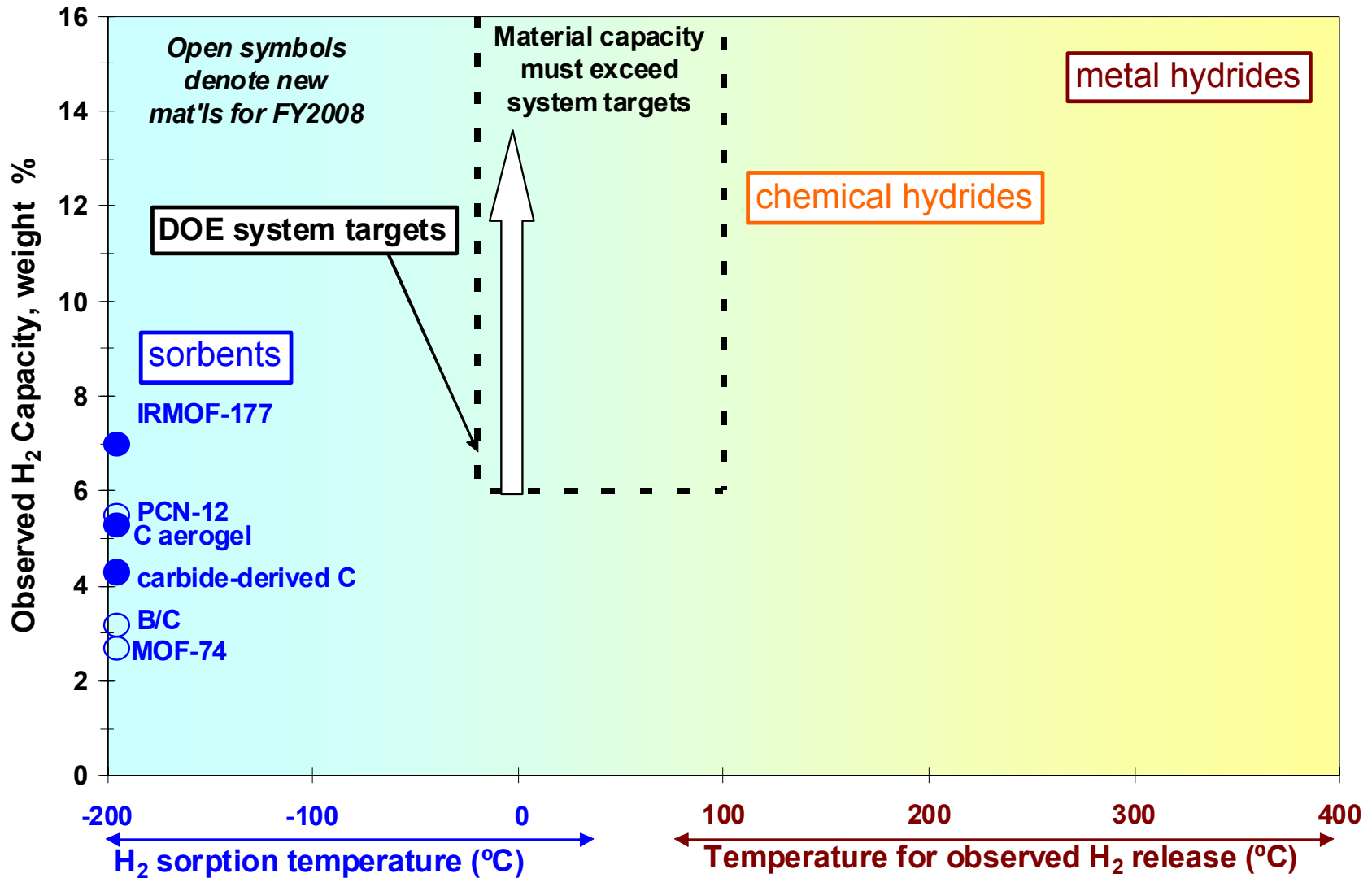
Material Capacity vs. Temperature





Progress

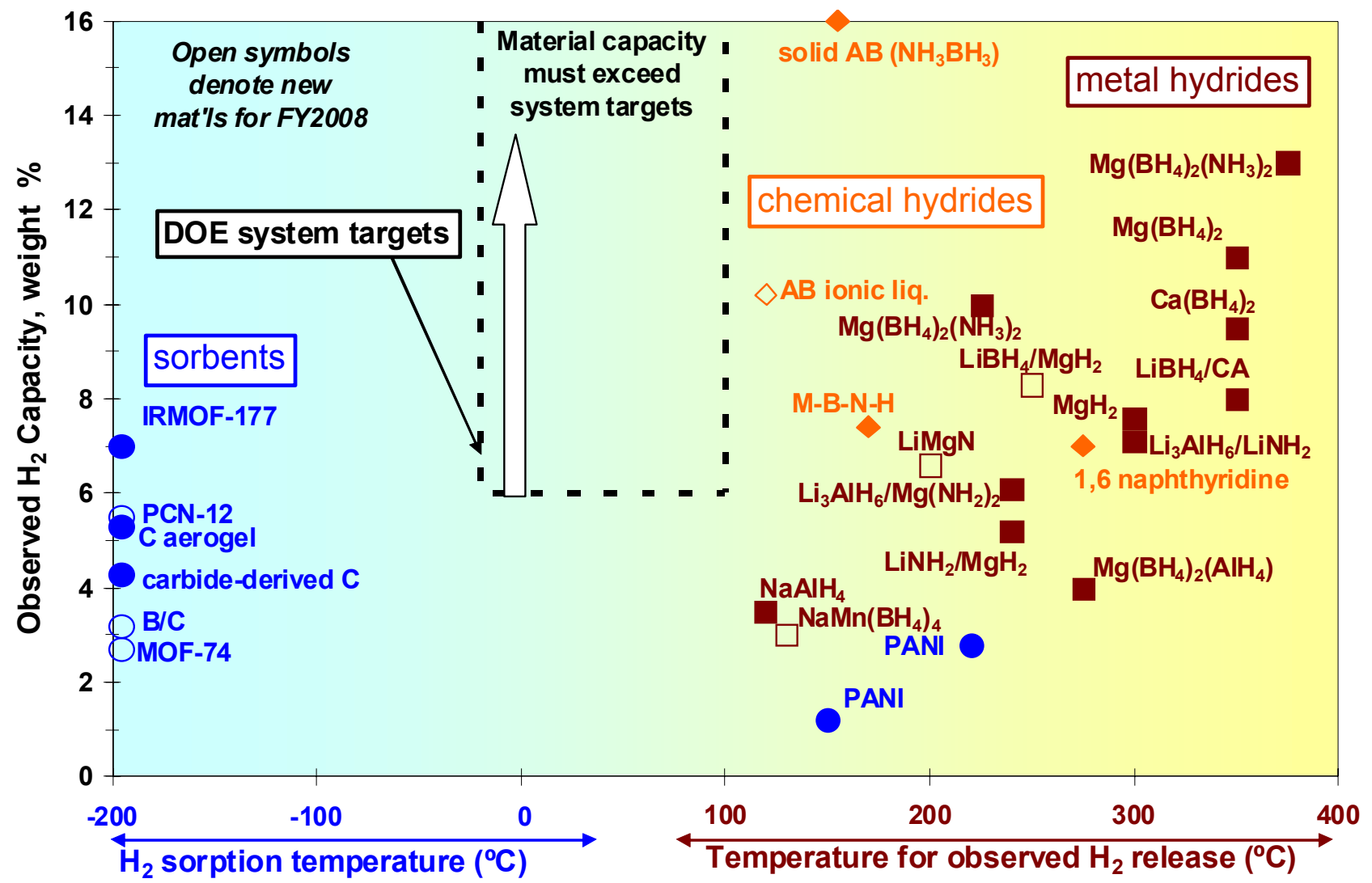
Material Capacity vs. Temperature





Progress

Material Capacity vs. Temperature

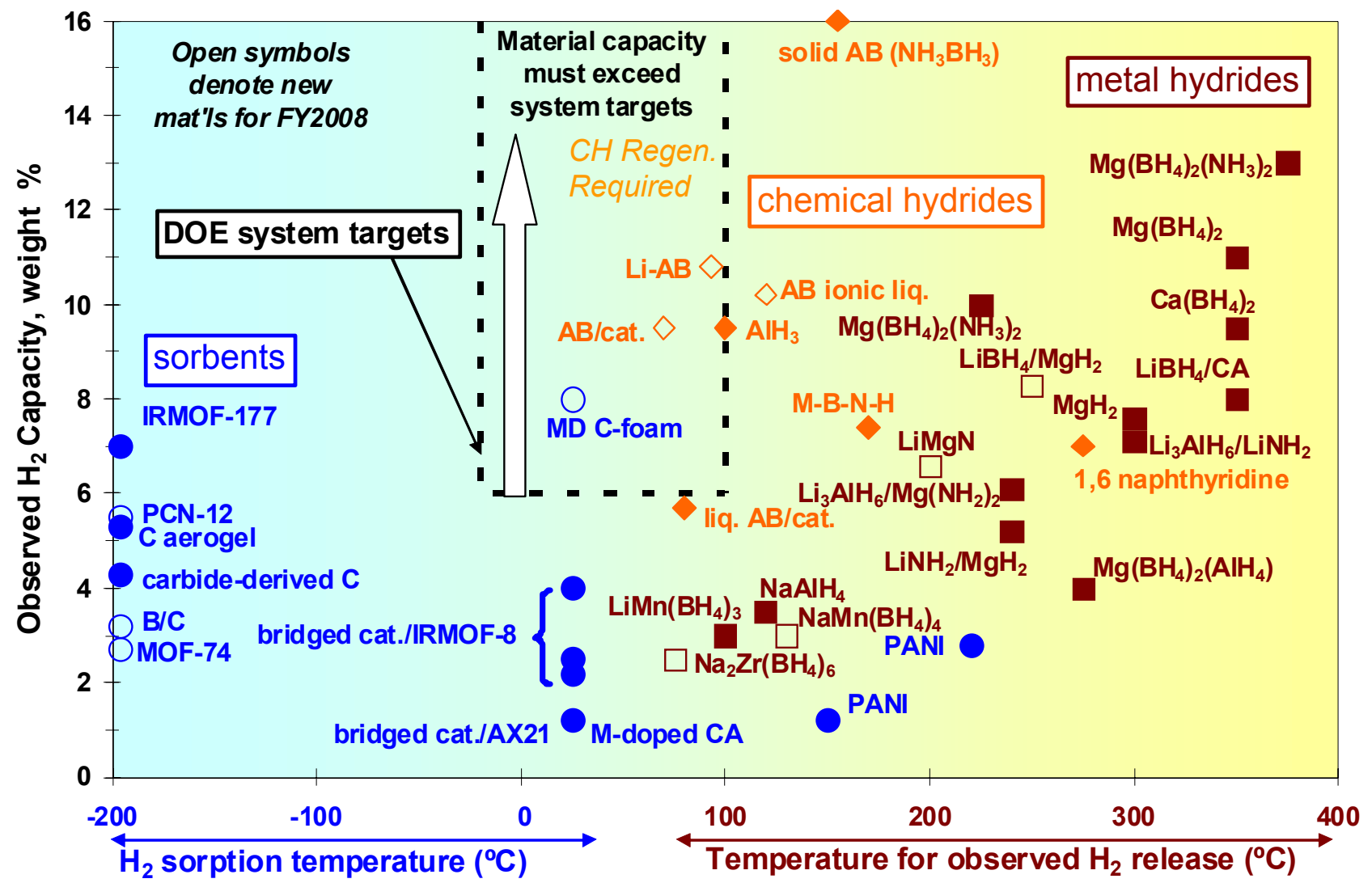


DOE: G. Thomas (2007), G. Sandrock (2008)



Progress

Material Capacity vs. Temperature

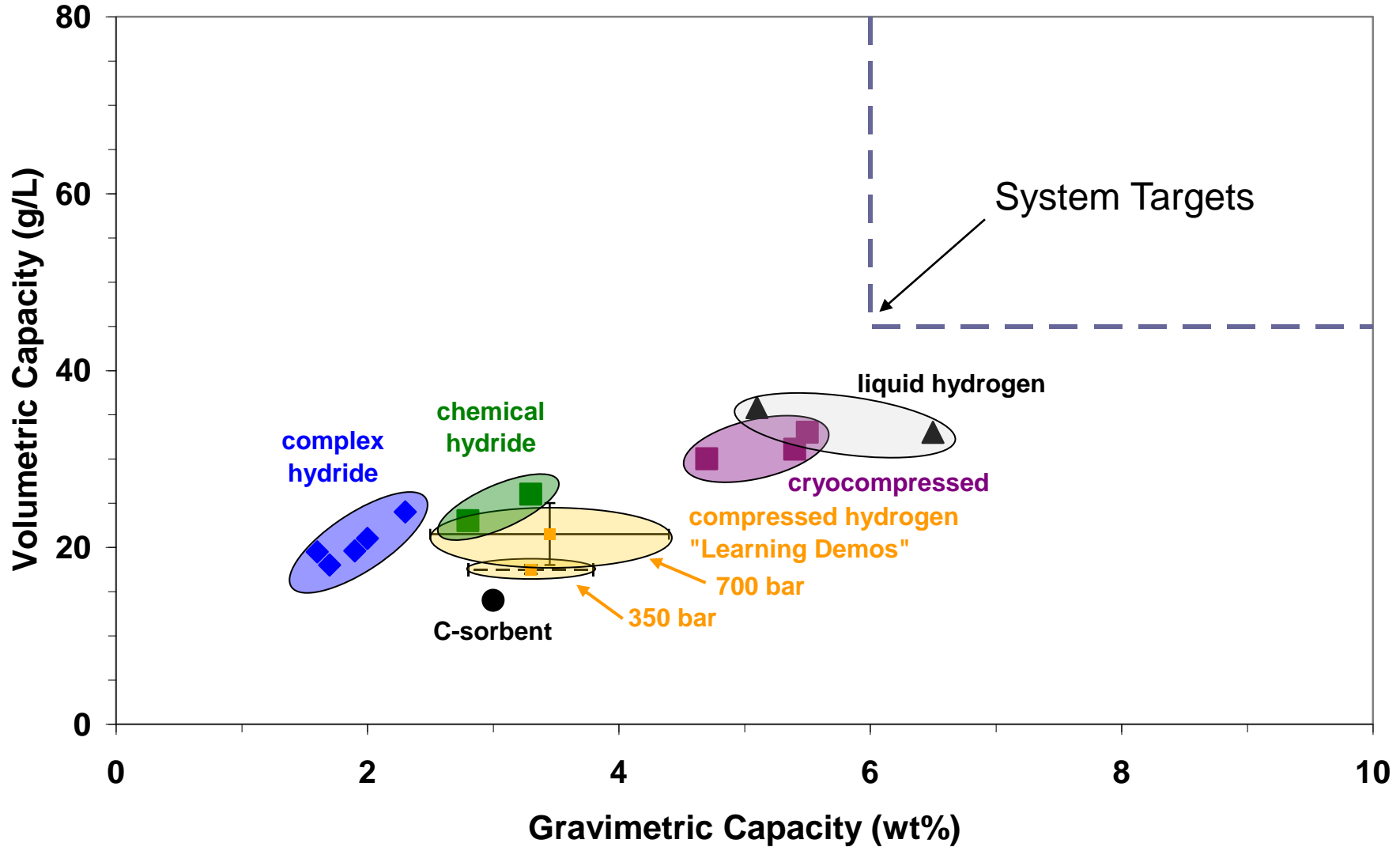


DOE: G. Thomas (2007), G. Sandrock (2008)



Current Status

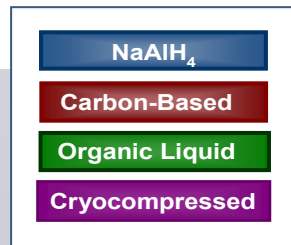
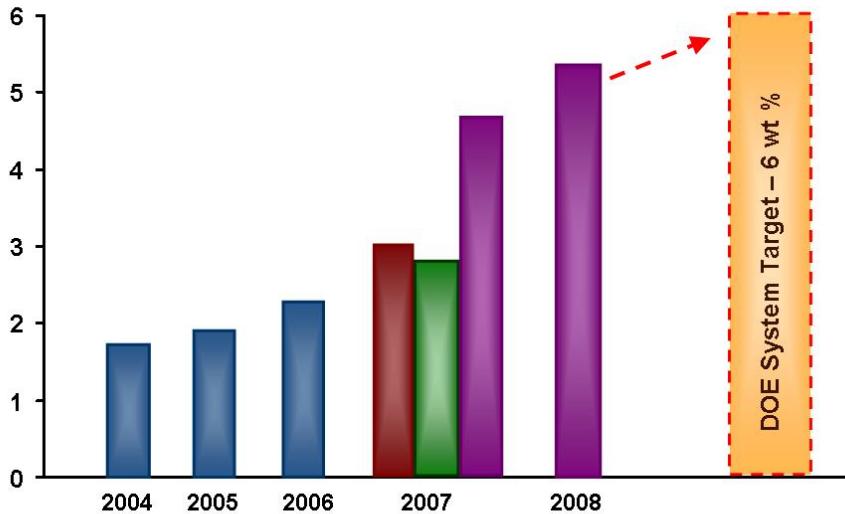
No technology meets targets





Hydrogen Storage System Progress

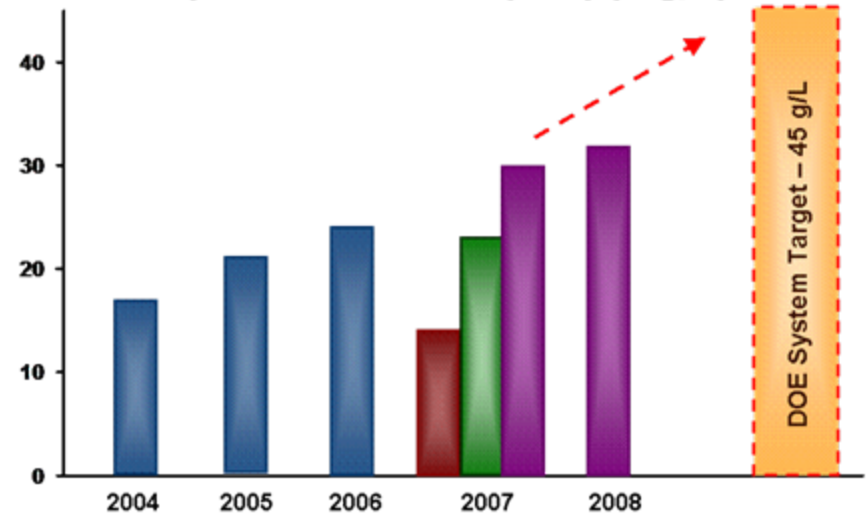
System Gravimetric Capacity (in weight %)



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

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

System Volumetric Capacity (in g/L)





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 H₂ 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





Progress and Status- Tanks

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

System Gravimetric Capacity

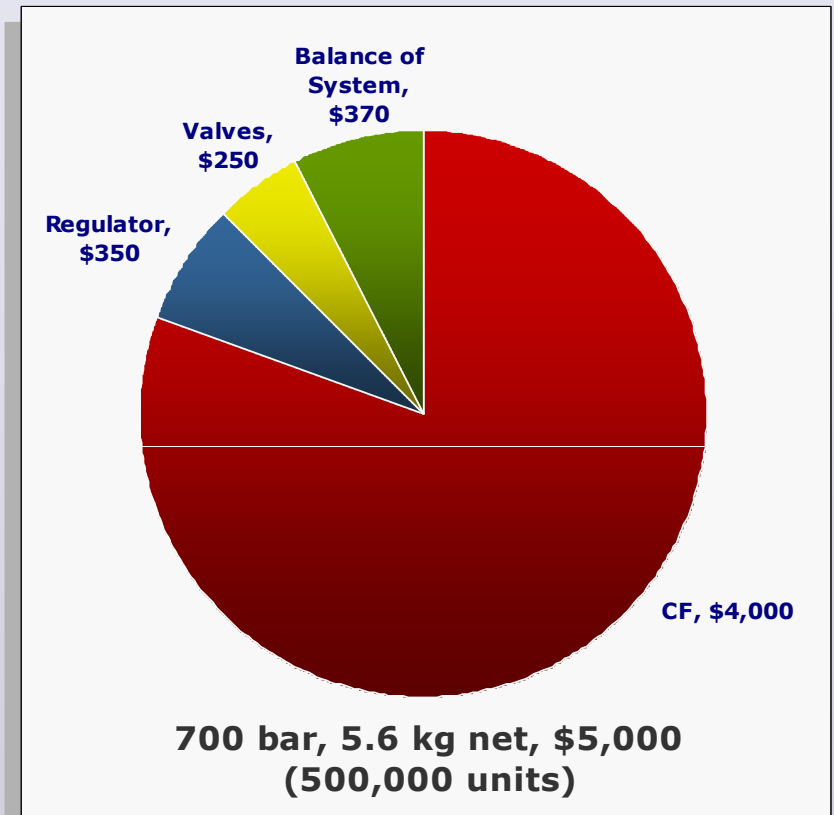
350 bar: 2.8-3.8 wt.%

700 bar: 2.5-4.4 wt%

System Volumetric Capacity

350 bar: 17-18 g/L

700 bar: 18-25 g/L



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**

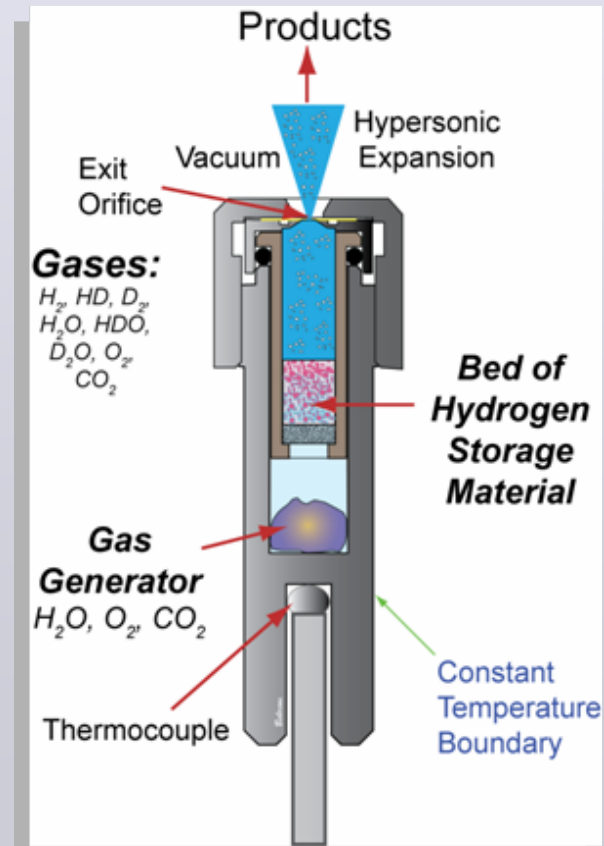
K. Gross, H2 Technology Solutions/HyEnergy, LLC/NREL

Systems Analysis

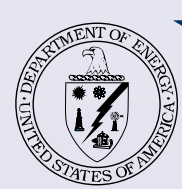
- **Preliminary well to tank efficiency analysis conducted**
- **System capacity and cost analysis conducted for multiple approaches**

Argonne, TIAX

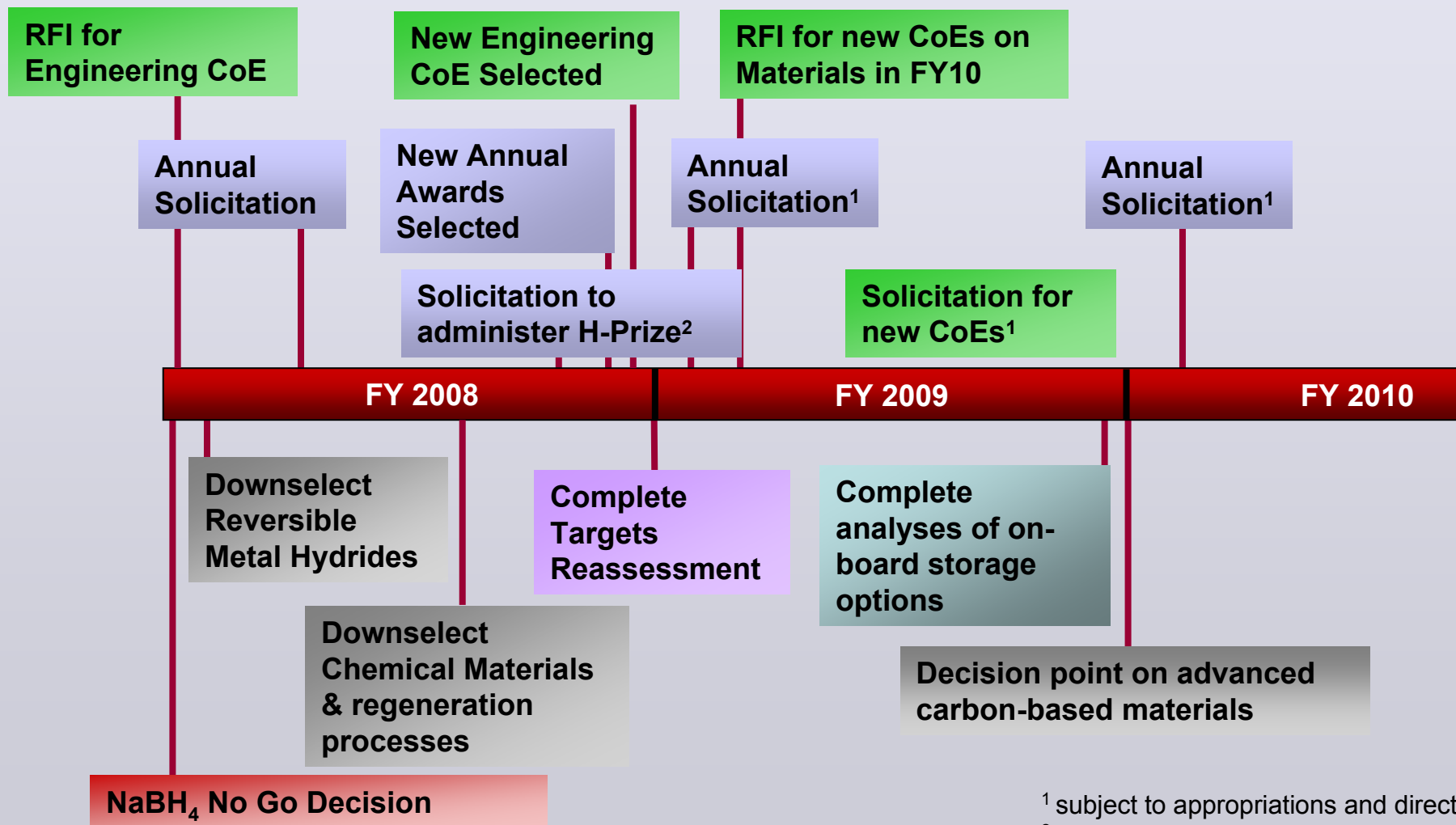
- **Reactivity of hydrogen storage materials assessed under various exposures – An IPHE Collaboration**



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



Key Hydrogen Storage Milestones & Future Plans



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



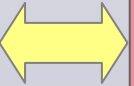
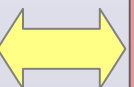
Hydrogen Storage Collaborations

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)

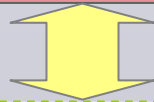
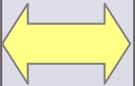


DOE

(Energy Efficiency & Renewable Energy- EERE)
National Hydrogen Storage Project

H₂ Storage Applied R&D

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



INDUSTRY

- FreedomCAR & Fuel Partnership
Tech teams:
 - H₂ 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)

<p>DOE – Basic Energy Sciences</p> <p>~30 Projects</p>	<p>NSF</p> <p>New projects in basic science</p>	<p>NIST</p> <ul style="list-style-type: none"> • Neutron scattering • Measurements 	<p>DOT</p> <p>Material handling/transport</p>	<p>DOD – Defense Logistics Agency</p> <p>6 projects & prototypes</p>
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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

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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

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

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



Reviewer Reminders

Mark your calendars-

Next Annual Review is week of

May 18, 2009



Thank you



Additional Details



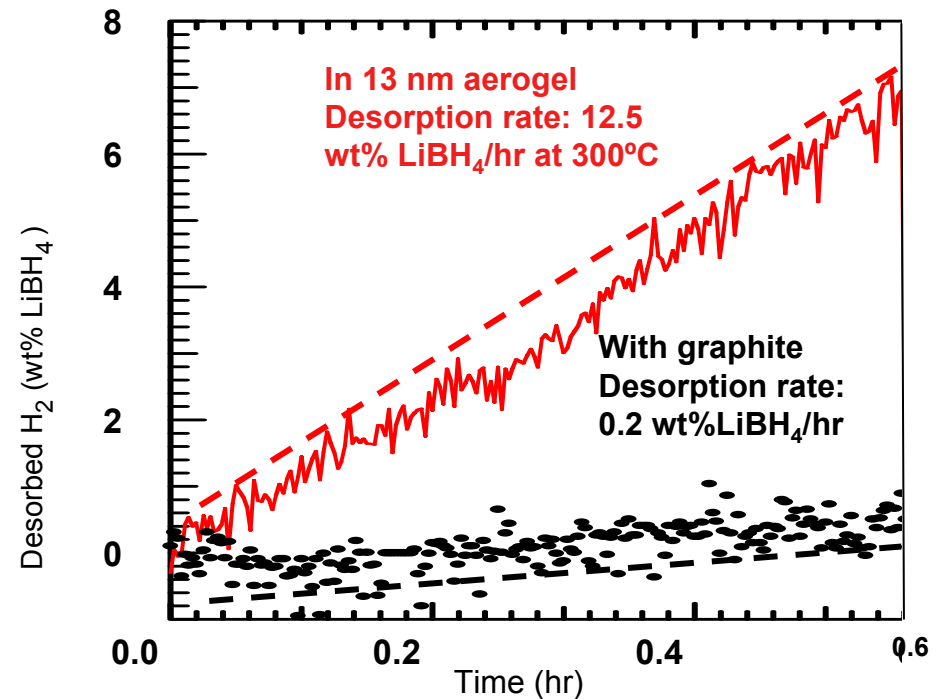
Accomplishments

Metal Hydride Examples

- Developed theory tool and screened > 16 million compositions
- Identified > 40 single step reactions as promising so far (with > 6 wt% H₂ and 15 < ΔU₀ < 75 kJ/mol H₂)

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

Increased kinetics
60-fold using LiBH₄
in aerogel



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



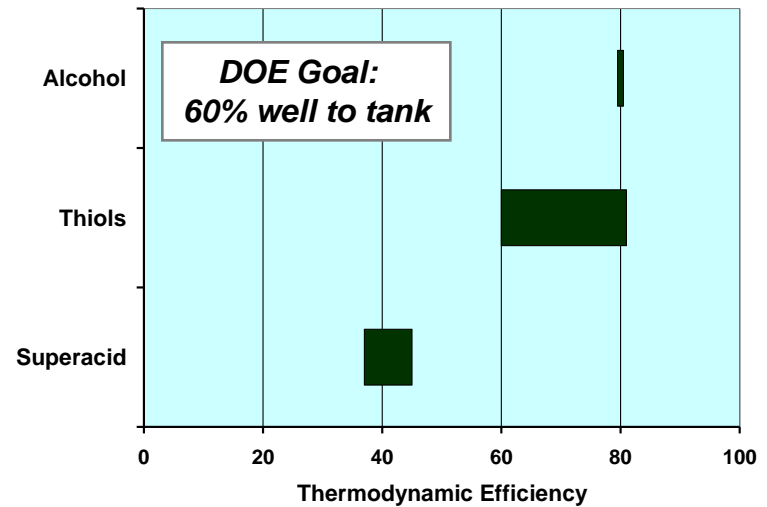
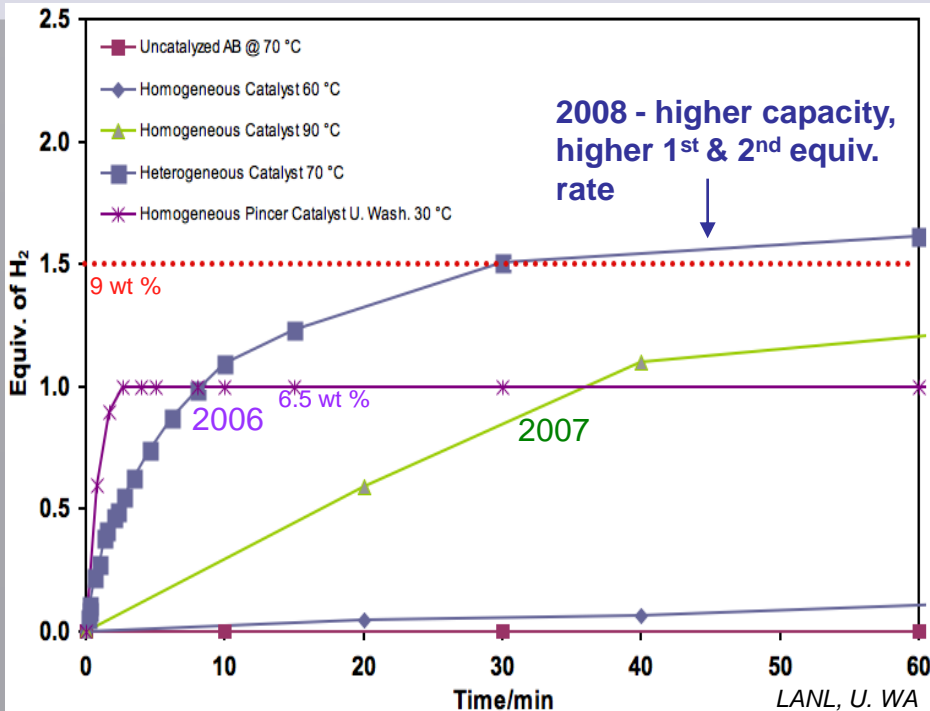
Accomplishments

Ammonia borane

$\text{NH}_3\text{BH}_3 \rightarrow \text{BNH}_x + 3\text{H}_2$ 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



Progress

Hydrogen Sorption Examples

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

- Tailored binding energies
 - ✓ PCN-12 $\Delta H_f \sim 12$ 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

