The U.S Department of Energy's National Hydrogen Storage Project: Goal, Progress and Future Plans

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U.S. DOE Hydrogen Program

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Overview

- The challenge of on-board H_2 storage
- DOE Hydrogen storage targets
- Are we making progress?
  - Recent R&D examples from the DOE Program
  - Examples of nanotechnology benefits & needs
- Future Plans

Hydrogen Storage: The "Grand Challenge"

Goal: On-board hydrogen storage for > 300 mile driving range and meet all performance (wt, vol, kinetics, etc.) , safety and cost requirements.

These Are System Targets

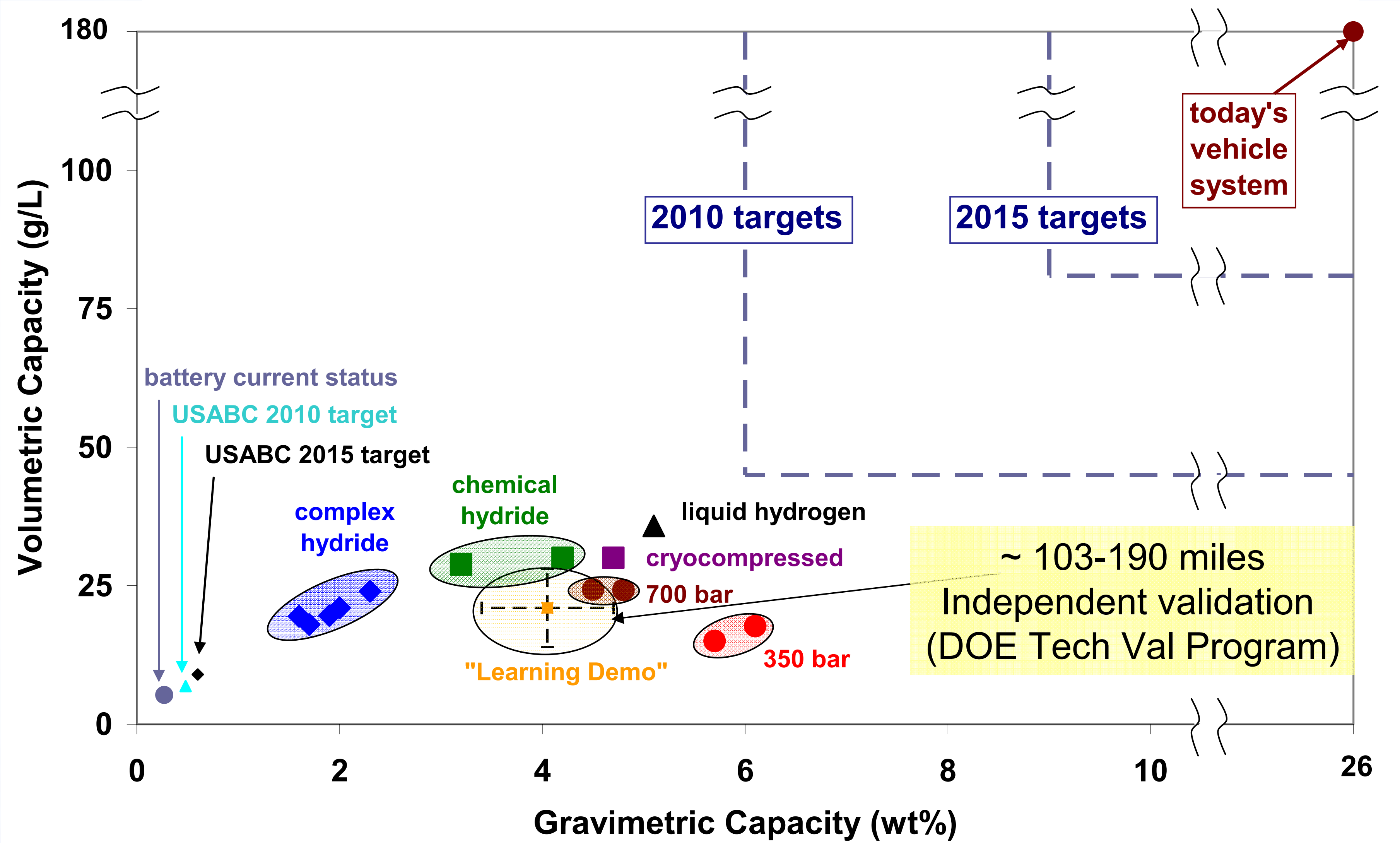
Material capacities must be higher!

Examples of Targets	2010	2015
System Gravimetric Capacity (net)	6 wt.% (2.0 kWh/kg)	9 wt.% (3.0 kWh/kg)
System Volumetric Capacity (net)	1.5 kWh/L (45 g/L)	2.7 kWh/L (81 g/L)
Storage System Cost	\$4/kWh (~\$133/kg H_2)	\$2/kWh (\$67/kg H_2)
Min. Full Flow Rate	0.02 g/s/kW	0.02 g/s/kW
Refueling Time (for 5 kg)	3 min	2.5 min
Cycle Life (Durability)	1000 cycles	1500 cycles

More targets and explanations at www.eere.energy.gov/hydrogenandfuelcells/

Results: Current Status vs. Targets

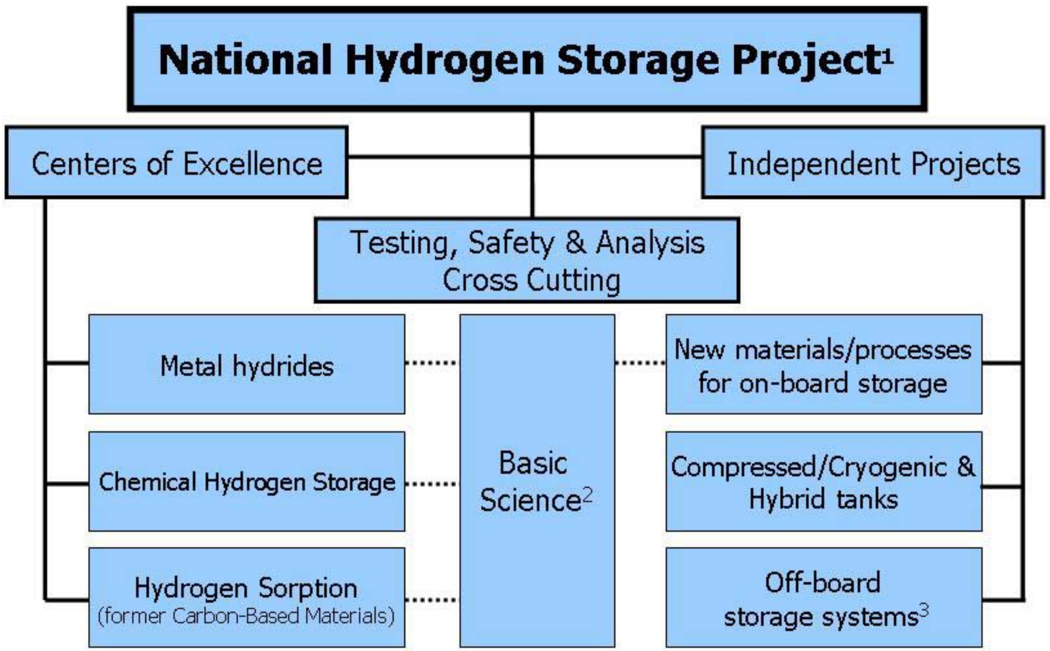
No technology meets targets- results include data from vehicle validation



Note: Estimates from developers. To be periodically updated.
Costs exclude regeneration/processing. Complex hydride system data projected. Data points include analysis results.

Strategy: Diverse Portfolio with Materials Focus

"…DOE should continue to elicit new concepts and ideas, because **success in overcoming the major stumbling block of on-board storage is critical** for the future of transportation use of fuel cells."[1]



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

- **Systematic approach**
  - Theory & experiment
  - Go/no-gos & downselects
  - Independent analysis & testing
- **~ 40 universities, 15 companies, 10 federal labs**
- **Aims to address NAS & other peer review recommendations**
- **Annual solicitation for increased flexibility**
- **Close coordination with basic science**
- **Strong auto & energy industry input-FreedomCAR & Fuel Partnership**
- **Coordination with other agencies & globally**

1. NRC H_2 Economy Report (2004),p.44

Applied R&D Hydrogen Storage "Grand Challenge" Partners:

Diverse Portfolio with University, Industry and National Lab Participation

Centers of Excellence

Metal Hydride Center

National Laboratory:
Sandia-Livermore

Industrial partners:
General Electric
HRL Laboratories
Intematix Corp.

Universities:
CalTech
Stanford
Pitt/CMU
Hawaii
Illinois
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
Penn State
Rice
Michigan
North Carolina
Pennsylvania

Federal Lab Partners:
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

Independent Projects

Advanced Metal Hydrides
UTRC, UOP
Savannah River Nat'l Lab
Univ. of Connecticut

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

Chemical Hydrogen Storage
Air Products & Chemicals
RTI
Millennium Cell
Safe Hydrogen LLC
Univ. of Hawaii

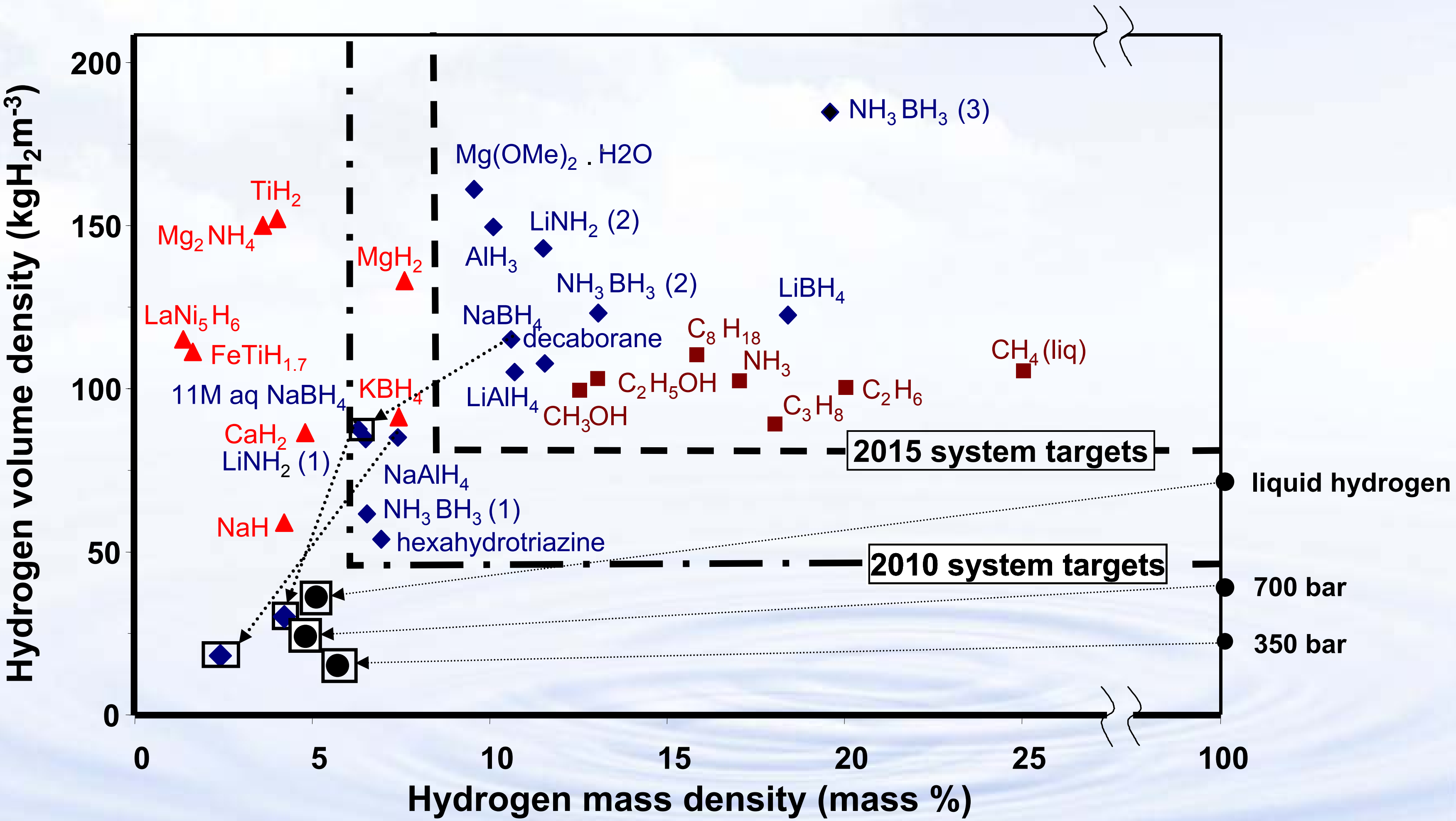
Other New Materials & Concepts
Alfred University
Michigan Technological University
UC-Berkeley/LBL
UC-Santa Barbara
Argonne Nat'l Lab

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, Georgia, Missouri-Rolla, Tulane, Southern Illinois; Labs: Ames, BNL, LBNL, ORNL, PNNL, SRNL

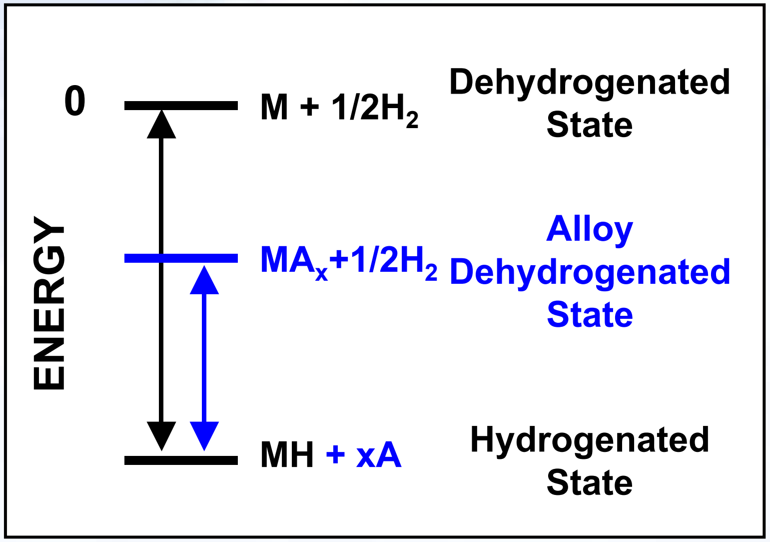
No current system meets targets, but there are some materials with potential…



G. Thomas et al, DOE Annual Program Review
Adapted from Schlapbach et al for material capacities

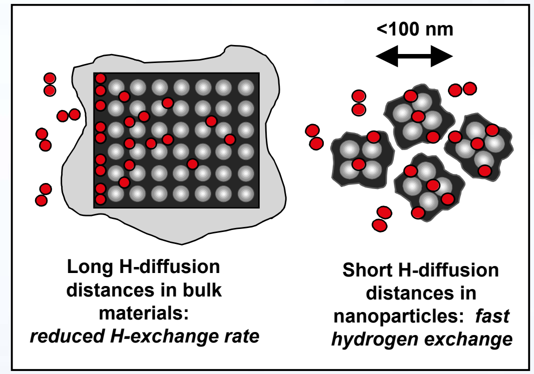
Exciting Possibilities- Destabilized hydrides and nano-engineering

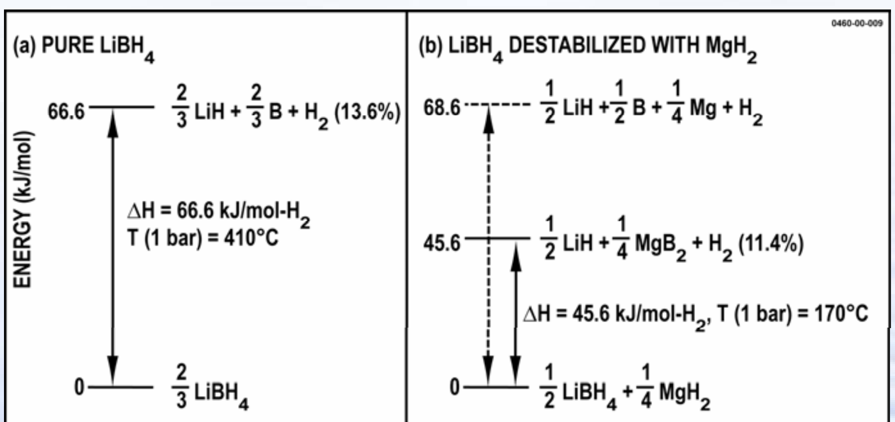
E.g., New system (11.4 wt. % and 0.095 kg/L) – $LiBH_4$ / MgH_2



Strategies:

- **Alter Thermodynamics by Hydride Destabilization**
- **Enhance Kinetics by Nano-engineering**



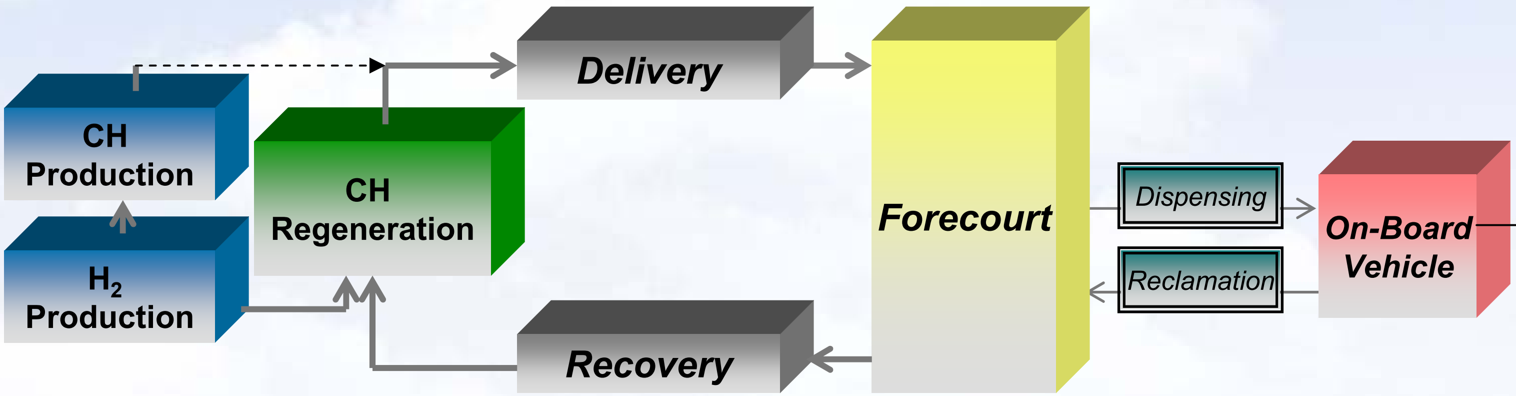


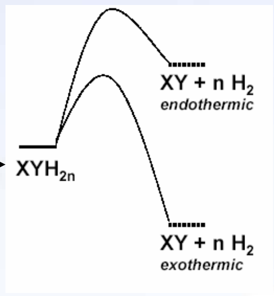
- **Reversibility: 9 to 10 wt. %**
- **Formation of MgB_2 can reduce T(1 bar) by ~ 240 °C**
- **But T still high (~375°C); kinetics slow**

J.J. Vajo, *et al.*, J. Phys. Chem. B, 108, 13977-13983 (2004).

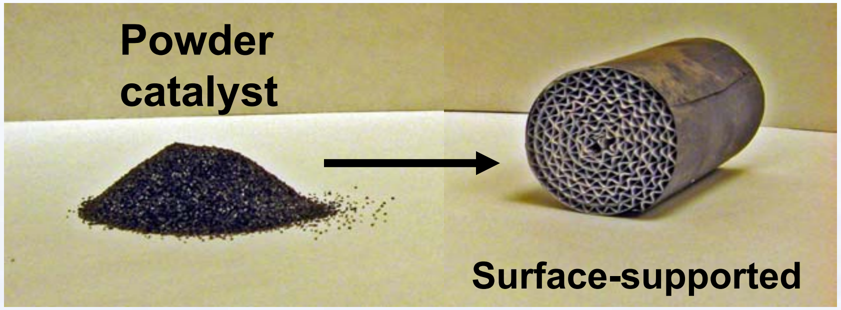
J. Vajo, S. Skeith, and F. Mertens, J. Phys. Chem. B, 109, 3719-3722 (2005).

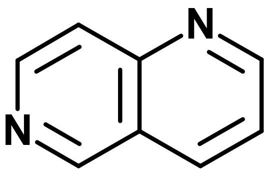
Recent Progress- Chemical Hydrogen Storage





Organic liquid carriers & catalysts





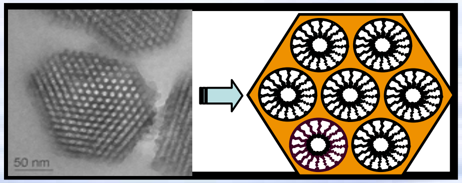
1,6-Naphthyridine

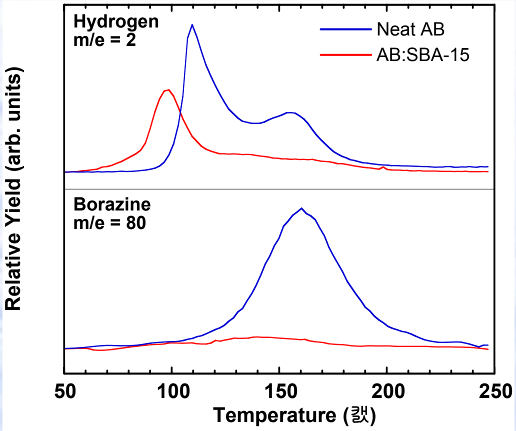
7.2 wt. % H_2, ~70 g H_2/l

Ambient-temp. liquid

Cooper, Pez, et al, Air Products

- Mesoporous scaffolds internally coated with ammonia borane show >6 wt% capacity, hydrogen release at < 80 C and reduced borazine formation





Autrey, Gutowski, et al, PNNL

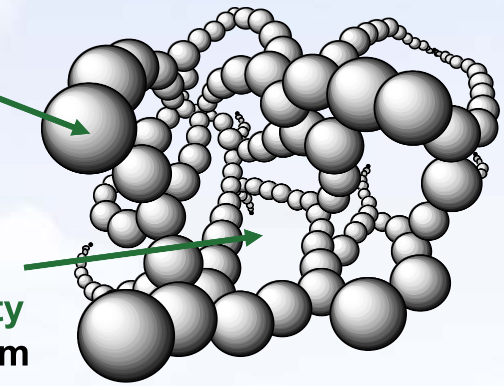
Results: Carbon Aerogels as Nanoporous Scaffolds

Examples of improving kinetics & reducing temperatures

CAs: unique porous materials of 3D networks of interconnected nanometer-sized carbon particles

Primary Carbon Particles ($2 \leq d \leq 25$ nm) containing microporosity ($d < 2$ nm)

Mesoporosity $2 \leq d \leq 50$ nm



Baumann et al, LLNL & Ahn et al, Caltech

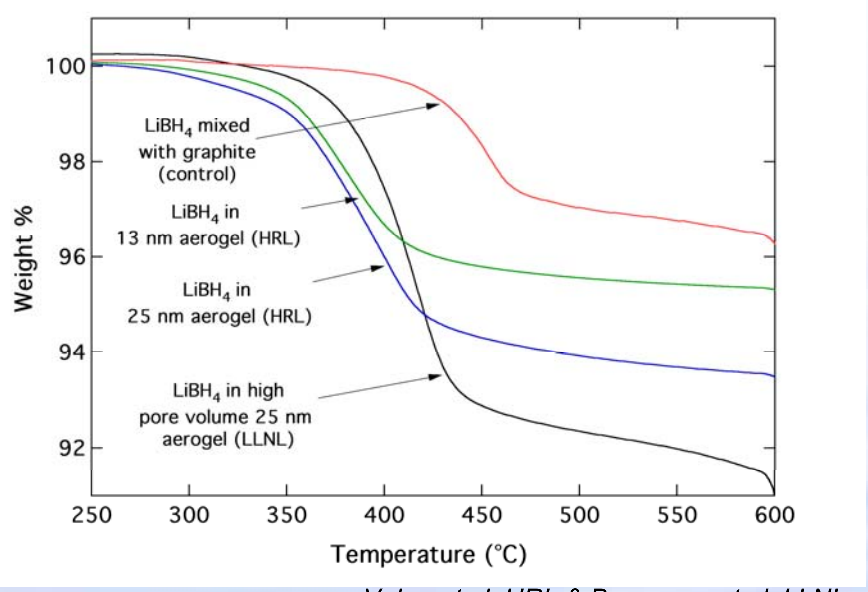
$LiBH_4 \rightarrow LiH + B + {}^3/_2H_2$ (13.6 wt.%)

(J. Vajo, HRL and T. Baumann, LLNL)

- Faster kinetics for borohydride in aerogel

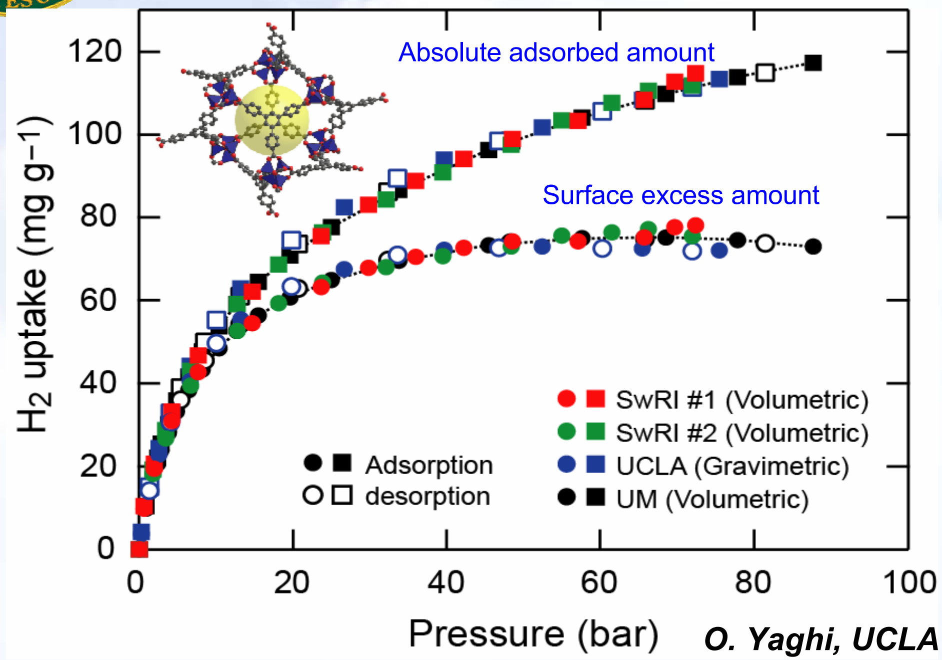
  70 C lower reaction temp (13 & 26 nm pores)

- Capacity penalty can be reduced with high volume aerogel ~ 8 wt.%



Vaho, et al, HRL & Baumann, et al, LLNL

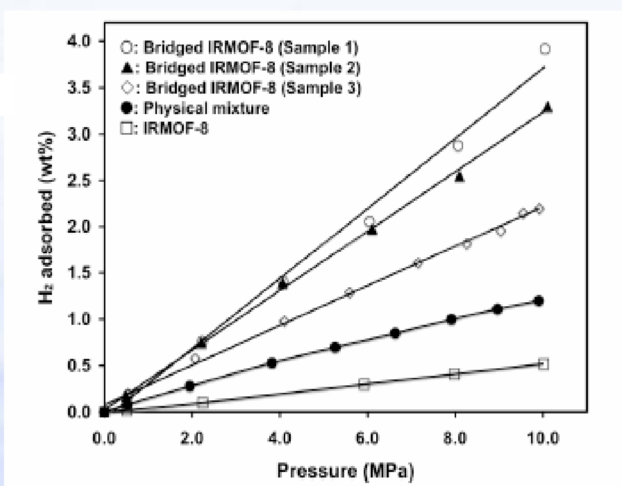
Results: Sorbent Materials



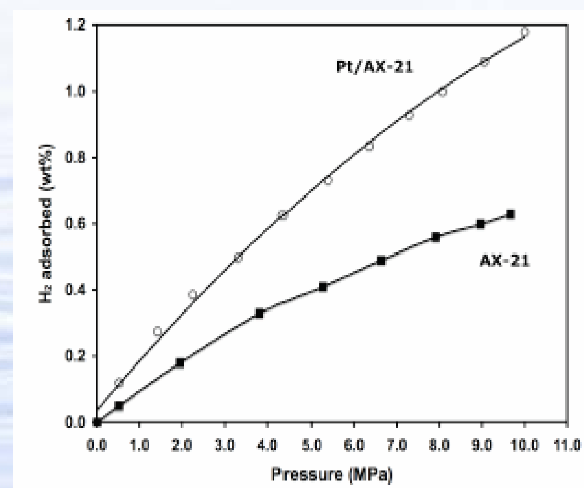
O. Yaghi, UCLA

Independent verification of MOF-177 (O. Yaghi et al,- highest capacity to date worldwide; > 7 wt.%, 77 K)

Independent verification of > 2x increase in capacity due to spillover (R. Yang et al)



Room Temp!



R. Yang, U. MI

R. Yang, U MI, P. Parilla, et al, NREL & HS Center

Examples of Hydrogen Storage Collaboration

IEA – HIA TASK 22

A total of 43 projects have been proposed for Task 22. This includes participation by 15 countries, 43 organizations, and 46 official experts.

- **Reversible Solid State Hydrogen Storage for Fuel Cell Power supply system** *(Russian Academy of Sciences)*
- **NESSHY – Novel Efficient Solid Storage for Hydrogen** *(National Center for Scientific Research "Demokritos," EU)*
- **Hydrodes & Nanocomposites in Hydrogen Ball Mills** *(University of Waterloo, Canada)*
- **Combination of Amine Boranes with MgH_2 & $LiNH_2$** *(Los Alamos National Lab, USA)*
- **Fundamental Safety Testing & Analysis** *(Savannah River National Lab, USA)*

Examples of U.S.-Korea R&D interests in hydrogen storage

Metal decorated polymers:

H. Lee, W.I. Choi, and J. Ihm, "Combinatorial Search for Optimal Hydrogen-Storage Nanomaterials Based On Polymers", Physical Review Letters, 97, 056104-1 (2006). (Seoul National University, Korea)

Conducting polymers:

S.J. Cho, K.S. Song, J.W. Kim, T.H. Kim, and K. Choo, "Hydrogen Sorption in HCl-Treated Polyaniline and Polypyrrole: New Potential Hydrogen Storage Media", Fuel Chemistry Division Reprints, 47, 790 (2002).

(Korea Institute of Energy Research)

Areas of Interest for Potential Collaboration

IPHE Hydrogen Storage Scoping Paper lists general areas of interest to IPHE (see www.iphe.net):

- Materials-based systems that are reversible on-board, such as high-capacity metal hydrides, high surface area sorbents and carbon
- Chemical hydrogen storage systems, such as chemical hydrides, which must be regenerated off-board
- Standardized testing of materials and systems for hydrogen storage capacities, including standardization of units of measure
- Systems analyses which includes life cycle, efficiency, safety and environmental impact analyses

Summary

- New Materials & Concepts are critical- address volumetric capacity, T, P, kinetics, etc. (not just wt. %!)
- Nanotechnology has potential to address critical needs in hydrogen storage

Hydrogen Fuel Initiative Budget

Activity	Funding ($ in thousands)			
	FY2005 Approp	FY2006 Approp	FY2007 Actual	FY2008 Request
Hydrogen Fuel Initiative				
EERE Hydrogen (HFCIT)	166,772	153,451	193,551	213,000
Fossil Energy (FE)	16,518	21,036	23,611[1]	12,450
Nuclear Energy (NE)	8,682	24,057	18,665	22,600
Science (SC)	29,183	32,500	36,500	59,500
DOE Hydrogen TOTAL	**221,155**	**231,044**	**272,327**	**307,550**
Department of Transportation	549	1,411	1,420	1,425
Hydrogen Fuel Initiative TOTAL	**221,704**	**232,455**	**273,747**	**308,975**

1 FY07 Request

EERE Hydrogen Budget

Activity	Funding ($ in thousands)			
	FY 2005 Approp	**FY 2006** Approp	**FY 2007** Actual	**FY 2008** Request
Hydrogen Production & Delivery	13,303	8,391	34,594	40,000
Hydrogen Storage R&D	22,418	26,040	34,620	43,900
Fuel Cell Stack Component R&D	31,702	30,710	38,082	44,000
Technology Validation	26,098	33,301	39,566	30,000
Transportation Fuel Cell Systems	7,300	1,050	7,518	8,000
Distributed Energy Fuel Cell Sys.	6,753	939	7,419	7,700
Fuel Processor R&D	9,469	637	4,056	3,000
Safety, Codes & Standards	5,801	4,595	13,848	16,000
Education	0	481	1,978	3,900
Systems Analysis	3,157	4,787	9,892	11,500
Manufacturing R&D	0	0	1,978	5,000
Technical/Program Mgt. Support	535	0	0	0
Congressionally Directed Activities	40,236	42,520	0	0
TOTAL	**166,772**	**153,451**	**193,551**	**213,000**

For More Information

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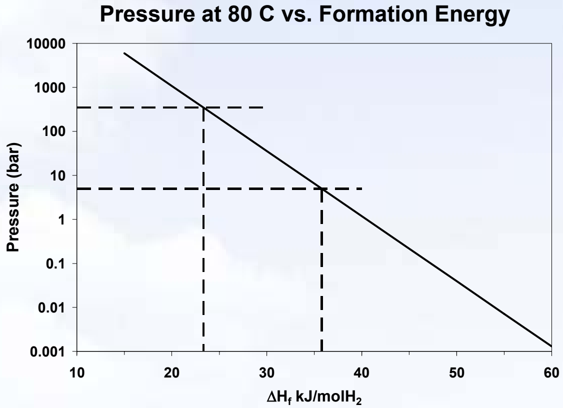
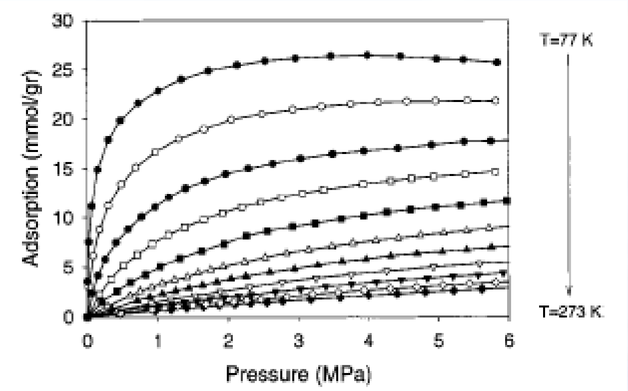
Thank you

It's not just about capacity- much research is focused on tailoring kinetics & thermodynamics…

- Hydride heat of formation
  - pressure limits (~20-35 kJ/molH_2)
  - refueling (<20 kJ/molH_2)



- Surface heat of adsorption
  - operating temperature
  - release temperature



- Activation barrier for regeneration
  - energy efficiency
  - near thermo-neutral