U.S. DEPARTMENT OF ENERGY

Hydrogen Storage

Session Review

Carole Read, Grace Ordaz, Ned Stetson, George Thomas[1]
Jesse Adams, Jim Alkire, Paul Bakke, and
Sunita Satyapal

2007 DOE Hydrogen Program

Merit Review and Peer Evaluation Meeting

May 15, 2007

[1] Sandia- Retired, on assignment to DOE, Washington DC

Outline

- Goals & Objectives
- Results: Progress in the last year
  - ✓ Evaluation of Center Model
- Future Plans
  - ✓ New Awards
  - ✓ Milestones & Budget

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

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

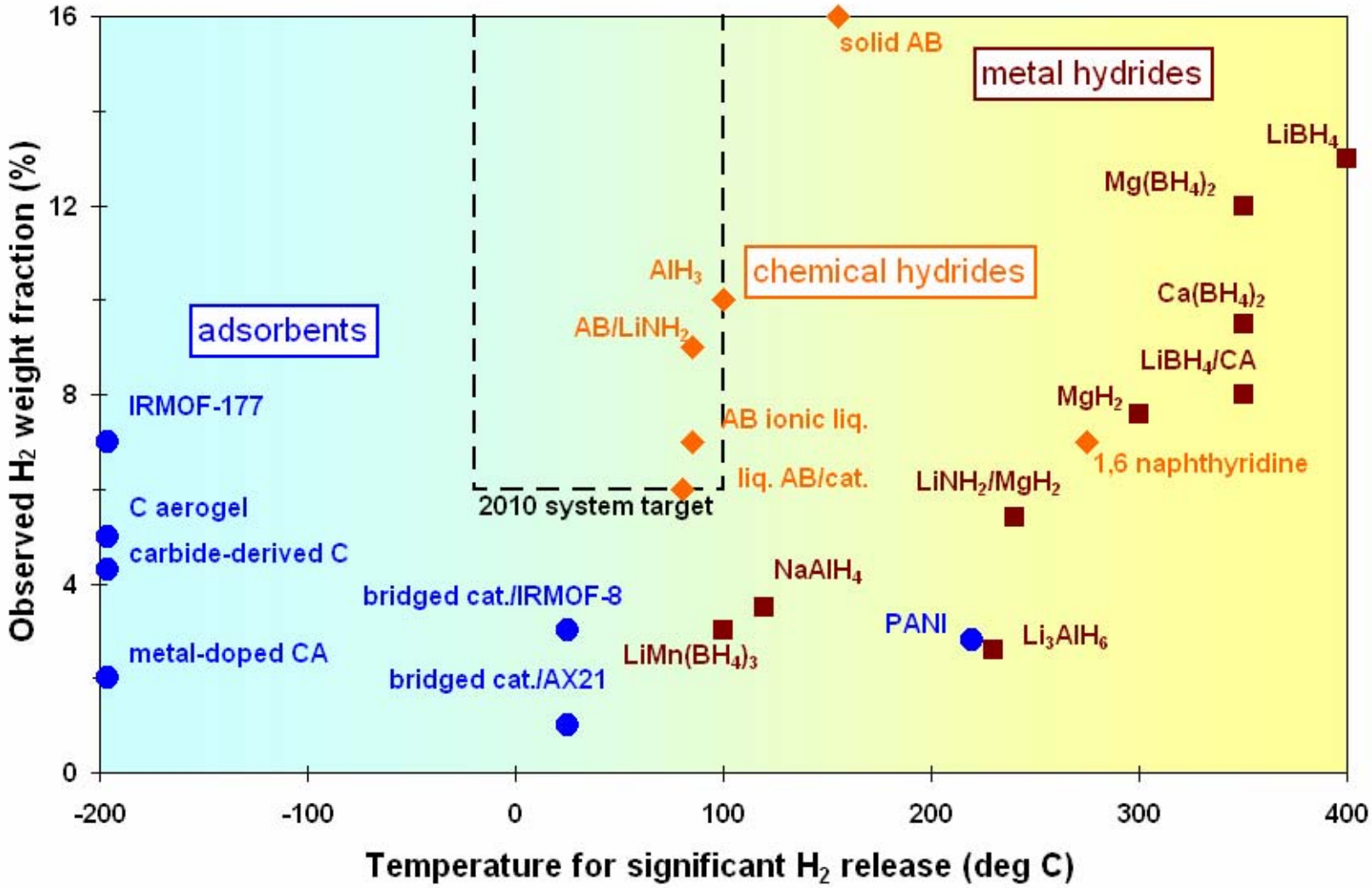
More targets and explanations at www.eere.energy.gov/hydrogenandfuelcells/

FreedomCAR & Fuel Partnership

Selected Examples of Progress: High capacity materials also focused on improving thermodynamics, kinetics, regeneration

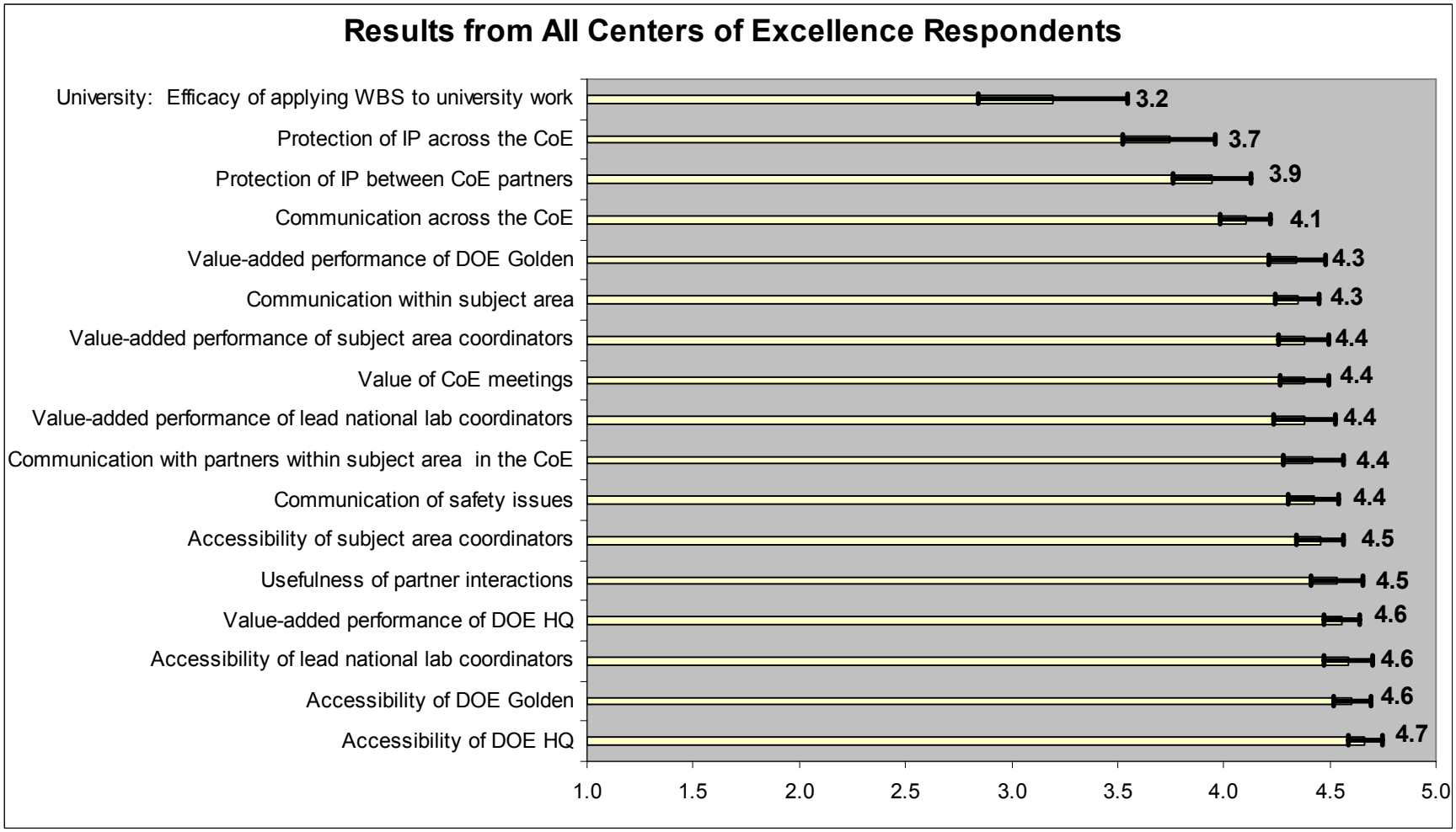
	Metal Hydrides	Chemical H_2 Storage	Adsorbents/Carbon
2006	Alane ~8-10 wt%,~150 g/L (<150 C) Borohydrides >9 wt%,~100 g/L (~250 - 350 C) Destabilized Binary hydrides ~5-7wt%,~60-90 g/L (~250 C) Li Mg Amides ~5.5wt%,~80 g/L (>200 C)	4,7 Phenanthroline (organic liquids) ~7 wt%, ~65 g/L(<225 C) Seeded Ammonia Borane ~9 wt%,~90 g/L(>120 C) Ammonia Borane/Li amide ~7 wt%, ~54 g/L(~85 C)	Metal-Organic Frameworks IRMOF-177 ~7 wt%,~30 g/L(77K) Bridged catalysts/IRMOF-8 ~1.8 wt.%,~10 g/L (room temperature) Metal/carbon hybrids, MetCars (*theory) ~6-8wt%*,~39 g/L*
2007	Alane (AlH_3) regeneration Chemical, electrochemical, supercritical fluids $LiBH_4$/C aerogels 6-8 wt.%, ~55-75 g/L (~300 C) Reversible $Ca(BH_4)_2$ ~9.6 wt.%, ~105 g/L (~350 C) $Mn(BH_4)_2$ 9-13 wt.% (>100 C) $Mg(BH_4)_2$ 9-12 wt.%, ~110 g/L (~350 C) Destabilized hydrides DFT identified new reactions $LiBH_4/MgH_2$, $CaH_2/LiBH_4$, $LiNH_2/LiH/Si$	1,6-Naphthyridine ~7 wt.%, ~70 g/L (275 C) Surface supported catalyst Amine boranes Ionic liquids ~7 wt.%, 39 g/L (85 C) $AB/LiNH_2$, AB/LiH ~9 wt.%, ~70 g/L (85 C) Solid AB >16 wt.%, >199 g/L (155 C) (>3g/s/kgAB) Liquid AB/catalyst ~ 6 wt.% (~ 80 C) Regeneration 2 step process, est.>50% eff.	Bridged cat./IRMOF-8 >3 wt.%, 100 bar (25 C) ~20 kJ/mol Bridged cat./AX-21 >1 wt.%, 100 bar (25 C) C aerogels ~5 wt.%, ~30 g/L (77 K) Metal-doped C aerogels ~2 wt.% (77 K) ~7-7.5 kJ/mol PANI 2.8 wt.%, 25 bar (25 C) Release at ~100-220 C

Progress: Material Capacity vs. Temperature



G. Thomas, et al., DOE (April 2007)

Programmatic Results: 1st CoE Evaluation



Assessment of CoE model: Multi-institutional critical mass applied R&D is proving to be effective. IP and WBS for universities were main issues.

Programmatic Results: 1st CoE Evaluation

Evaluation participation was good; 51 formal responses out of ~87 (plus continued informal input)

- IP was a key concern
- For university partners, there is difficulty adapting to milestone-driven work
- Input is that DOE has to balance technical direction vs micromanagement

- Participation by each center varied
  - 19 for Carbon
  - 11 for Metal hydride
  - 12 for Chemical hydride
  - Responses varied slightly by center

Current centers planned for 5 years (to FY 2010)

Center concept will be formally re-evaluated at the end of current agreements

Hydrogen Storage - Safety Processes & Research

Processes

- Safety plans complete for all "Grand Challenge" projects
  - Identification & analysis of safety vulnerabilities & risks
  - Risk mitigation, training
  - Reporting processes & communicating lessons learned
- Site visits/Safety Panel reviews*
  - Address potential safety issues
  - Share and discuss new insights
  - Identify project-specific findings that can have broader benefit in the DOE program.
- Monthly cross-center conference calls
- Online resources: e.g., www.h2incidents.org

Projects

- Safety evaluation of storage materials and systems:
  - internationally recognized **standard testing techniques** to quantitatively evaluate both materials and systems
  - **fundamental chemical kinetics** of environmental reactivity & inhibitor combinations with solid state hydrides
  - **amelioration methods and systems** to mitigate the risks of using these systems to acceptable levels

* Coordinated by PNNL, includes industry, govt and university experts

New Hydrogen Storage Awards (April 12, 2007)

$8.2 million over 4 years — to support 6 projects*

NEW MATERIALS R&D

Argonne National Laboratory, *Argonne, IL* — $1.9 M*
PI D. J. Liu and Partner L. Yu, Univ. of Chicago
"Novel Hydrogen Storage Media Through Nanostructured Polymeric Materials"

University of Hawaii, *Honolulu, HI* — $0.9 M*
PI Craig Jensen and Partner G. S. McGrady, Univ. of New Brunswick
"Recharging of Light Metal Hydrides through Supercritical Fluid Hydrogenation"

Miami University of Ohio, *Oxford, OH* — $1.4 M*
PI Hongcai (Joe) Zhou
"A Biomimetic Approach to New Adsorptive Carbonaceous Hydrogen Storage Materials"

United Technologies Research Center, *East Hartford, CT* — $1.0 M*
PI Dan Mosher, Partners E. Ronnebro, Sandia and Albemarle Corp.
"Catalyzed Nano-Framework Stabilized High Density Reversible H_2 Storage Systems"

MATERIALS SAFETY R&D

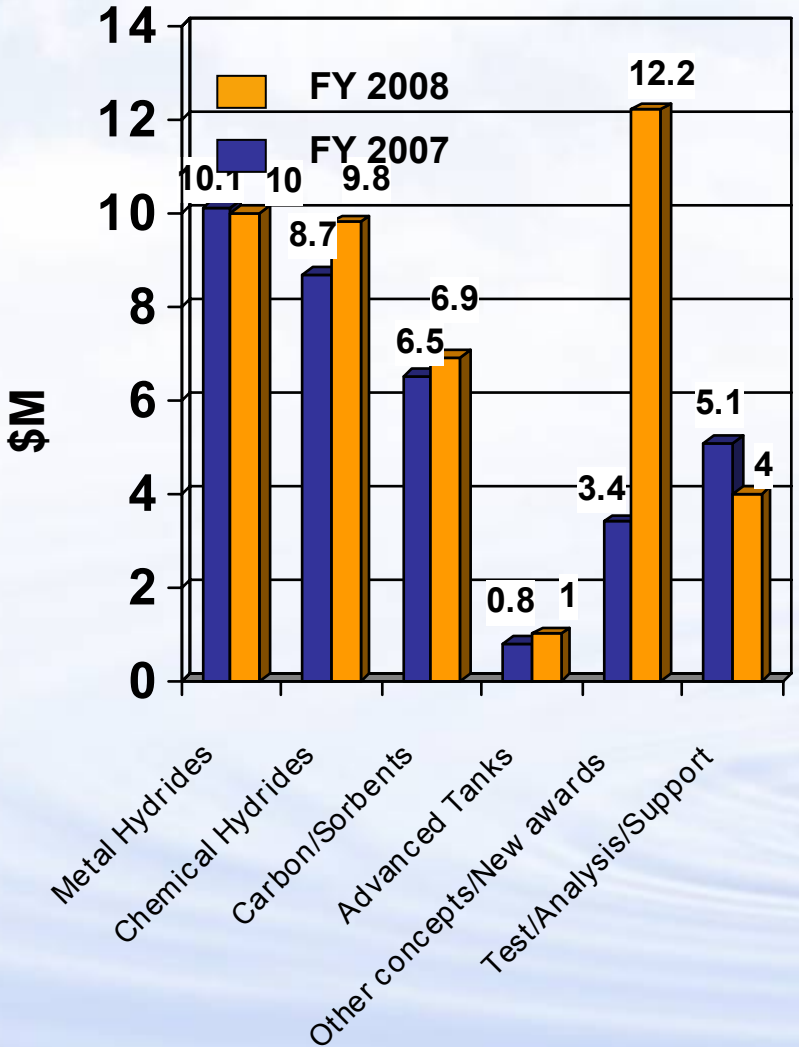
Sandia National Laboratories, *Livermore, CA* — $2.0 M*
PI Daniel Dedrick
"Safety Properties of Metal Hydrides Within the Context of Systems"

United Technologies Research Center, *East Hartford, CT* — $1.1 M*
PI Dan Mosher, Partners Kidde Fenwal and Hy-Energy
"Quantifying & Addressing the DOE Safety Target With Analysis & Testing of H_2 Storage Materials & Systems"

**Subject to final award negotiations*

Applied R&D Hydrogen Storage Budget

FY2008 Budget Request = $43.9M
FY2007 Appropriation = $34.6M
(FY2006 Appropriation = $26.0M)

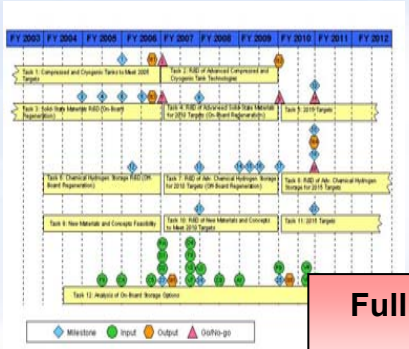


- **Emphasis:** Ramp up materials R&D: metal hydrides, chemical hydrogen storage and adsorbents for on-board storage through CoE & independent projects
- Tailor materials to focus on temperature, pressure, kinetics (as well as capacity)
- New Center of Excellence planned-Engineering Sciences*

Close coordination with Basic Science
$36.4M (FY07)
$59.5M (FY08)
Includes basic science for hydrogen storage, production and use (e.g., catalysis, membranes, etc.)

*subject to appropriations

Key Milestones & Future Plans



Assessment of Center Approach

New Awards Announced

RD&D Plan Updates online

RFI on New Center of Excellence

Go/No Go $NaBH_4$

Full Proposals Due

2006 | 2007 | 2008

Mar | Jun | Sep | Dec | Mar | Jun | Sep | Dec | Mar

Theory Focus Session

Test Facility Validation

2nd System Prototype Complete

No-Go on pure Single walled Nanotubes

Cryo-compressed Tank Assessment

Annual Solicitation *

Downselect Reversible Metal Hydrides

Assess & update targets if required

New CoE Solicitation *

Downselect Chemical H_2 Storage Mat'ls

Keep up the sustained effort and high technical quality work & be flexible!

Address volumetric capacity, T, P, kinetics, etc. (not just wt. %!)

*Subject to appropriations and direction

For More Information

Hydrogen Storage Team

Sunita Satyapal, Team Leader
Overall Storage/ FreedomCAR Tech Team/International
202-586-2336
sunita.satyapal@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
202-586-3152
carole.read@ee.doe.gov

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

George Thomas*
On Assignment to DOE
**retired, Sandia*
202-586-8058
george.thomas@ee.doe.gov

Jesse Adams
Field Office Project Officer
303-275-4954
jesse.adams@go.doe.gov

James Alkire
Field Office Project Officer
303-275-4795
jim.alkire@ee.doe.gov

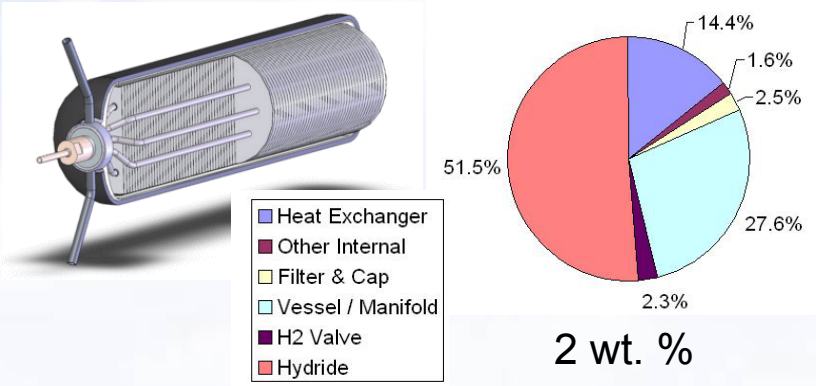
Paul Bakke
Field Office Project Officer
303-275-4916
paul.bakke@go.doe.gov

Basic Science: Harriet Kung (harriet.kung@science.doe.gov)

Additional Information

Results: New System Prototypes Demonstrated

2nd Gen Complex Hydride Prototype Built (Ti-$NaAlH_4$)



2 wt. %

Estimated 2.0 wt% & 21 g/L (Projected 2.3 wt.% and 24 g/L)

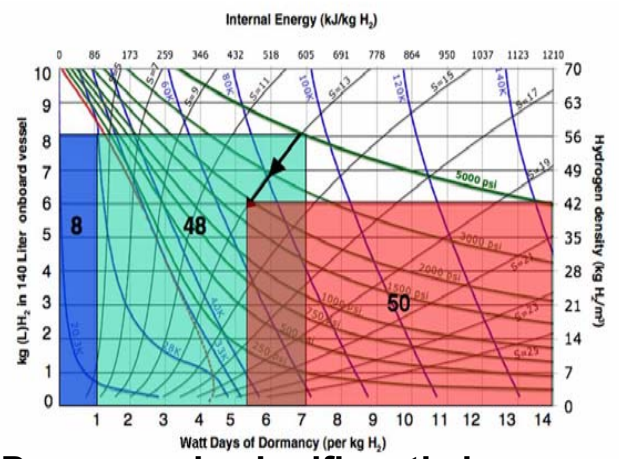
Key Issues:

- Kinetics; thermal integration
- Material packing
- Reversible capacity at low temp
- Depth of discharge

Moser et al., UTRC

Cryo-Compressed Tank Concept Demonstrated w/ DOE Tech Val.

- High P for urban driving & LH_2 for maximum range
- LH_2 boiloff is reduced
- 4.7% H_2 wt. and 30 g/L (ANL estimate)



Dormancy is significantly improved

LLNL's Cryocompressed tank in Quantum-LLNL modified Prius; driven ~650 miles on one tank (10 kg LH_2 at 25-35 mph)

Aceves, Berry, et al. LLNL

Applied R&D "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
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

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.

Project Types:

- Experimental
- Engineering
- Theoretical Modeling (scientific or engineering)
- Safety Aspects of Hydrogen Storage Materials

Classes of Storage Media

- Reversible Metal Hydrides
- Regenerative Hydrogen Storage Materials
- Nanoporous Materials
- Rechargeable Organic Liquids and Solids

- **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 & Pacific Northwest National Labs, USA)*
- **Fundamental Safety Testing & Analysis** *(Savannah River National Lab, USA)*

DoD: DEFENSE LOGISTICS AGENCY

New Storage Awards (4/07):

- **High throughput - Combinatorial Screening:** U of Central Florida, UC Berkeley & Symyx, Miami U (Ohio) & NREL
- **Reversible System Dev't & Demonstration:** Energy Conversion Devices, U of Missouri (phase 1 design)

Interagency Hydrogen R&D Task Force (OSTP)

NSF- proposal review in process (5/07)

NIST- neutron scattering