The U.S. National Hydrogen Storage Project Overview

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Larry Blair, Grace Ordaz, Carole Read, Ned Stetson, George Thomas
U.S. DOE Hydrogen Program

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Combinatorial/High Throughput Techniques for Hydrogen Storage Meeting
Bethesda, MD
We import ~ 55% of our oil today – projected to go up to 68% by 2025 if we continue business as usual.

Transportation is the largest consuming sector of petroleum (67% of total U.S. consumption).
• About 2/3rd of petroleum demand within the transportation sector is for light duty vehicles

U.S. CO₂ Emissions by Sector

• About 1/3rd of CO₂ emissions is due to the transportation sector

Potential Oil Savings Scenarios - Fuel Substitution

needed in the long term

Hydrogen is one part of a comprehensive strategy

Near term reduction in oil use → Hybrid vehicles for improved efficiency

Long term elimination of oil dependency → Hydrogen substitution in fuel cell vehicles
Hydrogen as an Energy Carrier

Why H₂?
• Multiple domestic resources
• Non toxic, water vapor emissions
• Decouple C emissions from tailpipe
• Flexibility (transportation, stationary, portable)
• High energy content; efficiency of fuel cells

Critical Path Technology Barriers:
• Hydrogen Storage (>300 mile range)
• Hydrogen Production Cost ($2.00-3.00 per gge)
• Fuel Cell Cost (~$30 per kW)

Economic/Institutional Barriers:
• Codes and Standards (Safety, and Global Competitiveness)
• Hydrogen Delivery (Investment for new Distribution Infrastructure)
• Education

*Transition only
The Hydrogen Storage Challenge

### Key System Targets

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric capacity</td>
<td>6 wt% (2 kWh/kg)</td>
<td>9 wt% (3 kWh/kg)</td>
</tr>
<tr>
<td>Volumetric capacity</td>
<td>45 g/L (1.5 kWh/L)</td>
<td>81 g/L (2.7 kWh/L)</td>
</tr>
<tr>
<td>System Cost</td>
<td>$4/kWh</td>
<td>$2/kWh</td>
</tr>
</tbody>
</table>

Many more: [www.hydrogen.energy.gov](http://www.hydrogen.energy.gov)

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**Gasoline System**

**Today’s Vehicle (system)**

- Fuel Cell Efficiency, Conformable Tanks
- 2015 target

**Energy Density (kWh/L)**

- Liquid H₂ (20K, 1 bar)
- Compressed H₂ (300K)
  - 350 bar (5,000 psi)
  - 700 bar (10,000 psi)
Many other requirements…

- Usable, specific-energy from H₂ (Gravimetric Capacity) (3 kWh/kg)
- Usable, energy density from H₂ (Volumetric Capacity) (2.7 kWh/L)
- System cost ($2/kWh net)
- Fuel cost includes off-board costs such as liquefaction, compression, regeneration etc. ($2-3/gge)
- Operating ambient temperature (-40/60°C (sun))
- Min/max delivery temperature (-40/85°C)
- Cycle life variation (99% of mean (min) @ 90% confidence)
- System fill time (2.5 min)
- Start time to full flow (min. ambient) (2 sec)
- Start time to full flow (20°C) (0.5 sec)
- Min full flow rate (0.02 g/s kW)
- 90% energy efficiency for reversible onboard systems
- 60% for regenerable off-board (well-to-wheels)
- Require 99.99% H₂ (4 max. levels for selected contaminants)
- Permeation & leakage (Federally enclosed area safety standard in SCC/h)
- Toxicity (Meets/exceeds applicable standards)
- Safety (Meets/exceeds applicable standards)
- Loss of useable H₂ (0.05 g/h/kg H₂ Stored)

Weight

Volume (& conformability)

System cost (& fuel cost)

Durability/Operability

Charging/Discharging Rates

Efficiency

Fuel Purity

Environmental Health & Safety

Commercially viable & efficient H₂ Storage Systems

U.S. Department of Energy
Hydrogen Storage Options

Reversible On-Board

High Pressure Tanks
- High Pressure Hydrogen
- Glass Microspheres

Cryogenic Tanks
- Liquid Hydrogen
- Low temp
- Cryocompressed liquid/gas mix

Adsorbents (Physiosorption based)
- MOFs
- Doped CNTs
- Nanostructures
- Polymers

Metal Hydrides
- Alanates
- Alanes
- Lithium Amides
- Destabilized metal hydrides

Chemical Hydrides
- Sodium Borohydride
- Organic Liquids
- Magnesium Hydride
- Slurries
- Ammonia Boranes

Regenerable Off-Board
“...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.”

- Balanced portfolio
- ~ 40 universities, 15 companies, 10 federal labs
- Robust effort in both theory & expt’l work
- Annual solicitation for increased flexibility
- Close coordination with basic science
- Coordination with industry, other agencies & globally

Strategy: Diverse Portfolio with Materials Focus

National Hydrogen Storage Project

Centers of Excellence

Testing, Safety & Analysis
Cross Cutting

Independent Projects

Basic Science

Metal hydrides

Chemical Hydrogen Storage

Hydrogen Sorption
(former Carbon-Based Materials)

New materials/processes
for on-board storage

Compressed/Cryogenic &
Hybrid tanks

Off-board
storage systems


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 elements
# Centers of Excellence

<table>
<thead>
<tr>
<th>Metal Hydride Center</th>
<th>Hydrogen Sorption Center</th>
<th>Chemical Hydrogen Storage Center</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Laboratory: Sandia-Livermore</td>
<td>National Laboratory: NREL</td>
<td>National Laboratories: Los Alamos, Pacific Northwest</td>
</tr>
<tr>
<td><strong>Industrial partners:</strong></td>
<td><strong>Industrial partners:</strong></td>
<td><strong>Industrial partners:</strong></td>
</tr>
<tr>
<td><strong>Universities:</strong></td>
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<tr>
<td><strong>Federal Lab Partners:</strong></td>
<td><strong>Federal Lab Partners:</strong></td>
<td><strong>Federal Lab Partners:</strong></td>
</tr>
<tr>
<td>Brookhaven, JPL, NIST, Oak Ridge, Savannah River</td>
<td>Lawrence Livermore, NIST, Oak Ridge</td>
<td>Lawrence Livermore Nat’l Lab, Quantum, Argonne Nat’l Lab, TIAAX LLC, SwRI, UTRC, Sandia Nat’l Lab, Savannah River Nat’l Lab</td>
</tr>
</tbody>
</table>

# 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, TIAAX LLC
- SwRI, UTRC, Sandia Nat’l Lab
- Savannah River Nat’l Lab

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# 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
Hydrogen Storage - Current Status & Recent Progress

No technology meets targets
Promising materials continue to be identified

Current status:
~ 103-190 miles through independent validation
(DOE “Learning Demonstration” activity)

Estimates from developers & analysis results; periodically updated by DOE. “Learning Demo” data is for 63 vehicles.
Summary of Current Assessment

Challenges are technology specific: Pros and Cons for each Progress is being made but too early to eliminate whole areas

**Key 2010 Targets:**

<table>
<thead>
<tr>
<th></th>
<th>High P Tanks</th>
<th>Chemical Hydrides</th>
<th>Metal Hydrides</th>
<th>Carbon/Sorbents</th>
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</thead>
<tbody>
<tr>
<td>Volume (1.5 kWh/L)</td>
<td>H</td>
<td>M</td>
<td>M</td>
<td>M/H</td>
</tr>
<tr>
<td>Weight (2.0 kWh/kg)</td>
<td>M</td>
<td>M</td>
<td>M/H</td>
<td>M</td>
</tr>
<tr>
<td>Cost ($4/kWh)</td>
<td>M/H</td>
<td>M/H¹</td>
<td>M/H</td>
<td>M/H</td>
</tr>
<tr>
<td>Refueling Time (3 min, for 5 kg)</td>
<td>L²</td>
<td>L</td>
<td>M/H</td>
<td>M</td>
</tr>
<tr>
<td>Discharge Kinetics (0.02 g/s/kW)</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>L/M</td>
</tr>
<tr>
<td>Durability (1000 cycles)</td>
<td>L</td>
<td>M</td>
<td>M</td>
<td>M</td>
</tr>
</tbody>
</table>

RD&D Plan: see http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

**Thermal Mgmt:** Key Issues for MH (CH, C/S)

For CH, MH and S- assessment based on potential to meet targets, though systems not yet demonstrated in most cases.

¹For CH: Storage system may meet cost but fuel cost of $2-$3/kg is challenge for CH regeneration.

²Assumes communication protocols

U.S. Department of Energy
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

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)

- Reversible Solid State Hydrogen Storage for Fuel Cell Power supply system (Russian Academy of Sciences)
- Hydrodes & Nanocomposites in Hydrogen Ball Mills (University of Waterloo, Canada)
- Combination of Amine Boranes with MgH₂ & LiNH₂ (Los Alamos & Pacific Northwest National Labs, USA)
- Fundamental Safety Testing & Analysis (Savannah River National Lab, USA)

NSF- proposal review in process (5/07)
NIST- neutron scattering
Summary

We need to accelerate the pace of hydrogen storage R&D!

Theory-guided experimental approach is current focus.

Combinatorial/high throughput techniques for both synthesis and screening are needed to complement current portfolio.
For More Information

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www.hydrogen.energy.gov
Thank you

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www.hydrogen.gov
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 through CoE & independent projects
- Tailor materials to focus on T, P, 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  U.S. Department of Energy
Synergy between Basic Science and Applied Research, Development and Demonstration

Basic Research
Develop and use theoretical models & fundamental experimentation to generate knowledge:
- Fundamental property & transport phenomena
- Novel material structures, characterization
- Theory, modeling, understand reaction mechanisms

Applied Research & Development
Apply theory & experimentation to design & develop novel, high-performance materials to meet specific performance targets:
- Develop new materials, leverage knowledge from basic research
- Optimize materials and testing to improve performance
- Design, develop and demonstrate materials, components and prototype systems to meet milestones.

Technology Validation & Demonstration
Test Systems under Real World Conditions
- Demonstrate and validate performance against targets
- Gain knowledge (e.g. fueling time, driving range, durability, cost, etc.) and apply lessons learned to R&D