2004 Annual DOE Hydrogen Program Review

Hydrogen Storage

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Carole J. Read
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Office of Hydrogen, Fuel Cells and Infrastructure Technologies

The State of the Art will help in the near-term, but is impractical for the long-term --- compressed and liquid hydrogen tanks:
- Will enable vehicle/infrastructure learning demonstrations & initial market penetration
- Have limited range & high energy penalty (liquid), preventing full market penetration
- Are approaching their weight & volume limits
- May have off-board storage applications

→ DOE R&D focus is on materials-based storage technologies.

Today’s Average Vehicle
370mi-20gal

Daimler Sprinter
90mi-26gal-3600psi

Honda FCX
235mi-42gal-5000psi

GM Opel Zafira Minivan
170mi-26gal-10,000psi
Unacceptable Hydrogen Storage Option

"It runs on hydrogen."
Main Barriers are Weight, Volume, Cost, and Refueling Time

What do these targets mean? For a 5-kg H₂ system...

<table>
<thead>
<tr>
<th>Storage Parameter</th>
<th>2005</th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric Capacity (Specific energy)</td>
<td>1.5 kWh/kg</td>
<td>2.0 kWh/kg</td>
<td>3.0 kWh/kg</td>
</tr>
<tr>
<td></td>
<td>0.045 kg H₂/kg</td>
<td>0.060 kg H₂/kg</td>
<td>0.090 kg H₂/kg</td>
</tr>
<tr>
<td><strong>System Weight:</strong></td>
<td>111 Kg</td>
<td>83 Kg</td>
<td>55.6 Kg</td>
</tr>
<tr>
<td>Volumetric Capacity (Energy density)</td>
<td>1.2 kWh/L</td>
<td>1.5 kWh/L</td>
<td>2.7 kWh/L</td>
</tr>
<tr>
<td></td>
<td>0.036 kg H₂/L</td>
<td>0.045 kg H₂/L</td>
<td>0.081 kg H₂/L</td>
</tr>
<tr>
<td><strong>System Volume:</strong></td>
<td>139 L</td>
<td>111 L</td>
<td>62 L</td>
</tr>
<tr>
<td>Storage system cost</td>
<td>$6 /kWh</td>
<td>$4 /kWh</td>
<td>$2 /kWh</td>
</tr>
<tr>
<td><strong>System Cost:</strong></td>
<td>$1000</td>
<td>$666</td>
<td>$333</td>
</tr>
<tr>
<td>Refueling rate</td>
<td>.5 Kg H₂/min</td>
<td>1.5 Kg H₂/min</td>
<td>2.0 Kg H₂/min</td>
</tr>
<tr>
<td><strong>Refueling Time:</strong></td>
<td>10 min</td>
<td>3.3 min</td>
<td>2.5 min</td>
</tr>
</tbody>
</table>
FreedomCAR On-Board Hydrogen Storage Targets are based on vehicle requirements --- NOT on what storage technologies can achieve.

- The baseline is today’s vehicles and customer expectations of them, e.g. 370 mile weighted average range
- Fuel economy gains of 2.5X - 3.0X were assumed for fuel cell vehicles
- Today’s fuel systems are assumed to include “conformable” components, shaped to fill in available space under the vehicle floorboard and within the chassis
- Some allowance – approximately 20% - can be provided in the capacity targets for fully-conformable storage systems
Storage calculations used real volumes and weights of gasoline fuel storage systems in current production vehicles, including:

- Fuel tank
- Fuel filler tubes
- Gas cap
- Hoses
- Fuel lines
- Fuel pump
- Fuel filter
- Carbon vapor canister
- Leak detection device
- Purge control solenoid
- Rollover check valve
- Tank hanger straps, clips, & other fasteners
No current H₂ storage technology meets the 2015 targets.
No current $H_2$ storage technology meets the cost targets.

For valid comparison, storage system cost must include the cost of the “first charge” so that any “pre-conditioning,” i.e. compression, liquefation, or off-board regeneration cost is considered.
Some improvement in system energy density may be achieved by improving the balance of plant.

<table>
<thead>
<tr>
<th>Storage Approach</th>
<th>Current System Densities (relative to fuel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed hydrogen</td>
<td>~70%</td>
</tr>
<tr>
<td>Liquid hydrogen</td>
<td>~55 - 60%</td>
</tr>
<tr>
<td>Solid state</td>
<td>~40 - 50%</td>
</tr>
</tbody>
</table>

Greatest potential for improvement is with solid state systems.
Hydrogen Storage R&D – Planning and Implementing

- **Grand Challenge Issued**
- **Draft R&D Plan Published**
- **H₂ Storage “Think Tank”**
- **International Conference on Hydrogen Storage Materials, Lucca, Italy**
- **Basic Energy Sciences Workshop**
- **Compressed/Liquid Hydrogen Workshop**
- **Grand Challenge Selections Announced**
2004 and 2005 DOE H₂ Storage Projects

**Complex Metal Hydrides**
- SNL Metal Hydride Center
- UTRC
- UOP
- SNL (Livermore)
- U. Hawaii

**Chemical Hydrogen Storage**
- LANL/PNNL Chem. Hydride Ctr
- Millennium Cell
- Safe Hydrogen
- Air Products
- INEEL
- Research Triangle Institute

**Carbon-Based Materials**
- NREL Carbon-Based Center
- University of Pennsylvania
- Gas Technology Institute
- SUNY - Syracuse

**New Materials & Concepts**
- Cleveland State University
- Alfred University
- Carnegie Institute
- Michigan Tech University
- UC Berkeley
- UC Santa Barbara
- University of Michigan
- University of Missouri
- University of Connecticut
- TOFTEC

**Testing**
- SwRI
- Analysis
- TIAx

**Compressed/ Liquid Tanks**
- Quantum
- LLNL
- Gas Technology Institute
Hydrogen Storage R&D – Funding Distribution

Emphasis: Centers of Excellence and new materials projects to focus on 2010 hydrogen storage goals:
- 2.0 kWh/kg, 1.5 kWh/liter, $4/kWh

FY2005 Budget Request = $30.0M
FY2004 Appropriation = $29.4M

* Focus of compressed and liquid hydrogen R&D is cost reduction and off-board storage.
• Identified methods to improve kinetics in solid-state materials & pathways to greater capacity (U. Hawaii, SNL)

• Demonstrated 10,000-psi tanks with improved energy density, 10X greater cycle life, & fast-fill capability (Quantum)

• Developed and tested novel 5000-psi cryo-compressed tank demonstrating good performance after cryogenic temperature cycling (LLNL)
The DOE “Grand Challenge” will form the basis of the National Hydrogen Storage Project.
### Sandia National Laboratory - Livermore

- Light element advanced complex hydrides
- Destabilized binary hydrides
- Intermetallic hydrides
- Lithium amides
- Other reversible hydrides

<table>
<thead>
<tr>
<th>General Electric</th>
<th>CalTech</th>
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<tbody>
<tr>
<td>Hughes Research Labs</td>
<td>Stanford</td>
</tr>
<tr>
<td>Intematix Corp.</td>
<td>Univ. of Hawaii</td>
</tr>
<tr>
<td>BNL</td>
<td>Univ. Illinois-UC</td>
</tr>
<tr>
<td>JPL</td>
<td>Univ. Nevada-Reno</td>
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<tr>
<td>NIST</td>
<td>Univ. of Pittsburgh</td>
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<tr>
<td>ORNL</td>
<td>University of Utah</td>
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</tbody>
</table>
Los Alamos National Laboratory in partnership with Pacific Northwest National Laboratory

- Novel boron chemistry (boron hydrides, aminoboranes, polyborane anions)
- Regeneration chemistry & life cycle analysis
- Nanoparticles & light elements

<table>
<thead>
<tr>
<th>Intematix Corp.</th>
<th>Penn State</th>
</tr>
</thead>
<tbody>
<tr>
<td>Millennium Cell</td>
<td>Univ. Alabama</td>
</tr>
<tr>
<td>Rohm and Haas</td>
<td>UC-Davis</td>
</tr>
<tr>
<td></td>
<td>UCLA</td>
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<td></td>
<td>Univ. of Pennsylvania</td>
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<tr>
<td></td>
<td>Univ. of Washington</td>
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</tbody>
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Carbon – Based Materials
Center of Excellence

**National Renewable Energy Laboratory**

- Activated/hybrid carbon nanotubes
- Conducting polymers
- Metal organic frameworks
- Hybrid carbon aerogels
- Other novel carbon-based materials

<table>
<thead>
<tr>
<th>Air Products &amp; Chemicals</th>
<th>CalTech</th>
</tr>
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<tbody>
<tr>
<td>LLNL</td>
<td>Duke</td>
</tr>
<tr>
<td>NIST</td>
<td>Penn State</td>
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<tr>
<td>ORNL</td>
<td>Rice Univ.</td>
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<table>
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<tr>
<th>Univ. Michigan</th>
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<tr>
<th>Univ. NC - CH</th>
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<tr>
<th>Univ. of Pennsylvania</th>
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Fourteen independent projects will address new materials and/or processes.

<table>
<thead>
<tr>
<th>Lead Institution</th>
<th>Area of Research</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alfred University</td>
<td>Glass microspheres – Photo enhanced diffusion</td>
</tr>
<tr>
<td>Michigan Technological University</td>
<td>Metal perhydrides</td>
</tr>
<tr>
<td>SUNY-Syracuse</td>
<td>Nanostructured activated carbon</td>
</tr>
<tr>
<td>UC-Berkeley</td>
<td>Magnesium nanomaterials</td>
</tr>
<tr>
<td>UC-Santa Barbara</td>
<td>Organic/inorganic framework materials, metal hydrogen complexes</td>
</tr>
<tr>
<td>University of Connecticut</td>
<td>Lithium nitride</td>
</tr>
<tr>
<td>University of Michigan</td>
<td>Metal organic frameworks</td>
</tr>
<tr>
<td>University of Missouri - St. Louis</td>
<td>Clathrates</td>
</tr>
<tr>
<td>University of Pennsylvania</td>
<td>Carbon based nanomaterials- carbide derived carbon</td>
</tr>
<tr>
<td>Carnegie Institute</td>
<td>Clathrates</td>
</tr>
<tr>
<td>Research Triangle Institute</td>
<td>Amine borane complexes</td>
</tr>
<tr>
<td>Gas Technology Institute</td>
<td>Electron charged graphite; Off-Board Storage</td>
</tr>
<tr>
<td>TOFTEC, Inc.</td>
<td>Carbon and boron nitride</td>
</tr>
<tr>
<td>TIAX LLC</td>
<td>System analysis on fuel chain efficiency, environmental impact and cost</td>
</tr>
</tbody>
</table>
Key Milestones

- Complete construction of materials test facility (4Q, 2004)
- Complete chemical hydride life-cycle analysis (3Q, 2006)
- Demonstrate 4 wt% storage capacity on carbon nanotubes (4Q, 2005)
- Validate compressed and liquid tanks in complete system achieving 2005 targets (3Q, 2006)
- Complete assessment of composite materials and design parameters for 10K psi compressed tank (3Q, 2004)
- Go/no-go decision on carbon nanotubes (4Q, 2006)
- Down-select complex hydride materials (4Q, 2006)
- Down-select new materials / concepts (4Q, 2006)
- Down-select from chemical hydrides (4Q, 2006)
DOE Hydrogen Storage Team

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• **JoAnn Milliken**: *Team Leader*  
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www.eere.energy.gov/hydrogenandfuelcells
Detailed R&D Timeline/Milestones
Milestones

Compressed/Liquid Tanks
1. Complete feasibility study of hybrid tank concepts (4Q, 2005)
2. Compressed and cryogenic liquid storage tanks achieving the 2005 targets to Tech Val (3Q, 2006)
3. Go/no-go decision on insulated pressure vessels for cryogenic tanks with minimum evaporative losses (4Q, 2006)
4. Go/No-Go decision on liquid and compressed tank technologies (4Q, 2006)
5. Advanced compressed/cryo tank technologies to Tech Val (4Q, 2009)

Reversible Solid-State Materials
7. Complete verification of test facility (2Q, 2005)
8. Go/no-go decision point on carbon nanotubes (4Q, 2006) (Reproducibility plan in place)
9. Complete prototype complex hydride integrated system meeting 2005 targets (2Q, 2006)
10. Downselect complex hydride materials (4Q, 2006)
11. Complex hydride integrated system meeting 2005 targets (3Q, 2007, to fuel cells and technology validation)
12. Complete prototype complex hydride integrated system meeting 2010 targets (4Q, 2008)
13. Go/no-go decision on continuation of complex hydride R&D (4Q, 2009)
14. Go/no-go decision point on other carbon nanostructures (4Q, 2009)

Chemical Storage
15. Downselect from hydride regeneration processes (2Q, 2005)
16. Demonstrate efficient hydride regeneration laboratory process (2Q, 2006)
17. Complete chemical hydride life-cycle analysis (3Q, 2006)
18. Demonstrate scaled-up hydride regeneration process (4Q, 2006)
19. Complete prototype hydride integrated system (4Q, 2006)
20. Downselect from chemical storage approaches for 2010 targets (4Q, 2006)
21. Full-cycle, integrated chemical hydride system meeting 2005 targets (2Q, 2007, to fuel cells and technology validation)
22. Demonstrate advanced hydride regeneration laboratory process (4Q, 2008)
23. Complete prototype advanced chemical storage integrated system (2Q, 2009)
24. Demonstrate scaled-up advanced hydride regeneration process (4Q, 2009)
25. Go/no-go decision point on chemical storage R&D for 2015 targets (4Q, 2009)
Milestones, cont’d

New Materials/Concepts
26. Downselect from new materials/concepts (4Q, 2006)
27. Downselect the two most promising new materials/concepts for continued development (4Q, 2009)

Analysis
28. Safety requirements/protocols for onboard storage (3Q, 2004, from safety)
29. Update onboard storage targets (4Q, 2006)
30. Complete analysis of best storage option for 2010 targets (4Q, 2007)
31. Analysis results to delivery (4Q, 2007)
32. Complete analysis of best storage option for 2015 targets (4Q, 2009)
33. Analysis results to delivery (4Q, 2009)