Overview of Storage Development
DOE Hydrogen Program

Safe, efficient and cost-effective storage is a key element in the development of hydrogen as an energy carrier

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Livermore, CA

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Hydrogen storage requires something more than a can or a bucket.

Hydrogen has the highest mass energy density of any fuel:

120 MJ/kg (LHV) 144 MJ/kg (HHV)

However

At ambient conditions (300 K, 1 atm.):
the energy content of 1 liter of H2 is only 10.7 kJ,
three orders of magnitude too low for practical applications.

Issues:

1. What are the options available for storage?
2. What are the theoretical limits to storage density and how close can we come?
3. How do we organize a development program to achieve adequate stored energy in an efficient, safe and cost-effective manner?
## Mass energy densities for various fuels

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Hydrogen weight fraction</th>
<th>Ambient state</th>
<th>Mass energy density (MJ/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>1</td>
<td>Gas</td>
<td>120</td>
</tr>
<tr>
<td>Methane</td>
<td>0.25</td>
<td>Gas</td>
<td>50 (43)²</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.2</td>
<td>Gas</td>
<td>47.5</td>
</tr>
<tr>
<td>Propane</td>
<td>0.18</td>
<td>Gas (liquid)¹</td>
<td>46.4</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.16</td>
<td>Liquid</td>
<td>44.4</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.13</td>
<td>Liquid</td>
<td>26.8</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.12</td>
<td>Liquid</td>
<td>19.9</td>
</tr>
</tbody>
</table>

(1) A gas at room temperature, but normally stored as a liquid at moderate pressure.  
(2) The larger values are for pure methane. The values in parantheses are for a “typical” Natural Gas.
Maximum energy density is achieved in liquid state

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Hydrogen weight fraction</th>
<th>Ambient state</th>
<th>Liquid volumetric energy density (MJ/liter)</th>
<th>Hydrogen volumetric energy density in liquid (MJ/liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>1</td>
<td>Gas</td>
<td>$8.4 - 10.4^3$</td>
<td>$8.4 - 10.4^3$</td>
</tr>
<tr>
<td>Methane</td>
<td>0.25</td>
<td>Gas</td>
<td>$21 (17.8)^2$</td>
<td>$12.6 (10.8)^2$</td>
</tr>
<tr>
<td>Ethane</td>
<td>0.2</td>
<td>Gas</td>
<td>23.7</td>
<td>12</td>
</tr>
<tr>
<td>Propane</td>
<td>0.18</td>
<td>Gas (liquid)$^1$</td>
<td>22.8</td>
<td>10.6</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0.16</td>
<td>Liquid</td>
<td>31.1</td>
<td>13.2</td>
</tr>
<tr>
<td>Ethanol</td>
<td>0.13</td>
<td>Liquid</td>
<td>21.2</td>
<td>12.3</td>
</tr>
<tr>
<td>Methanol</td>
<td>0.12</td>
<td>Liquid</td>
<td>15.8</td>
<td>11.9</td>
</tr>
</tbody>
</table>

(1) A gas at room temperature, but normally stored as a liquid at moderate pressure.
(2) The larger values are for pure methane. The values in parantheses are for a “typical” Natural Gas.
(3) The higher value refers to hydrogen density at the triple point.
Hydrogen energy content in liquid fuels

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Hydrogen density is nearly the same in all fuels. This narrow range suggests a natural benchmark for comparison of storage performance.
## Maximum storage densities (w/o system)

<table>
<thead>
<tr>
<th>Storage Method</th>
<th>Energy Density MJ/liter</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High pressure gas</strong></td>
<td></td>
</tr>
<tr>
<td>- ambient temperature</td>
<td>3600 psi: 2.0</td>
</tr>
<tr>
<td></td>
<td>5000 psi: 2.75</td>
</tr>
<tr>
<td>- cryogenic system</td>
<td>150 K: 3.5</td>
</tr>
<tr>
<td></td>
<td>20 K: 8.4</td>
</tr>
<tr>
<td><strong>Liquid hydrogen</strong></td>
<td>8.4</td>
</tr>
<tr>
<td><strong>Reversible storage media</strong></td>
<td></td>
</tr>
<tr>
<td>- carbon structures</td>
<td></td>
</tr>
<tr>
<td>- nanotubes</td>
<td>?</td>
</tr>
<tr>
<td>- fullerenes</td>
<td>?</td>
</tr>
<tr>
<td>- hydrides</td>
<td></td>
</tr>
<tr>
<td>- intermetallics</td>
<td>10.8 - 12.0</td>
</tr>
<tr>
<td>- alanates</td>
<td>8.25</td>
</tr>
<tr>
<td>- composite materials</td>
<td></td>
</tr>
<tr>
<td><strong>Chemical methods</strong></td>
<td></td>
</tr>
<tr>
<td>- liquid fuel + reformer</td>
<td>Eff. gasoline</td>
</tr>
<tr>
<td></td>
<td>methanol</td>
</tr>
<tr>
<td>50%:</td>
<td>6.6</td>
</tr>
<tr>
<td>75%:</td>
<td>9.9</td>
</tr>
<tr>
<td>- off-board reprocessing</td>
<td></td>
</tr>
</tbody>
</table>
Programmatic guidelines

• A balanced program between scientific discovery and engineering validation is needed.
  – Portion of program invested in high risk approaches.
  – Collaboration with industry at all levels.
  – International partnerships beneficial.
  – Leverage off other programs.

• Program should not downselect technologies too early
  – Options should be fully explored.
  – Different technologies suited for different applications.

• Realistic goals should be set as metrics for progress.
  – Evaluate goals on a continuing basis
  – continue to refine roadmap
DOE Hydrogen Storage Program

Materials Development

- Carbon Nanotubes (Heben, NREL)
- Carbon Fullerenes (Loutfy, MER)
- Alanates/catalysts Catalyst Enhanced Storage* (Jensen, U. of H.)
  - Alanates/ subst. bulk scale-up, safety (Gross, SNL)
- Polymer Dispersed Hydride* (Jarvi, United Techn.)

Pressure Tank Development

- Lightweight tanks (Mitlitsky, LLNL)
- Conformable tanks (Haaland, Thiokol)
- Cryogenic tanks (Aceves, LLNL)
- Pressure Tank Safety (Odegard, SNL)

Engineering Validation

- Integrated PV system (Sapru, ECD)
- FC/Hydride Powerplant (Story, SNL)
- Hydride/Organic Slurry (Breault, ThermoPower)
- Thermal Compression* (DaCosta, Ergenics)

* new starts

collaborative programs
Materials Development

- Carbon nanotubes  
  - M. Heben, NREL  
  - near-term goal: ~6 wt.%  
  - synthesis, processing, hydrogen absorption/desorption

- Carbon fullerenes  
  - R. Loutfy, MER  
  - feasibility of fullerene-based storage

- Alanate hydrides  
  - C. Jensen, Univ. of Hawaii  
  - NaAlH4 : 5.5 wt.% hydrogen capacity  
  - catalysts, properties

- Hydride development  
  - K. Gross, SNL  
  - near-term goal: 5.5 wt.% at <100 C (NaAlH4)  
  - bulk synthesis, scaled-up beds, characterization, safety studies

- Catalytically enhanced storage  
  - C. Jensen, Univ. of Hawaii  
  - new start

- Polymer dispersed metal hydrides  
  - T. Jarvi, United Technologies  
  - new start
Pressure Tank Development

- Lightweight tanks  
  F. Mitlitisky, LLNL  
  - goal: >10 wt.% 5000 psi

- Conformable tanks  
  R. Golde, Thiokol Propulsion Co.  
  - high pressure tanks with improved packing efficiency

- Cryogenic hydrogen vessels  
  S. Aceves, LLNL  
  - design and testing for improved volume density

- Composite tank testing  
  B. Odegard, SNL  
  - comparison of high pressure hydrogen tank failure to other fuels.  
    CNG, gasoline, methanol.
Engineering Validation

- PV/electrolysis/metal hydride  K. Sapru, ECD
  - modeling and integration of storage with renewable energy sources

- Metal hydride/ organic slurry  R. Breault, Thermo Power
  - chemical hydride for PEMFC vehicles
  - hydrogen transmission and storage

- Fuelcell/hydride powerplant  G. C. Story, SNL
  - for underground mine and tunneling locomotive

- Thermal hydrogen compression  D. DaCosta, Ergenics, Inc.
  - new start
Other hydrogen storage programs (US)

- **DOE/OTT**
  - Fuels for Fuel Cells Program (P. Devlin)
    Parallel development of fuel processor and onboard H storage.

- **DOE/OIT**
  - Low cost hydrides for mine vehicles (SRTC)
    Part of Mining Industry of the Future initiative.

- **IEA**
  - Task 12 will be completed Oct. 2000
  - New task being formed: Advanced Solid and Liquid State Hydrogen Storage Materials (G. Sandrock)

- **Industry Projects**
Other hydrogen storage programs (non US)

- Canadian Projects
  - Alanates (A. Zaluska, McGill Univ.)
  - Nanocrystalline Mg-based hydrides (Hydro-Quebec)
  - Carbon adsorption (IRH)

- European Projects
  - Liquid hydrogen storage (BMW)
  - Refueling station (BMW)

- WENET (Japan)
  - Metal-H complex ions (S. Suda, Kogakuin Univ.)
  - Others
Some highlights from this year

• Continuing progress in nanotubes
  – high purity synthesis and processing methods.
  – > 6 wt.% appears feasible.

• Important progress achieved on alanates
  – 5.5 wt.% at low temperatures appears feasible.

• Continued improvement in lightweight and conformable tanks
  – more efficient packing of high pressure tanks

• Integration of storage with applications
  – PV system
  – mine vehicle

• Three new starts
  – catalyst enhanced storage
  – polymer dispersed hydride
  – thermal hydrogen compression