Comparison of On-board Hydrogen Storage Options

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We are in the process of evaluating the performance and cost of various hydrogen storage options for the DOE.

**Well-to-Wheels**

**Vehicle Integration**

**Storage System**

- Material
- Material wt %
- P, T requirement
- Thermo, kinetics

- BOP requirements
- System size, cost
- System issues

- Power unit and thermal integration
- Vehicle cost, weight
- Fuel economy

- Fuel chain requirement
- Ownership cost
- WTW energy use, GHG
On-board cost and performance estimates are based on detailed technology assessment and cost modeling.

### Performance and Tech Assessment
- Literature Review
- System Design and Configurations
- Process Modeling
- Outline Assumptions
- Developer Feedback

### Cost Modeling
- Document BOM
- Determine Material Costs
- Identify Processes and Mnf. Equipment
- Sensitivity Analyses

### Overall Model Refinement
- Developer and Stakeholder Feedback
- Revise Assumptions and Model Inputs
To date, we have evaluated compressed gas tanks, sodium alanate, and sodium borohydride storage technologies.

<table>
<thead>
<tr>
<th>Category</th>
<th>Initial Cases</th>
<th>Tech Status</th>
<th>Storage State</th>
<th>H₂ Release</th>
<th>Refueling</th>
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</thead>
<tbody>
<tr>
<td>Compressed and Liquid Hydrogen</td>
<td>5,000 &amp; 10,000 psi</td>
<td>Mature (low volume)</td>
<td>Gas</td>
<td>Pressure regulator</td>
<td>H₂ gas</td>
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<tr>
<td>Reversible Onboard: Metal Hydrides, Alanates</td>
<td>Sodium Alanate</td>
<td>Proof of Concept</td>
<td>Solid</td>
<td>Endothermic desorption</td>
<td>H₂ gas and HTF loop</td>
</tr>
<tr>
<td>Regenerable Offboard: Chemical Hydrides</td>
<td>Sodium Borohydride</td>
<td>Early Prototype</td>
<td>Aqueous solution</td>
<td>Exothermic hydrolysis</td>
<td>Aqueous solution in/out</td>
</tr>
<tr>
<td>High Surface Area Sorbents: Carbon</td>
<td>TBD</td>
<td>R&amp;D</td>
<td>Solid (low T?)</td>
<td>Endothermic desorption</td>
<td>H₂ gas (low T?)</td>
</tr>
</tbody>
</table>

1 HTF = Heat Transfer Fluid
Two type III compressed hydrogen tanks were designed to accommodate 5,000 and 10,000 psi storage pressures.

- Metal Boss (aluminum) for Tank Access (some constructions may also use a plug on the other end)
- Liner (polymer, metal, laminate)
  - HDPE 6.3 mm thick
  - Al 2.3 mm thick
- Wound Carbon Fiber Structural Layer with Resin Impregnation
  - (V_f CF:Epoxy 0.6:0.4; W_f 68/32)
- Impact Resistant Foam End Dome
- Damage Resistant Outer Layer (typically glass fiber wound)
A sodium alanate storage tank was designed to accommodate both high pressure and rapid heat exchange.
A sodium borohydride storage system was designed to accommodate solution storage and water management.

System Designs  Sodium Borohydride Components

- **Storage Tank**
- **Reactor**
- **Condenser**
- **Liquid Separator**

- $\text{H}_2$, water vapor & aqueous borates
- $\text{H}_2$ & water vapor
- Aqueous borates
- $\text{H}_2\text{O}$
- $\text{H}_2\text{O}$ vapor

**Dimensions**:
- Storage Tank: 696 mm x 80 mm
- Reactor: 222 mm x 57 mm
- Condenser: 16" x 16"
- Liquid Separator: 222 mm x 57 mm

**Additional Information**:
- $\text{H}_2$ at 70°C, RH 100%
- $\text{H}_2\text{O}$ at 14.3 gls, 145°C, RH 100%
- Heat transfer duty = 32 kW
- Air: 1740 std hr @ 50°C
- $\text{H}_2\text{O}$ at 12.7 gls, 70°C to borate and purge tank
Manufacturing processes and equipment are determined based on the individual component designs.

In this case, we assume a tank manufacturing process that loads the alanate in automated steps.
The complete storage systems require significant BOP for overall flow control and thermal management.
We have evaluated system designs based on the current technology, which does not always meet DOE targets.

<table>
<thead>
<tr>
<th>Issues</th>
<th>Comments/Impact of Meeting Target</th>
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</table>
| **Transient and Start-up** | • Additional components or advanced designs may be needed  
• May impact on-board efficiency and usable hydrogen stored                                      |
| **Material Life**        | • Limited amount of real-world data  
• Reformulated materials or advanced designs may be needed  
• Major impact on life-cycle cost  
• May impact on-board efficiency and usable hydrogen stored if material performance degrades over time |
| **Safety**               | • Not all systems will have the same inherent safety  
• Additional components will be needed                                                                                  |
| **Refueling**            | • Off-board requirements will be very different  
• Major impact on life-cycle cost and fuel chain efficiency  
• May impact on-board efficiency and usable hydrogen stored                                                                       |
Compressed hydrogen storage at 5,000 and 10,000 psi resulted in the lowest overall system weight.

- Sodium Borohydride
- Sodium Alanate
- 5,000 psi
- 10,000 psi

**2007 Target = 4.5 wt%**
Results  Volume Comparison

Sodium borohydride system with volume exchange design would be somewhat smaller than a 10,000 psi system.

Note: Volume results do not include void spaces between components (i.e., no packing factor was applied).
Factory cost of the sodium borohydride system is projected to be lower than the other systems evaluated thus far.

Note: Factory cost results do not include refueling costs over the life of the storage system.
Both basic research and system-level engineering need to continue if a viable storage system is to be developed.

<table>
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<tr>
<th>Technology</th>
<th>Potential Advantages</th>
<th>Potential Disadvantages</th>
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| 5,000 & 10,000 psi  | • High gravimetric density  
                       | • Most mature  
                       | • Relatively low fuel cost  
                       | • Relatively high fuel chain efficiency | • Will not meet volumetric density target  
                       |                                                             | • High factory cost  
                       |                                                             | • High-pressure storage |
| Sodium Alanate      | • Lower-pressure storage  
                       | • Relatively low fuel cost  
                       | • Relatively high fuel chain efficiency | • Low gravimetric density  
                       |                                                             | • High factory cost  
                       |                                                             | • High energy, P, T requirements  
                       |                                                             | • Slow startup |
| Sodium Borohydride  | • Conformable tank  
                       | • Low factory cost  
                       | • Low-pressure storage  
                       | • “Pumpable” | • One-tank design and water management challenges  
                       |                                                             | • Fuel cost and fuel chain efficiency TBD |
We will continue to support DOE and the Grand Challenge participants as they refine designs, processes, and materials.

- Preliminary results will continue to be refined based on developer/stakeholder feedback and progress.
- Off-board (WTT) analysis will begin on the initial cases.
- Task 1 report will summarize the results for the initial cases.
- Work with DOE, ANL and COEs to select and evaluate new cases.
Acknowledgment

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  - UTRC and MCell Teams
  - ANL, SNL, SRNL, LLNL
  - Hydrogen Storage and Delivery Tech Teams

- Rest of the project team
  - Gas Technology Institute, Prof. Robert Crabtree (Yale University), Prof. Daniel Resasco (U. of Oklahoma)