Hydrogen Storage  Project Overview

In 2004, DOE has selected TIAX to evaluate the lifecycle cost and WTW energy use and GHG emissions of various hydrogen storage options.

Well-to-Wheels

Storage System

Material

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

Vehicle Integration

• 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

Preliminary Results – Do Not Cite
We are in the process of completing the on-board assessment of the initial cases for reversible on-board and regenerable off-board categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Initial Cases</th>
<th>Tech Status¹</th>
<th>Storage State</th>
<th>H₂ Release</th>
<th>Refueling Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed and Liquid Hydrogen</td>
<td>5,000 &amp; 10,000 psi</td>
<td>Pre-commercial</td>
<td>Gas</td>
<td>Pressure regulator</td>
<td>cH₂ gas</td>
</tr>
<tr>
<td>Reversible On-board: Metal Hydrides and Alanates</td>
<td>Sodium Alanate (UTRC)</td>
<td>Proof of Concept</td>
<td>Solid</td>
<td>Endothermic desorption</td>
<td>cH₂ gas and HTF loop</td>
</tr>
<tr>
<td>Regenerable Off-board: Chemical Hydrides</td>
<td>Sodium Borohydride (MCell)</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>cH₂ gas (low T?)</td>
</tr>
</tbody>
</table>

¹ For discussion purposes only. Developer claims may vary.
As we finalize the sodium alanate and sodium borohydride cases, our findings show they will not meet the 2007 weight and volume targets.

<table>
<thead>
<tr>
<th>Storage Parameter</th>
<th>Units</th>
<th>2007 Target</th>
<th>Sodium Alanate</th>
<th>Sodium Borohydride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific energy (mass)</td>
<td>kWh/kg (kg H₂/kg)</td>
<td>1.5 (0.045)</td>
<td>0.53 (0.016)</td>
<td>1.1 (0.033)</td>
</tr>
<tr>
<td>Energy density (volume)¹</td>
<td>kWh/L (kg H₂/L)</td>
<td>1.2 (0.036)</td>
<td>0.61 (0.018)</td>
<td>0.96 (0.029)</td>
</tr>
<tr>
<td>Storage system cost</td>
<td>$/kWh ($/kg H₂)</td>
<td>6 (200)</td>
<td>11 (370)</td>
<td>4.7 (160)</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$/gge</td>
<td>3</td>
<td>TBD</td>
<td>TBD</td>
</tr>
<tr>
<td>Refueling rate</td>
<td>kg H₂/min</td>
<td>0.5</td>
<td>0.3</td>
<td>N/A</td>
</tr>
<tr>
<td>Min full-flow rate</td>
<td>(g/s)/ kW</td>
<td>0.02</td>
<td>0.004</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Note: Targets must be met simultaneously. Results are not accurate to the number of significant figures shown.

¹ Volume results do not include void spaces between components (i.e., no packing factor was applied).

Detailed cost, weight, and volume results and comparisons are presented in the preliminary results section.
Hydrogen Storage  Compressed Hydrogen

Under a previous DOE contract, we evaluated the cost of compressed H₂ tank systems designed to accommodate 5,000 and 10,000 psi 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
(Vf CF:Epoxy 0.6:0.4; Wf 68/32)

Impact Resistant Foam End Dome

Damage Resistant Outer Layer (typically glass fiber wound)
Hydrogen Storage  Sodium Alanate

Our sodium alanate (NaAlH₄) tank design is based on the 2004 literature, particularly UTRC’s published prototype and scaled-up concepts.

**TIAX Base Case Design with Insulation (5.6 kg H₂):**

- **HTF Manifold**
- **50 HX Tubes**
- **Sintered SS Filters**
- **Mid Tank**
- **Metal Foam**

**Legend**
- Al = Aluminum
- GF = Glass Fiber
- CF = Carbon Fiber
- HTF = Heat Transfer Fluid
- HX = Heat Exchanger
- SS = Stainless Steel
A sodium alanate storage system would be complex relative to a conventional compressed hydrogen (cH\textsubscript{2}) storage system.
Likewise, the sodium borohydride system as demonstrated by MCell consists of several process vessels with greater complexity than cH₂.
System-level design assumptions were used to develop individual component specifications and designs for each storage technology.

**Storage Tank**

- Hydrogen and water vapor
- Aqueous borates

**Condenser**

- Heat transfer duty: 32 kW
- H₂ (g) at 70°C, 100% RH
- H₂O (l) at 14.3 g/l, 70°C, 100% RH

**Liquid Separator**

- H₂, water vapor, and aqueous borates

**Reactor**

- H₂ vapor
- Aqueous borates

**Sodium Borohydride**

Component Design

Hydrogen Storage  Sodium Borohydride
Hydrogen Storage  System Design Issues

Processing costs are estimated based on manufacturing steps that could be scaled-up to high volume.

Tank Manufacturing

*Super Binder needs to be discovered.*
Hydrogen Storage  Sodium Alanate  

**Bottom-up BOP Cost**

DFMA® software is used to estimate balance of plant (BOP) component costs based on material, machining and assembly costs.

**Example: Pressure Relief Valve**

- Material = $5.80
- Assembly = $2.20
- Total = $8.00

R6000 series pressure relief valve from Circle seal controls, inc.
Preliminary Results – Do Not Cite

Hydrogen Storage  Sodium Alanate  System Cost Sensitivity - Multivariable

Multivariable sensitivity analysis is used to estimate the dependence and sensitivity of cost on/to the critical cost drivers.

<table>
<thead>
<tr>
<th>System Cost</th>
<th>$/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>14.40</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>1.67</td>
</tr>
<tr>
<td>Base Case</td>
<td>13.15</td>
</tr>
</tbody>
</table>

Base Case $13/kWh

Target Forecast: System Cost ($/kWH)

<table>
<thead>
<tr>
<th>Sensitivity Chart</th>
<th>Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2 Wt%</td>
<td>-0.73</td>
</tr>
<tr>
<td>NaAlH4 Cost ($/kg)</td>
<td>0.52</td>
</tr>
<tr>
<td>Media Volume Percentage</td>
<td>-0.08</td>
</tr>
<tr>
<td>CF Thickness</td>
<td>0.05</td>
</tr>
<tr>
<td>SS304 Cost</td>
<td>0.05</td>
</tr>
<tr>
<td>Prepreg T700S Carbon Fiber Cost</td>
<td>0.04</td>
</tr>
<tr>
<td>Preform polymer ligaments/foam</td>
<td>-0.03</td>
</tr>
<tr>
<td>Infiltration (aluminium)</td>
<td>0.03</td>
</tr>
<tr>
<td>Filling Sodium Alanates into Al Foam</td>
<td>-0.03</td>
</tr>
<tr>
<td>Laser Brazing Liner</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Measured by Rank Correlation

Forecast: System Cost ($/kWH)

5,000 Trials  67 Outliers

Base Case $13/kWh

SL/JB/012308/0D268 TIAX_Overview Presentation_DOE Analysis Mtg_Jan 06_final.ppt
Hydrogen Storage  Sodium Borohydride

The current designs for the sodium alanate and sodium borohydride systems will likely be heavier than compressed hydrogen storage.

![Weight Comparison Diagram]

H₂ Capacity = 5.6 kg

![Bar Graph]

Wt% = 3.2%

H₂ Capacity = 5.6 kg

2007 Target = 4.5 wt%

Sodium alanate and sodium borohydride systems will likely be similar in volume to compressed hydrogen storage systems.

2007 Target = 1.2 kWh/L

Hydrogen Storage  Sodium Borohydride  Cost Comparison

Although the factory cost of the NaBH₄ system will be much lower than the compressed hydrogen and alanate systems, fuel costs may be higher.

Next, we will finalize the Alanate and Sodium Borohydride on-board results, conduct a WTW analysis, and begin new technology assessments.

- Finalize results for the on-board Alanate and Sodium Borohydride systems and publish interim report
- Conduct off-board and vehicle integration analyses for Alanate and Sodium Borohydride systems
- Begin assessment of next storage technology - TBD
- Continue to work with DOE, H2A, other analysis projects, developers, National Labs, etc.
A complete Well-to-Wheels (WTW) assessment requires an evaluation of both the on-board and off-board performance and cost.

<table>
<thead>
<tr>
<th>Analysis Tasks</th>
<th>Tank-to-Wheels (On-board)</th>
<th>Well-to-Tank (Off-board)</th>
<th>Well-to-Wheels (Lifecycle)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Performance</td>
<td>✓ Material wt %</td>
<td>• Regeneration efficiency and requirements</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>✓ P, T requirement</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Thermo, kinetics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System-level Performance</td>
<td>✓ Storage system weight and volume</td>
<td>• WTT GHG emissions (g/MJ H₂)</td>
<td>• WTW GHG emissions (g/mile)</td>
</tr>
<tr>
<td></td>
<td>• Vehicle fuel economy (mi/kg H₂)</td>
<td>• WTT Primary energy use (MJ/MJ H₂)</td>
<td>• WTW Primary energy use (MJ/mile)</td>
</tr>
<tr>
<td></td>
<td>• Powertrain weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Thermal, power requirements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost</td>
<td>✓ Storage system factory cost:</td>
<td>• Equivalent H₂ selling price ($/kg)</td>
<td>• Ownership cost ($/mile)</td>
</tr>
<tr>
<td></td>
<td>✓ Material</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Subsystems</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Balance of plant</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>✓ Process</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

✓ = Completed for sodium alanate and sodium borohydride systems.
Hydrogen Storage      Next Steps      WTT Analysis Approach

Our WTT analysis will make use of existing (or planned) models to calculate cost and performance for each technology on a consistent basis.

Conceptual Design
- System layout and equipment requirements
- Safety equipment, site prep, land costs

Process Simulation
- Energy requirements
- High and low volume equipment costs
- Hydrogen cost (capital, O&M, etc.)

Capital Cost Estimates
- Equipment size/ specs
- Full volume equipment costs

GREET Post Processor
- WTT energy use
- WTT GHG

H2A Model
- Site Plans
- Site Plans
- Site Plans

1061 De Anza Blvd.
Cupertino, CA 95014
WTT energy use and GHG emissions will be calculated using the appropriate fuel cycle efficiencies and GHG factors.

**WTT GHG Emissions**

- Gasoline: Petroleum
- CH2: On-Site NG SR
- CH2: Central NG SR, Mobile Fueler
- CH2: Central NG SR, LH2 Truck
- CH2: On-Site Electrolysis, U.S. Mix
- MgH2 Slurry: SOM, Truck

**WTT Primary Energy**

- Vehicle CO2
- Fuel Cycle

Global Warming Potential
Weighted GHG emissions
CO₂, N₂O, CH₄
per unit fuel delivered

Non-Fossil Power

ILLUSTRATIVE
A complete ownership cost assessment will require that both vehicle purchase cost and operating costs be considered.

Ownership Cost Example

ILLUSTRATIVE
Preliminary Results – Do Not Cite

**Hydrogen Storage**  
**Next Steps**  
**Ownership Cost Assumptions**

Ownership costs results depend on a number of relatively simple assumptions.

<table>
<thead>
<tr>
<th>Preliminary Ownership Cost Assumptions</th>
<th>Gasoline ICEV</th>
<th>cH₂ FCV</th>
<th>NaBH₄ FCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Discount Factor on Capital</td>
<td>15%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td>Annual Mileage (mi/yr)</td>
<td>14,000</td>
<td>14,000</td>
<td>14,000</td>
</tr>
<tr>
<td>Vehicle Energy Efficiency Ratio</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Fuel Economy (mpgge)</td>
<td>30</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>H₂ Storage Requirement (kg H₂)</td>
<td></td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>Fuel Price ($/eq gal)</td>
<td>2.00</td>
<td>3.00</td>
<td>4.69</td>
</tr>
<tr>
<td>O&amp;M Cost ($/mi)</td>
<td>0.043</td>
<td>0.043</td>
<td>0.043</td>
</tr>
<tr>
<td>H₂ Storage Cost ($/kWh)</td>
<td></td>
<td>13</td>
<td>5</td>
</tr>
<tr>
<td>Vehicle Retail Price¹ ($/vehicle)</td>
<td>$19,246</td>
<td>$28,547</td>
<td>$27,055</td>
</tr>
</tbody>
</table>

¹ Projected, high-volume price with mark-ups. Includes glider, powertrain, and fuel storage costs.

ILLUSTRATIVE