Analyses of Hydrogen Storage Materials and On-Board Systems

Project ID # ST1

Cryo-compressed and Liquid Hydrogen System Cost Assessments

DOE Merit Review
June 10, 2008

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This presentation does not contain any proprietary, confidential, or otherwise restricted information
Overview

**Timeline**
- Start date: June 2004
- End date: June 2009
- 54% Complete

**Barriers**
- Barriers addressed
  - B. Cost
  - C. Efficiency
  - K. System Life Cycle Assessments

**Budget**
- Total project funding
  - DOE share = $1.5M
  - No cost share
- FY07 = $170k
- FY08 = $350k (plan)

**Collaboration**
- Argonne and other National Labs
- Centers of Excellence and other developers
- Tech Teams and other stakeholders
# Objectives

This project provides an independent cost assessment of the hydrogen storage technologies being developed for the DOE Grand Challenge.

<table>
<thead>
<tr>
<th>Objective</th>
<th>Description</th>
<th>Technology Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overall</strong></td>
<td>Help guide DOE and developers toward promising R&amp;D and commercialization</td>
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<td>pathways by evaluating the status of the various on-board hydrogen storage</td>
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<td>technologies on a consistent basis</td>
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<tr>
<td><strong>On-Board Assessment</strong></td>
<td>Evaluate or develop system-level designs to estimate weight, volume, and</td>
<td>• Liquid H₂&lt;br&gt;• Compressed H₂&lt;br&gt;(update)*</td>
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<tr>
<td></td>
<td>bottom-up factory cost for the on-board storage system</td>
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<tr>
<td></td>
<td>• Sodium Alanate&lt;br&gt;• SBH</td>
<td>• AC&lt;br&gt;• Liquid HC&lt;br&gt;• Ammonia Borane</td>
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<tr>
<td><strong>Off-Board Assessment</strong></td>
<td>Evaluate or develop designs and cost inputs to estimate refueling</td>
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<td></td>
<td>cost and Well-to-Tank energy use and GHG emissions for the fuel chain</td>
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<tr>
<td></td>
<td>• Liquid H₂&lt;br&gt;• Compressed H₂</td>
<td>• SBH*</td>
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<tr>
<td></td>
<td>• SBH*</td>
<td>• Liquid HC&lt;br&gt;• Ammonia Borane</td>
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</tbody>
</table>

* Results presented in Backup Slides.

Note that previously analyzed systems will continually be updated based on feedback and new information.

SBH = Sodium Borohydride, HC = Hydrocarbon, AC = Activated Carbon
The on-board cost and performance assessments are based on detailed technology assessment and bottom-up cost modeling.

### Technology Assessment
- Perform Literature Search
- Outline Assumptions
- Develop System Requirements and Design Assumptions
- Obtain Developer Input

### Cost Model and Estimates
- Develop BOM
- Specify Manufacturing Processes and Equipment
- Determine Material and Processing Costs
- Develop Bulk Cost Assumptions

### Overall Model Refinement
- Obtain Developer and Industry Feedback
- Revise Assumptions and Model Inputs
- Perform Sensitivity Analyses (single and multi-variable)

BOM = Bill of Materials
We completed on-board cryogenic system assessments and updated compressed and SBH cost estimates since the last Review.

- Completed cryo-compressed and preliminary liquid hydrogen (LH$_2$) on-board storage system cost assessments
  - Based on the LLNL 2$^{\text{nd}}$ generation cryo-compressed system with modifications
  - Included processing and detailed component cost estimates
  - Updated carbon fiber cost based on industry feedback ($13/lb fiber)
  - $14/kWh and $8/kWh (preliminary) for cryo-compressed and LH$_2$, respectively
- Updated compressed hydrogen (cH$_2$) on-board storage system estimates
  - Based on Tech Team and industry feedback for pressure requirements and material cost ($13/lb fiber)
  - $17/kWh and $27/kWh for 5,000 and 10,000 psi storage, respectively
- Updated Sodium Borohydride (SBH) on-board and off-board system estimates
  - Based on latest information provided by developers (primarily MCell and Rohm and Haas)
  - The higher SBH concentration assumed by MCell results in reduced on-board system size, but still does not meet the DOE 2010 targets
  - New off-board regeneration pathways could reduce costs, but the resulting selling price is still in excess of the goal of $2-3 \text{ kg/H}_2$ using the base case assumptions
The LLNL second generation tank design was the basis of our cryo-compressed storage system cost assessment.

**Key Cryo-compressed Tank Specifications**

- 151 L (38 gal, 10.7 kg) LH$_2$
- -253 °C min temp
- 5,000 psi (~350 bar) max pressure
- 3 mm (0.118”) thick Al liner
- 12 mm (0.47”) T700S carbon fiber, 60% fiber vol, 2.25 SF, 82% translation strength
- 40 mm (1.57”) vacuum gap w/ 40 layer of MLVI, 10-5 torr, ~1 W HT rate
- 3 mm (0.118”) thick SS304 outer shell

Additional modifications were made based on literature and developer feedback.
Processing and assembly/inspection costs were generated by developing process maps, and obtaining developer feedback.

Processing Steps for Cryo-tank Insulation, Assembly, and Inspection

- **SS Outer Tank Dome Stamping**
  - Capex: $1.3 M
  - # of Labor: 2
  - Cycle Time: 0.1 Mins

- **Inner Tank Assembly**
  - Capex: $50K
  - # of Labor: 2
  - Cycle Time: 30 Mins

- **Attach the MIL onto Composite Tank**
  - Capex: $200K
  - # of Labor: 2
  - Cycle Time: 30 Mins

- **Vacuum Space Piping Assembly**
  - Capex: $100K
  - # of Labor: 2
  - Cycle Time: 60 Mins

- **Cut the MIL into Required Shape**
  - Capex: $200K
  - # of Labor: 1
  - Cycle Time: 5 Mins

- **Laminate Multiple Insulation Layer**
  - Capex: $200K
  - # of Labor: 1
  - Cycle Time: 10 Mins

- **SS Outer Tank Body Welding (One End)**
  - Capex: $200K
  - # of Labor: 1
  - Cycle Time: 0.2 Mins

- **Welding (On One End)**
  - Capex: $200K
  - # of Labor: 1
  - Cycle Time: 0.5 Mins

- **Vacuum Space Piping Assembly**
  - Capex: $100K
  - # of Labor: 2
  - Cycle Time: 30 Mins

- **SS Outer Tank Body Welding**
  - Capex: $200K
  - # of Labor: 1
  - Cycle Time: 5 Mins

- **Outer Tank Assembly**
  - Capex: $200K
  - # of Labor: 2
  - Cycle Time: 60 Mins

- **Tank Insulation Vacuum Processing**
  - Capex: $300K
  - # of Labor: 0.1
  - Cycle Time: 1440 Mins / 10 tanks

- **Final System Inspection**
  - Capex: $200K
  - # of Labor: 1
  - Cycle Time: 30 Mins
The costs of key processing steps were estimated from capital equipment, labor, and other operating costs assuming high volumes (500,000 units/year) and a high level of automation.

<table>
<thead>
<tr>
<th>Cryo-compressed Key Processing Steps</th>
<th>Process Cost per Tank</th>
<th>% of Total Processing Cost</th>
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</thead>
<tbody>
<tr>
<td>Al Liner Fabrication, Assembly, &amp; Inspection</td>
<td>$76</td>
<td>13%</td>
</tr>
<tr>
<td>Carbon Fiber Winding Process</td>
<td>$56</td>
<td>10%</td>
</tr>
<tr>
<td>SS Vacuum Shell Fabrication</td>
<td>$14</td>
<td>2%</td>
</tr>
<tr>
<td>MLVI Wrapping</td>
<td>$108</td>
<td>18%</td>
</tr>
<tr>
<td>In-vessel Assembly</td>
<td>$42</td>
<td>7%</td>
</tr>
<tr>
<td>Ex-vessel Assembly</td>
<td>$128</td>
<td>22%</td>
</tr>
<tr>
<td>Vacuum Processing</td>
<td>$119</td>
<td>20%</td>
</tr>
<tr>
<td>Final Inspection</td>
<td>$40</td>
<td>7%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>$583</strong></td>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>

Processing costs make up 13% of the total cryo-compressed system cost.

Note: Details provided in Backup Slides.
Carbon fiber and cryogenic valves are the dominant costs, accounting for approximately 50% of the overall system cost.

**Cryo-compressed System Cost, 10.7 kg LH₂ Capacity (10.1 kg Usable) = $4,527 ($13.6/kWh)**

- **Carbon Fiber Composite, $1,448**
- **MLVI, $224**
- **SS Vacuum Shell, $308**
- **Al Liner & End Fittings, $130**
- **Balance of Vessel, $215**
- **Cryogenic Valves, $900**
- **Electronic Control System, $150**
- **Pressure Regulator, $250**
- **Other BOP, $541**
- **Assembly & Inspection, $329**
- **Hydrogen, $32**

*Component costs including processing*

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*a* Costs per kWh are based on a projected 10.1 kg (336 kWh) “usable” hydrogen assuming 94% drive cycle utilization (ANL 2006).

*b* The total system cost could be reduced by ~5% by using an aluminum shell rather than stainless steel.
Variability in the carbon fiber (CF) related costs and valve costs can significantly affect the overall cost of the cryo-compressed system.

### Key Sensitivity Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Baseline</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety Factor</td>
<td>2.35</td>
<td>1.80</td>
<td>3.0</td>
</tr>
<tr>
<td>CF Prepreg (Fiber &amp; Matrix) Cost ($/lb)</td>
<td>16.6</td>
<td>12.8</td>
<td>20.4</td>
</tr>
<tr>
<td>Cryogenic Control Valve Cost ($)</td>
<td>150</td>
<td>100</td>
<td>250</td>
</tr>
<tr>
<td>CF Tensile Strength (MPa)</td>
<td>2,940</td>
<td>2,550</td>
<td>3,100</td>
</tr>
<tr>
<td>Cryogenic Relief Valve Cost ($)</td>
<td>75</td>
<td>40</td>
<td>150</td>
</tr>
<tr>
<td>Pressure Regulator Cost ($)</td>
<td>250</td>
<td>150</td>
<td>350</td>
</tr>
<tr>
<td>SS304 Cost ($/kg)</td>
<td>4.7</td>
<td>3.7</td>
<td>5.8</td>
</tr>
<tr>
<td>CF Translation Strength (%)</td>
<td>81.5%</td>
<td>78%</td>
<td>85%</td>
</tr>
<tr>
<td>MLVI Cost ($/kg)</td>
<td>50</td>
<td>35</td>
<td>65</td>
</tr>
</tbody>
</table>

#### Comments/Source

- **Safety Factor**: Baseline is typical industry standard; Min and Max based on discussions with Quantum and Dynatek (2005).
- **CF Prepreg (Fiber & Matrix) Cost ($/lb)**: Based on discussion w/ Toray (2007); re: T700S fiber ($10-$16/lb, $13/lb baseline); 1.27 prepreg/fiber ratio (DuVall 2001).
- **Cryogenic Control Valve Cost ($)**: Discussions with Circle Seal (2007), Valcor (2007), and tank developers (2007).
- **CF Tensile Strength (MPa)**: Baseline from TIAX netting analysis using optimized wrap angle for pressure vessel geometry; Min from Toray T700S data sheet (2007); Max assumes 5% increase over baseline; 60% fiber by volume assumed.
- **Cryogenic Relief Valve Cost ($)**: Discussions with Circle Seal (2007) and Swagelock (2007) vendors.
- **Pressure Regulator Cost ($)**: Discussions with TESCOM vendor and tank developers (2007).
- **SS304 Cost ($/kg)**: Baseline, Min, and Max are the average, min, and max monthly costs, respectively, from Sep '06 – Aug '07 (MEPS International 2007) deflated to 2005$ by ~6%/yr.
- **CF Translation Strength (%)**: Based on Quantum (2005) for 5,000 psi CF tanks.
- **MLVI Cost ($/kg)**: Estimates based on discussions with MPI (2007).
The cryo-compressed tank design was used as a starting point for the liquid hydrogen system cost assessment. 

**Sketch of Key LH₂ System Components**

Modifications were made based on literature and developer feedback.
Control and relief valves account for a combined 30% of the total cost, but costs are relatively evenly distributed among major components.

Preliminary Liquid System Cost, 
10.7 kg LH₂ Capacity (10.1 kg Usable) = $2,715 ($8.1/kWh)

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a Costs per kWh are based on a projected 10.1 kg (336 kWh) "usable" hydrogen assuming 94% drive cycle utilization (ANL 2006) for cryo-compressed drive cycle efficiency. Utilization needs to be updated for LH₂.

b The total system cost could be reduced by ~8% by using an aluminum shell rather than stainless steel.
Variability in the cryogenic valve costs can significantly affect the overall cost of the liquid system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Base-line</th>
<th>Min</th>
<th>Max</th>
<th>Comments/Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryogenic Control Valve Cost ($)/unit</td>
<td>105</td>
<td>70</td>
<td>175</td>
<td>Discussions with Circle Seal (2007), Valcor (2007), and tank developers (2007)</td>
</tr>
<tr>
<td>Cryogenic Relief Valve Cost ($)/unit</td>
<td>50</td>
<td>35</td>
<td>75</td>
<td>Discussions with Circle Seal (2007) and Swagelock (2007) vendors</td>
</tr>
<tr>
<td>Pressure Regulator Cost ($)/unit</td>
<td>150</td>
<td>100</td>
<td>250</td>
<td>Discussions with Circle Seal (2007), Valcor (2007), and tank developers (2007)</td>
</tr>
<tr>
<td>SS 304 Cost ($)/kg</td>
<td>4.7</td>
<td>3.7</td>
<td>5.8</td>
<td>Baseline, Min, and Max are the average, min, and max monthly costs, respectively, from Sep ’06 – Aug ’07 (MEPS International 2007) deflated to 2005$ by ~6%/yr</td>
</tr>
<tr>
<td>Electronic Control Box Cost ($)/unit</td>
<td>150</td>
<td>100</td>
<td>200</td>
<td>Estimate based on interviews with technology experts (includes microcontroller, valve relays, analog inputs, and power regulator)</td>
</tr>
<tr>
<td>MLVI Cost ($)/kg</td>
<td>50</td>
<td>35</td>
<td>65</td>
<td>Estimates based on discussions with MPI (2007)</td>
</tr>
</tbody>
</table>

Baseline = $8.1/kWh
The cryo-compressed and liquid hydrogen on-board systems are projected to be cheaper than pressurized-only options.

$\text{System Cost, } $/\text{kWh}$

<table>
<thead>
<tr>
<th>System</th>
<th>10.7 kg LH$_2$</th>
<th>~5.6 kg H$_2$</th>
<th>2010 Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryo-Compressed</td>
<td>$10.7/\text{kWh}$</td>
<td>$15.2/\text{kWh}$</td>
<td>$26.7/\text{kWh}$</td>
</tr>
<tr>
<td>LH$_2$ (preliminary)</td>
<td>$8.1/\text{kWh}$</td>
<td>$11.4/\text{kWh}$</td>
<td>$17.1/\text{kWh}$</td>
</tr>
<tr>
<td>Sodium Borohydride</td>
<td>$4.8/\text{kWh}$</td>
<td>$4.8/\text{kWh}$</td>
<td>$4.8/\text{kWh}$</td>
</tr>
<tr>
<td>Sodium Alanate</td>
<td>$8.1/\text{kWh}$</td>
<td>$8.1/\text{kWh}$</td>
<td>$8.1/\text{kWh}$</td>
</tr>
<tr>
<td>5,000 psi d</td>
<td>$11.4/\text{kWh}$</td>
<td>$11.4/\text{kWh}$</td>
<td>$11.4/\text{kWh}$</td>
</tr>
<tr>
<td>10,000 psi d</td>
<td>$17.1/\text{kWh}$</td>
<td>$17.1/\text{kWh}$</td>
<td>$17.1/\text{kWh}$</td>
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</table>

$\text{$/kWh}=13.6 \text{ a}$

- a Normalizing the cryo-compressed and liquid systems for 5.6 kg of usable hydrogen storage results in system costs of approximately $20/kWh and $14/kWh, respectively.
- b An aluminum shell (rather than SS) offers approximately 5% and 8% costs savings for the cryo-compressed and liquid systems, respectively.
- c The sodium alanate system requires high temp waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.

$\text{2010 Target ($4/kWh$)}$
The liquid system meets the 2010 weight target, and the cryo-compressed system would also meet the target with an aluminum shell\(^a\).

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<table>
<thead>
<tr>
<th>System Weight, kg</th>
<th>Cryo-compressed (^b)</th>
<th>LH(^b) (preliminary)</th>
<th>Sodium Borohydride</th>
<th>Sodium Alanate (^c)</th>
<th>5,000 psi</th>
<th>10,000 psi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wt(%)=5.5 (^a)</td>
<td>6.5 (^a)</td>
<td>3.3</td>
<td>5.3</td>
<td>4.0</td>
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</tbody>
</table>

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\(^a\) Normalizing the cryo-compressed and liquid systems for 5.6 kg of usable hydrogen storage results in system gravimetric capacities of approximately 4.0 wt\(\%\) and 4.4 wt\(\%\), respectively.

\(^b\) An aluminum shell (rather than SS) increases gravimetric capacities to 7wt\(\%\) and 9 wt\(\%\) for the cryo-compressed and liquid systems, respectively.

\(^c\) The sodium alanate system requires high temp waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
None of the on-board storage systems evaluated to date meet the 2010 volume target given our base case assumptions.

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

a Normalizing the cryo-compressed and liquid systems for 5.6 kg of usable hydrogen storage results in system volumetric capacities of approximately 28 g/L each.
b The sodium alanate system requires high temp waste heat for hydrogen desorption, otherwise the usable hydrogen capacity would be reduced.
Future Work

We will focus on the liquid hydrocarbon- (HC) and ammonia borane-based hydrogen storage systems for the remainder of FY08.

- Complete on-board assessments of APCI liquid HC system and begin assessment of ammonia borane system
  - Solicit feedback from developers and coordinate with ANL on final system requirements and design assumptions
  - Specify manufacturing processes and equipment and determine material and processing costs
  - Use sensitivity analysis to account for uncertainties and potential future technology developments
- Conduct off-board analyses for the liquid HC and ammonia borane systems
  - Finalize designs and cost inputs for the complete fuel chain
  - Estimate refueling cost and Well-to-Tank energy use and GHG emissions for the fuel chain
- Continue to work with DOE, H2A, other analysis projects, developers, National Labs, and Tech Teams to revise and improve past system models
  - Including finalize liquid hydrogen storage system results based on developer (e.g., Air Liquide) and stakeholder feedback
We have completed certain aspects of on-board and off-board evaluations for eight hydrogen storage technologies.

<table>
<thead>
<tr>
<th>Analysis To Date</th>
<th>cH₂</th>
<th>Alanate</th>
<th>MgH₂</th>
<th>SBH</th>
<th>Cryo-comp</th>
<th>LH₂</th>
<th>AC</th>
<th>Liquid HC</th>
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<tbody>
<tr>
<td><strong>On-Board</strong></td>
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<tr>
<td>Review developer estimates</td>
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<tr>
<td>Develop process flow diagrams and system energy balances</td>
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<td>WIP</td>
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<tr>
<td>Independent performance assessment (wt, vol)</td>
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<td>WIP</td>
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<tr>
<td>Independent cost assessment</td>
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<td>√</td>
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<td>WIP</td>
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<td><strong>Off-Board</strong></td>
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<tr>
<td>Review developer estimates</td>
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<tr>
<td>Develop process flow diagrams and system energy balances</td>
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<tr>
<td>Independent performance assessment (energy, GHG)</td>
<td>√</td>
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<td>Independent cost assessment</td>
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<tr>
<td><strong>Overall</strong></td>
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<tr>
<td>WTT analysis tool**</td>
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<tr>
<td>Solicit input on TIAX analysis</td>
<td>√</td>
<td>√</td>
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<td>WIP</td>
</tr>
<tr>
<td>* Preliminary results under review.</td>
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</tr>
<tr>
<td>a Working with ANL and H2A participants on separate WTT analysis tools.</td>
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</tbody>
</table>

* Preliminary results under review.
a Working with ANL and H2A participants on separate WTT analysis tools.

WIP = Work in progress

= Not part of current SOW