Insulated Pressure Vessels for Vehicular Hydrogen Storage

Salvador Aceves, Gene Berry, Francisco Espinosa, Tim Ross, Andrew Weisberg
Lawrence Livermore National Laboratory
May 18, 2006

This presentation does not contain any proprietary or confidential information
Overview

Timeline
• Start date: October 2004
• End date: September 2006
• Percent complete: 70%

Budget
• Total project funding
  – DOE: $515 k
  – SCAQMD: $350 k
• Funding received in FY05:
  – $225 k
• Funding for FY06:
  – $290 k

Barriers
• B. Weight and volume
• H. Sufficient fuel storage for acceptable vehicle range
• L. Hydrogen boil-off

Targets
• 2007 DOE volume target
• 2010 DOE weight target

Partners
• Demonstrated cryotank technology with SCI and SunLine, funded by SCAQMD
• Spencer composites, CRADA with Automotive Composites Consortium, aerospace work funded by DARPA
Rationale: Our Cryogenic *Capable* Vessels can Store either Gaseous H₂ or LH₂, Capturing the Advantages of Both

Cryogenic vessels operate across the entire H₂ phase diagram
A conventional tank with 8 kg LH₂ has 8 Watt-days of dormancy. An insulated 5000 psi vessel has 56 Watt-days of thermal endurance, which doubles as fuel (2 kg H₂) is consumed by driving.

A 5000 psi vessel can absorb an additional 48 Watt-days of heat (green) by warming to 90 K before venting.

Driving 120-160 miles consumes 2 kg H₂, isentropically cooling the remaining 6 kg of H₂ to 80 K, doubling the thermal endurance (red).

A conventional tank with 8 kg LH₂ warms to 28 K after absorbing 8 Watt-days of heat (blue) and vents.
Cooling high pressure H$_2$ can increase safety. Removing energy from the gas radically reduces theoretical burst energy at cryogenic temperatures.
Rationale: Why Insulate Pressure Vessels?

- Cryogenics lowers pressure vessel cost (2-3x less fiber for given capacity)
- Flexible refueling continuously matches storage method to drivers’ current needs (cost, range, safety)
- Vessel temperature partially self-regulated (cools when driven – more so when fuller and/or warmer)
- Greatly extended dormancy (~5-10x vs. LH$_2$) increasing as fuel is used
- Cold H$_2$ has less stored PV energy
- Adaptable for solid state storage materials (e.g. carbon)
Objective: Demonstrate long range (200 to 500 mile) hydrogen hybrid vehicle with insulated pressure vessel

The vehicle

- Toyota Prius converted to H₂ fuel by Quantum.
- Originally equipped with 5000 psi 68 L pressure vessels (1.6 kg H₂)
- Est. fuel economy 50 miles/ kg H₂

LLNL Cryotank

- 151 L capacity
- stores 3.5 kg H₂ at 300 K, 5000 psi
- stores 6 kg H₂ at 150 K, 5000 psi
- stores 10.7 kg LH₂ at 20 K, 1 atm
- Meets DOE 2010 weight goal and DOE 2007 volume goal using LH₂ (297 Liter vacuum jacket volume)
Approach: we are designing, building, testing and demonstrating a compact insulated pressure vessel for long range hydrogen vehicles.
Accomplishments: We demonstrated refueling with both liquid and compressed hydrogen with our first generation insulated pressure vessel

- Concept successfully demonstrated in SunLine pickup (SCAQMD funding)
- Wrote set of certification standards (funded by AQMD)
- Meets 2007 DOE weight target when full of LH$_2$
- *Vertical* orientation
Our second generation insulated pressure vessel improves orientation, weight and volume

- **Horizontal orientation**
- 51% internal/external volume efficiency – lots of room for improvement
- 48” long- Fits across compact pickup bed or inside trunk of midsize car
- Meets 2010 DOE weight goal and 2007 volume goal when full of LH$_2$
- Planned refueling and thermal management testing
- Planned demonstration of range and dormancy on H$_2$ Prius
Thermal and mechanical integration and instrumentation steps

1. Attach instrumentation and heater to inner pressure vessel
2. Install mechanical support rings and multilayer insulation
3. Slide insulated vessel into outer vacuum vessel
4. Weld vacuum vessel and install flanges for high pressure lines
We are conducting extensive vessel testing to verify performance and guarantee safety.

1. Vacuum test
2. Pressure test
3. Cryogenic cycling and dormancy test
4. Fueling test
## Detailed listing of weights and volumes of vessels and components for first and second generation cryotanks

<table>
<thead>
<tr>
<th>cryotank components</th>
<th>first generation</th>
<th>second generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>9.5 135</td>
<td>10.7 151</td>
</tr>
<tr>
<td>Internal pressure vessel</td>
<td>65 33</td>
<td>68 34</td>
</tr>
<tr>
<td>Insulation and vacuum shell</td>
<td>117 212</td>
<td>65 112</td>
</tr>
<tr>
<td><strong>Total, vessel &amp; vac. shell</strong></td>
<td><strong>191 380</strong></td>
<td><strong>144 297</strong></td>
</tr>
<tr>
<td>Computer</td>
<td>2.3 2.5</td>
<td>0.2 0.5</td>
</tr>
<tr>
<td>Computer Stand</td>
<td>2.3 0.5</td>
<td>0 0</td>
</tr>
<tr>
<td>Electronic boards</td>
<td>23 50</td>
<td>9 15</td>
</tr>
<tr>
<td>Level Sensor Box</td>
<td>0.9 2</td>
<td>0 0</td>
</tr>
<tr>
<td>Valve box</td>
<td>0 0</td>
<td>17 18</td>
</tr>
<tr>
<td>Pressure Transmitters</td>
<td>0.2 0.05</td>
<td>0.2 0.05</td>
</tr>
<tr>
<td>Pressure Gauges</td>
<td>2.7 0.5</td>
<td>2.7 0.5</td>
</tr>
<tr>
<td>Pressure Regulator</td>
<td>1.1 0.23</td>
<td>1.1 0.2</td>
</tr>
<tr>
<td>ASME Relief Valve</td>
<td>7 1.4</td>
<td>2.7 0</td>
</tr>
<tr>
<td>Circle Seal cryogenic valves</td>
<td>19.5 3.9</td>
<td>0 0</td>
</tr>
<tr>
<td>Nupro Relief Valves</td>
<td>0.5 0.09</td>
<td>0.2 0.05</td>
</tr>
<tr>
<td>Vent and fill valve</td>
<td>0.3 0.05</td>
<td>1.8 0</td>
</tr>
<tr>
<td>Rupture Disc</td>
<td>0.2 0.05</td>
<td>0.2 0.05</td>
</tr>
<tr>
<td>LH2 Fill Hose</td>
<td>10.7 10</td>
<td>0 0</td>
</tr>
<tr>
<td>Tank Frame</td>
<td>9.1 1.3</td>
<td>7 0.6</td>
</tr>
<tr>
<td>Heat Exchanger</td>
<td>6.8 5</td>
<td>3.2 0</td>
</tr>
<tr>
<td>Explosion proof (EP) Cond.</td>
<td>5 5</td>
<td>0 0</td>
</tr>
<tr>
<td>Non EP Conduit</td>
<td>5 5</td>
<td>1.4 1.4</td>
</tr>
<tr>
<td>EP Enclosure</td>
<td>11.4 14</td>
<td>0 0</td>
</tr>
<tr>
<td>Tubing</td>
<td>13.6 5</td>
<td>6.8 2.5</td>
</tr>
<tr>
<td>Aluminum Plate</td>
<td>9.1 3</td>
<td>0 0</td>
</tr>
<tr>
<td>Wire</td>
<td>13.6 2.7</td>
<td>4.5 0.9</td>
</tr>
<tr>
<td>Grounding Lugs</td>
<td>1.4 0.3</td>
<td>0.1 0.03</td>
</tr>
<tr>
<td>Misc. Nuts and Bolts</td>
<td>2.3 0.5</td>
<td>1.1 0.2</td>
</tr>
<tr>
<td>Miscellaneous Fittings</td>
<td>1.8 0.4</td>
<td>1.8 0.4</td>
</tr>
<tr>
<td><strong>Total for accessories</strong></td>
<td><strong>150 113</strong></td>
<td><strong>61 40</strong></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>341 493</strong></td>
<td><strong>205 337</strong></td>
</tr>
</tbody>
</table>

First generation

Second generation
Our second generation insulated pressure vessels filled with LH$_2$ can meet the 2007 volume and 2010 weight DOE targets (neglecting accessories)

**Weight targets**

<table>
<thead>
<tr>
<th>Material</th>
<th>2007 goal</th>
<th>2010 goal</th>
<th>2015 goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_2$</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>80 K CH$_2$</td>
<td>1.0</td>
<td>1.5</td>
<td>2.0</td>
</tr>
<tr>
<td>LH$_2$</td>
<td>1.5</td>
<td>2.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

**Volume targets**

<table>
<thead>
<tr>
<th>Material</th>
<th>2007 goal</th>
<th>2010 goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH$_2$</td>
<td>0.2</td>
<td>0.4</td>
</tr>
<tr>
<td>80 K CH$_2$</td>
<td>0.4</td>
<td>0.8</td>
</tr>
<tr>
<td>LH$_2$</td>
<td>0.8</td>
<td>1.6</td>
</tr>
</tbody>
</table>
Future work: we will develop improved insulated pressure vessels that can meet the DOE 2010 volume goal using LH$_2$

Current vessel

- 35 mm insulation thickness
- Volumetric efficiency: 51%
- 297 L, 1.2 kWh/L
- meets 2007 DOE volume goal with 1 atm LH$_2$

Custom fabricated vessel

- 12 mm insulation thickness
- Volumetric efficiency: 64%
- eliminated Al-Steel transition piece
- Embedded support rings
- 238 L, 1.5 kWh/L
- meets 2010 volume goal
Summary: we are developing an insulated pressure vessel that meets the DOE targets and achieves up to 500 mile driving range in a H₂ hybrid

- Our flexibly fueled insulated pressure vessels provide benefits with respect to compressed and liquid H₂ vessels
  - More compact than CH₂ tanks
  - Lower evaporative losses and storage energy than LH₂ tanks
- We designed, built, and tested a horizontal cryogenic vessel which meets the 2010 DOE weight and 2007 DOE volume goals on LH₂
  - Substantially more compact than previous generation vessel
  - Will be installed in a long range hydrogen hybrid vehicle to verify thermal endurance and range.
- We designed an advanced insulated pressure vessel concept to meet the DOE 2010 volume goal
Supplemental slides
Responses to reviewers’ comments:

- **It is not clear that insulated pressure vessels have advantages with respect to traditional LH₂ tanks.** Insulated pressure vessels offer energy savings through flexible refueling and greatly extended dormancy (~10x), virtually eliminating evaporative losses.

- **It is difficult to see how the 2015 or even the 2010 targets can be met.** Our current design meets the 2010 weight goal. We can meet the 2010 volume goal by increasing the volumetric efficiency. Achieving the 2015 targets will need a combination of pressurized LH₂, higher performance pressure vessels and/or conformability.

- **Mass and volume numbers are impressive but do not seem to include the full system.** We have listed the weight and volume of our vessels, vacuum jacket, and all accessories.

- **PI might benefit to collaborate with tank builders for future work.** We are working more closely with Structural Composites Industries on developing custom fabricated vessels to improve the volume performance of our future cryogenic capable tanks.
Publications and presentations

**Patents**

**Publications in Books and Technical Journals**

**Publications in Refereed Proceedings**

**Technical Report**
- **Proposed Standards for Hydrogen and Liquefied Natural Gas Insulated Pressure Vessels**, Report to the South Coast Air Quality Management District August 2004

**Presentations**
- **Cryogenic Hydrogen Storage**, Salvador Aceves, Invited Presentation, Materials for the Hydrogen Economy, September 2005
Critical Assumptions and Issues

- Need to demonstrate high insulation performance
- Need to demonstrate incorporation in the vehicle
- Need to demonstrate long vehicle range