Development of Improved Composite Pressure Vessels for Hydrogen Storage

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Lincoln Composites
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Project ID# ST047

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Overview

Timeline
• Start 1 Feb 2009
• End 31 Jan 2014
• 50% complete

Budget
• Project funding $2,000,000
  – DOE share $1,600,000
  – Contractor share $400,000
• FY10 = $250,000
• FY11 = $150,000

Barriers
• Barriers addressed
  – A. System Weight and Volume
  – B. System Cost
  – G. Materials of Construction
• Targets (2010)
  – Gravimetric capacity > 4.5%
  – Volumetric capacity > 0.045 kg H₂/L
  – Storage system cost - TBD

Partners
• HSECoE
  SRNL, PNNL, LANL, JPL, NREL, UTRC, GM, Ford, LC, Oregon State Univ, UQTR
• Project lead = Don Anton, SRNL
Objectives - Relevance

• Meet DOE 2010 and 2015 Hydrogen Storage Goals for the storage system by identifying appropriate materials and design approaches for the composite container

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravimetric capacity</td>
<td>&gt; 4.5%</td>
<td>&gt; 5.5%</td>
</tr>
<tr>
<td>Volumetric capacity</td>
<td>&gt; 0.028 kg H₂/L</td>
<td>&gt; 0.040 kg H₂/L</td>
</tr>
<tr>
<td>Storage system cost</td>
<td>TBD</td>
<td>TBD</td>
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</tbody>
</table>

• Maintain durability, operability, and safety characteristics that already meet DOE guidelines for 2010 and 2015

• Work with HSECoE Partners to identify pressure vessel characteristics and opportunities for performance improvement, in support of support of system options selected by HSECoE Partners

• Develop high pressure tanks as are required to:
  – Enable hybrid tank approaches to meet weight and volume goals
  – Allow metal hydrides with slow charging kinetics to meet charging goals
Phase 1 Approach

- *Establish and document baseline* design, materials, and manufacturing process
- *Evaluate potential improvements* for design, material, and process to achieve cylinder performance improvements for weight, volume, and cost
- *Down select* most promising engineering concepts as applicable to HSECoE selected systems
- *Evaluate* design concepts and ability to meet Go/No-Go requirements for moving forward
- *Document progress* in periodic reports and support HSECoE Partner meetings and teleconferences
Phase 1 Approach

• Material evaluation for cost and weight reduction, internal volume increase
  – Higher strength boss materials
  – Alternate fiber reinforcements
  – Reduced safety factors
  – Thinner liner

• Evaluate design and materials against operating requirements of storage systems selected by HSECoE Partners
  – Identify new solutions
  – Identify gaps for further development

• Maintain durability, operability, and safety
Progress – Baseline Design/Materials

- **Design**
  - Fiber reinforced composite
  - Plastic liner / permeation barrier
  - Metallic end bosses

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Service pressure</td>
<td>5000 psi</td>
<td>345 bar</td>
</tr>
<tr>
<td>Gas settling temperature</td>
<td>59 °F</td>
<td>15 °C</td>
</tr>
<tr>
<td>Maximum fill pressure</td>
<td>6500 psi</td>
<td>448 bar</td>
</tr>
<tr>
<td>Service life</td>
<td>20 years</td>
<td></td>
</tr>
<tr>
<td>Gas fill temperature limits</td>
<td>-40 to +149 °F</td>
<td>-40 to +65 °C</td>
</tr>
<tr>
<td>Operating temperature limits</td>
<td>-40 to +180 °F</td>
<td>-40 to +82 °C</td>
</tr>
<tr>
<td>Proof test pressure</td>
<td>7500 psi</td>
<td>517 bar</td>
</tr>
<tr>
<td>Minimum rupture pressure</td>
<td>11,700 psi</td>
<td>807 bar</td>
</tr>
<tr>
<td>Cylinder external diameter</td>
<td>21.4 inches</td>
<td>543 mm</td>
</tr>
<tr>
<td>Cylinder length at zero pressure</td>
<td>63 inches</td>
<td>1600 mm</td>
</tr>
<tr>
<td>Cylinder length at maximum fill pressure</td>
<td>63.34 inches</td>
<td>1609 mm</td>
</tr>
<tr>
<td>Cylinder empty weight</td>
<td>231 lbs</td>
<td>105 kg</td>
</tr>
<tr>
<td>Cylinder volume at zero pressure</td>
<td>15,865 cu. in.</td>
<td>260 L</td>
</tr>
<tr>
<td>Cylinder volume at service pressure</td>
<td>16,132 cu. in.</td>
<td>264.4 L</td>
</tr>
<tr>
<td>Cylinder internal diameter</td>
<td>19.2 inches</td>
<td>488 mm</td>
</tr>
</tbody>
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- **Materials**
  - T-700 Carbon fiber
  - Epoxy resin
  - HDPE liner
  - AA 6061-T6 bosses
Progress - Alternate Boss Material

- **Baseline is 6061-T6 Aluminum**
  - 316 Stainless Steel is another common material, used at higher pressures
  - Yield strength is not high for 6061-T6 or 316 SS
  - Stainless steel is significantly heavier and more expensive, but has better tensile strength and fatigue properties

- **Investigating 7075 Aluminum to reduce weight and cost**
  - High strength would allow reduction in boss size and allow aluminum use at high pressures
  - Proper heat treat is a challenge to get correct strength properties, avoid embrittlement

- **Accomplishments**
  - Near net shaped bosses machined from 7075-T6 Aluminum
  - Bosses have been heat treated to intended condition
  - Tensile testing confirms proper heat treatment

- **Benefits**
  - Yield strength is 2 times that of 6061-T6 or 316 SS
  - Weight of finished boss could be about 1/2 that of 6061-T6, 1/5 that of 316 SS
  - Cost of finished boss could be same to 1.5 times that of 6061-T6, 1/5 that of 316 SS
Progress - Alternative Fibers

• Baseline Fiber – T-700
  – PAN based
  – Excellent manufacturability

• Five alternate carbon fibers tested
  – Two indicated higher strength than baseline
  – Four potentially lower cost per pound
  – Initial testing did not meet expectations, strength/cost did not indicate improvement

• LC worked with two fiber suppliers to obtain improved strength
  – Subsequent testing with these fibers matched the baseline strength in burst test
  – Three fibers now could be used interchangeably

• Benefits of multiple qualified vendors
  – Expected to result in 10% to 15% lower fiber costs
  – Improved availability in times of fiber shortage
Progress – Reduced Safety Factor

• Safety factor influences performance
  – Fiber stress rupture and cyclic fatigue are directly related to stress ratio
  – Damage tolerance is affected

• Reduction in safety factor from 2.25 to 2.00 is planned
  – Studies indicate that high reliability is maintained
  – Field experience indicates safe operation as long as damage tolerance is addressed
  – Damage tolerance can be addressed by other design and testing

• Benefits of reduced safety factor
  – Cost of carbon fiber is reduced by about 10%
  – Potential for increased cylinder volume by about 2%
  – Potential for weight reduction by about 5%
  – Must be balanced against cost, envelope, and weight of other means of damage protection, if necessary
Progress – Thinner Liner

• Liner serves as a permeation barrier and winding mandrel
  – Permeation reduction is being investigated, 40% reduction currently feasible
  – Manufacturability issues with using a thinner liner (i.e. winding mandrel) are being addressed

• Benefits of thinner liner
  – Reduction in tare weight, about 4% of cylinder
  – Increase in internal volume, about 2%
  – Potential for reduction in cost, depending on cost of new liner materials
Progress – Thinner Liner
Alternate Liner Material Permeation versus Cost

- HDPE is baseline (1,1)
- Comparison of relative cost and permeation rates
- HDPE fillers show 40% reduction with limited cost increase
- Alternate materials show promise of significant permeation reduction
- Some alternate materials are prohibitively expensive
Future Work

• Alternate boss material
  – Incorporate 7075 aluminum into new designs
• Alternate fibers
  – Continue to monitor strength levels of top 3 fibers
• Reduced safety factor
  – Continue to evaluate damage tolerance of alternate fibers
  – Continue to evaluate improved damage tolerance using toughened epoxy resins
• Thinner liner
  – Continue to evaluate permeation reduction
    • Testing of full cylinders
    • Testing of additional liner materials
• Evaluate producibility of new liner materials
Future Work – Phase 2

• Support cylinder design activity of HSECoE team for baseline systems
• Define materials and demonstrate liner and resin matrix suitability for extreme high and low temperatures expected for baseline systems
  – Candidates exist for high temperature resin and liner
  – Candidates exist for low temperature resin
  – Low temperature liner is being investigated
• Provide means to incorporate hardware identified for selected designs
  – Internal and external insulation
  – Heat transfer hardware
Accomplishments

• Higher strength aluminum boss material confirmed
  – Lighter weight
• Alternate fibers qualified
  – Reduces cost, improves availability
• Reduced safety factor selected for carbon fiber
  – Reduces cost, weight
• Permeation reduced by 40%
  – Allows thinner wall, lighter weight
• 3 Face to Face Meetings with HSECoE Team in 2010
• Tech Team Review Meeting February 16-17, 2011, Washington, DC
Collaborations

• Periodic teleconferences with PNNL and team on pressure vessels and containment
• Periodic teleconferences with UTRC and team on IPPSS Modeling
• Periodic teleconferences with GM supporting storage system modeling
• Working with aerospace industry colleagues regarding stress rupture, including NASA, JPL
• Pressure vessel and containment group meeting was held at LC in November 2010
• Co-authored paper/presentation, “Potential Diffusion-Based Failure Modes of Hydrogen Storage Vessels for ON-Board Vehicular Use”, Yehia Khalil (UTRC), Norman Newhouse (LC), Kevin Simmons (PNNL), Daniel Dedrick (SNL), at AIChE 2010 Annual Meeting, Salt Lake City, November 2010
Summary

• Design, material and process improvements have been identified that support efforts to meet DOE 2010 and 2015 goals for the storage system

• Identified improvements to date include
  – Reduced cost and weight from improved boss material
  – Reduced fiber cost by developing alternate fibers of equal strength
  – Reduced cost, potential reduced weight and increased volume, by reducing carbon fiber factor of safety
  – Reduced weight, increased volume, by reducing liner thickness

• Specific value of improvements is dependent on overall system design
  – For cylinder itself, approximately 11% lower weight, 4% larger internal volume, 10% lower cost
  – For total system, influence of other components is needed