Development of Improved Composite Pressure Vessels for Hydrogen Storage

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Hexagon Lincoln
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Overview

Timeline

• Start 1 Feb 2009
• End 30 Jun 2014
• 65% complete

Budget

• Project funding $17,781,251
  • DOE Share $1,425,000
  • Cost Share $356,251
• FY12 = $215,000
• FY13 = $200,000

Barriers

• Barriers addressed
  – A. System Weight and Volume
  – B. System Cost
  – G. Materials of Construction

• Targets (2017)
  – Gravimetric capacity > 5.5%
  – Volumetric capacity > 0.040 kg H₂/L
  – Storage system cost - TBD

Partners

• HSECoE
  SRNL, PNNL, LANL, JPL, NREL, UTRC, GM, Ford, HL, Oregon State Univ, UQTR, Univ of Michigan, Caltech, BASF

• Project lead = Don Anton, SRNL
Objectives - Relevance

- Meet DOE 2010 and 2017 Hydrogen Storage Goals for the storage system by identifying appropriate materials and design approaches for the composite container
  - Gravimetric capacity: 2010 > 4.5%, 2017 > 5.5%
  - Volumetric capacity: 2010 > 0.028 kg H₂/L, 2017 > 0.040 kg H₂/L
  - Storage system cost: TBD

- Maintain durability, operability, and safety characteristics that already meet DOE guidelines for 2010 and 2017

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

- Develop high pressure tanks as required to:
  - Contain components and materials of the selected hydrogen storage system
  - Operate safely and effectively in the defined pressure and temperature range
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
Approach/Results

• Phase 1
  – Material evaluation for cost and weight reduction, internal volume increase
    • Projected cylinder improvements: 11% lower weight, 4% greater internal volume, 10% lower cost
  – Evaluate design and materials against operating requirements of storage systems selected by HSECoE Partners
    • Baseline design approach established
    • Liner material development is most significant issue
    • Maintain durability, operability, and safety

• Phase 2
  – Confirm operating conditions
  – Update baseline design and materials
  – Evaluate alternate designs
  – Evaluate alternate materials
  – Develop bench-top test vessel(s)
Progress – Phase 2 Test Vessel Criteria

- **Consensus input from HSECoE Partners:**

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Test Vessel 1</th>
<th>Test Vessel 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Pressure</td>
<td>200 bar</td>
<td>100 bar</td>
</tr>
<tr>
<td>Maximum operating pressure</td>
<td>250 bar</td>
<td>125 bar</td>
</tr>
<tr>
<td>Minimum operating pressure</td>
<td>Vacuum, &lt; 1e-5 torr</td>
<td>(same)</td>
</tr>
<tr>
<td>Internal liquid volume (dimensional priority)</td>
<td>~6 Liters</td>
<td>~2 Liters</td>
</tr>
<tr>
<td>Liner ID</td>
<td>16.6 cm (6.54 inches)</td>
<td>11.2 cm (4.41 inches)</td>
</tr>
<tr>
<td>Vessel OD/OAL</td>
<td>~2:1 aspect ratio</td>
<td>(same)</td>
</tr>
<tr>
<td>Temperature range</td>
<td>20ºK to 373ºK</td>
<td>80ºK to 373ºK</td>
</tr>
<tr>
<td>Vessel Type</td>
<td>Type 4</td>
<td>Type 1</td>
</tr>
</tbody>
</table>
Prior Results - Test vessel 1, Materials Testing

- **Baseline dimensions**
  - OD (Tank) = 183 mm (7.18 inches)
  - OAL = 372 mm (14.64 inches)
  - Volume = 5.68 liters

- **Baseline construction**
  - Fiber = T700
  - Resin = epoxy
  - Liner = HDPE
  - Bosses = 6061 Aluminum

- **Existing vessel design tested (360 x 1680 mm)**
  - Baseline materials (T700, Epoxy, HDPE)
  - Temperatures (min achieved) from 77°C (composite) to 108°C (liner)
  - Initial pressure 68 bar (1000 psi) at RT, ~ 34 bar at low temperature (stabilizes liner)
  - Two cylinders - two cycles each
  - No effect on room temperature burst properties.
    - 9253 psi & 9077 psi
    - Configuration nominal is 8978 psi, min required 8021 psi
Prior results - Liner material investigation

- Tensile Impacts of
  - HDPE (baseline)
  - Modified EVOH
  - HDPE with nano-additives
  - PA
  - PTFE

- Energy of impact provides relative values only
- Of materials tested, HDPE has best cold/cryo properties (tested to 144ºK)
Progress - Subscale Type 4 Cryo Testing

- Cryogenic testing has been conducted on subscale Type 4 tanks
  - Tank 1 leaked at 4129 psi
    - 62 bar (900 psi) hold
    - 13.8 bar/sec (200 psi/sec) pressurization
  - Tank 2 leaked at 3340 psi
    - 138 bar (2000 psi) hold
    - 13.8 bar/min (200 psi/min) pressurization
  - Pressure level greater than 2.25 x 60 bar
  - Leaking was from liner crack(s)
    - Crack appears to initiate at boss/liner interface
    - Region of high stress due to differential CTE
  - Laminate held up well
  - Considering method to re-seal liner and retest
Progress – Test vessel 2

• Type 1 subscale vessel
• Three piece aluminum construction
  – Allows ease of assembly and replacement of components
  – Cryo service compatibility
  – Higher weight, but lower cost (~30% to 50% lower than type 4)
• Available for use by HSECoE partners in Phase 2
  – Ambient burst test to confirm safety
Progress – Test Vessel 2 Design

- OAL = 10.867 inches
- Collar OD = 6.165 inches
- Cylinder OD = 4.848 inches
- Wall thickness = 0.220 inches
- Ports = 1-1/8 – 12
- Volume = 2 liters
- Service pressure = 100 bar
- Design safety factor = 2.25 (min)
- Burst pressure = 370 bar (actual)
Progress - Subscale Type 1 Cryo Testing

• Type 1 subscale tank cycled 200 times to service pressure at 80K
  – Pressure cycling with liquid nitrogen
  – No thermal cycling, not expected to be an issue
• Burst pressure was 460 bar (6675 psi)
  – Burst pressure was 370 bar for ambient test
  – Strength of 6061-T6 increases with decreasing temperature
  – Similar failure mode, ambient vs. cryo
• Confirms safety in cryo use
Progress - Full Scale Design Evaluations

- SMART milestones for report on full scale designs:
  - Evaluate Type 1 and Type 4 tanks
    - Designs compared on following slides
  - Design for 40°K to 160°K
    - Low temperature is not a problem for aluminum alloy Type 1
    - Liner issues for Type 4 with extreme temp (80K), need further development
      - Qualification tests passed at 219K (-54C)
      - Some testing successful between 80K and 219K
    - No issue expected for carbon fiber
  - Meet ASME pressure vessel code
    - ASME Code could be met when pressure was >210 bar, but overly conservative for 100 bar use
    - DOT/NHTSA has jurisdiction, FMVSS regulations would be met
  - Design for 60 bar service pressure
    - 60 bar and 100 bar service pressure considered in designs
  - Mass less than 10 kg and volume less than 120 L
    - Volume will depend on adsorbent efficiency
    - 60 L and 120 L designs compared
    - Weight could be met for 120 L design with Type 4 tank if optimized liner could be developed
Progress - Full Scale Design Comparisons

<table>
<thead>
<tr>
<th>Tank</th>
<th>Mat'l</th>
<th>P (bar)</th>
<th>FS</th>
<th>Dia (mm)</th>
<th>L (mm)</th>
<th>Vol (liter)</th>
<th>Wt (kg)</th>
<th>PV/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C</td>
<td>60</td>
<td>2.25</td>
<td>440</td>
<td>950</td>
<td>120</td>
<td>11.35</td>
<td>634</td>
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<tr>
<td>2</td>
<td>C</td>
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<td>2.25</td>
<td>390</td>
<td>640</td>
<td>60</td>
<td>5.73</td>
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<tr>
<td>3</td>
<td>G</td>
<td>60</td>
<td>3.5</td>
<td>400</td>
<td>660</td>
<td>60</td>
<td>15.36</td>
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<tr>
<td>4</td>
<td>G</td>
<td>100</td>
<td>3.5</td>
<td>410</td>
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<td>6</td>
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<td>60</td>
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<td>120</td>
<td>30.00</td>
<td>240</td>
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- Carbon tanks have highest performance (PV/W)
- Glass and aluminum tanks are similar performance
- Larger tanks will have slightly better performance
- Aluminum tank can be improved by choice of alloy and better control of strength
Progress - Optimizing

- Performance improvement by reducing Factor of Safety (FS) to 2.0
  - Stress rupture is still acceptable
  - Vacuum shell will provide additional damage tolerance

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<tr>
<td>1A</td>
<td>C</td>
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<td>2.0</td>
<td>434</td>
<td>950</td>
<td>120</td>
<td>10.58</td>
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- Performance improvement by using thinner liner, e.g. resin layer
  - Reduces cost and weight, increases volume
  - Permeation is reduced due to low temperature
  - Must avoid leakage and microcracking

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<td>8.61</td>
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Accomplishments

• Phase 1 improvements could be incorporated into Phases 2 & 3
  – 11% lower weight, 4% greater volume, 10% lower cost
• Phase 2 test vessels have been designed, manufactured, and tested
  – Team consensus on vessel requirements
  – Analysis and burst testing confirms design and safety
  – Allows team members to demonstrate internal components
• Cryogenic cycle and burst testing of Type 1 test tank to confirm suitability for Phase 2 and 3 system testing
• Patent being pursued for external vacuum insulating vessel, Hexagon Lincoln and PNNL inventors
Collaborations

• Monthly teleconferences with PNNL and team on pressure vessels and containment
• Monthly teleconferences with adsorbant team
• Monthly HSECoE Coordinating Council telecons
• Face to Face Meetings with HSECoE Team
  – May 14, 2012, Washington, DC
  – Oct 9-11, 2012, Mystic, CT
• Tech Team Review Meeting
  – March 20-21, 2012, Southfield, MI
Future Work - Planned Tasks

- **Design separable Type 1 tank as Phase 3 baseline**
  - Reduces program risk, allows reassembly
  - Identify internal mounting features

- **Design monolithic Type 1 tank**
  - Identify how to install components – larger boss opening vs. weldment
  - Type 1 tank lower cost than Type 4
  - Alternate baseline if assembly issues addressed

- **Develop Type 4 cryogenic liner**
  - Opportunity for significantly lighter weight
  - Confirm cryogenic strength of carbon fiber
  - Confirm ability of liner to handle 80C operating condition

- **Demonstrate Type 3 cryogenic tank**

- **Demonstrate External vacuum shell**
  - With PNNL
Summary

- Type 1 and Type 4 lab subscale tanks designed, fabricated and provided to HSECoE partners
- Type 1 subscale tank successfully burst tested at ambient and cryo temperatures
- Type 4 subscale tank successfully burst tested at ambient temperature, but leaked at cryo temperature
- Designs evaluated to achieve SMART milestones, opportunities for improvement identified
- Phase III planned tasks identified