Norman L. Newhouse, Ph.D., P.E.
Lincoln Composites, Inc.
August 11-12, 2011

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Overview

• Lincoln Composites has, with support from DOE, built composite tube trailers and can, therefore, address issues with:
  – Design
  – Materials
  – Manufacturing
  – Testing
  – Approvals
Objectives

• Meet market needs for cost effective, light weight, bulk transport of CNG and CH2
  – Requires composite cylinders for light weight (cargo is volume limited, not weight limited)
  – Requires cost effective fibers (high strength/$)
  – Requires reasonable safety factors
  – Requires appropriate manufacturing and testing

• Safety must be maintained
Design

• Baseline design is Type 4 construction
  – Full composite reinforcement
  – Plastic liner
  – End bosses molded into dome
• Same design as used on 100,000+ CNG fuel containers (minimizes risk)
• Contained in frame per ISO 1496-3
Materials

• Baseline fiber is Toray T-700
  – High strength/cost
  – Alternate fibers have been identified/qualified
• Epoxy resin
  – Environmentally stable
  – Low temperature cure
• HDPE liner
• Metal boss
• Steel frame
Manufacturing

- Welded liner assembly
- Filament wound construction
- Oven cured
- Proof tested
- Same process as used on 100,000+ CNG fuel containers (minimizes risk)
Testing

- Successful completion of all qualification tests for a 3600 pressure vessel
  - Hydrostatic Burst Test
  - Ambient Pressure Cycle Test
  - LBB (Leak Before Burst) Test
  - Penetration (Gunfire)
  - Environmental Test
  - Flaw Tolerance Test
  - High Temperature Creep Test
  - Accelerated Stress Rupture Test
  - Extreme Temperature Cycle Test
  - Natural Gas Cycle Test with Blowdown

Testing is consistent with requirements of established standards
Approvals

• No existing standard applies to large composite tube/trailer
• Developed specification in conjunction with American Bureau of Shipping (ABS)
• ABS approved design, worked with Lincoln Composites to gain regulatory approvals
  – Currently approved in 5 countries
  – Approval being sought in US, Canada, and other countries
## DOE Technical Targets

<table>
<thead>
<tr>
<th>Hydrogen delivery targets</th>
<th>ISO container with four 3600 psi tanks</th>
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<tbody>
<tr>
<td>$500/kg of hydrogen stored by FY2010, $300/kg by FY2015</td>
<td>The current ISO assembly, with four tanks installed, can store about 600 kg of compressed hydrogen gas at 3600 psi with a safety factor of 2.35. It is estimated that the cost will be $675-$750 per kg of hydrogen depending on market demand.</td>
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<tr>
<td>Volumetric capacity 0.03 kg/liter by FY2010, &gt;0.035 kg/liter by FY 2015</td>
<td>The baseline tank has a capacity of 150 kg hydrogen in a volume of ~8500 liters, achieving a performance of ~0.018 kg/liter.</td>
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<tr>
<td></td>
<td>This performance measure can be increased 33% to 0.024 kg/liter by increasing the service pressure to 5000 psi and 95% to 0.035 kg/liter by increasing the service pressure to 8300 psi.</td>
</tr>
<tr>
<td>Tube trailer delivery capacity 700 kg by FY2010 and 1,100 kg by FY2017</td>
<td>The current ISO assembly, with four tanks installed, will contain about 600 kg of hydrogen.</td>
</tr>
<tr>
<td></td>
<td>This can be increased 33% to about 800 kg by increasing the service pressure to 5000 psi and 44% to about 1150 kg by increasing the service pressure to 8300 psi.</td>
</tr>
</tbody>
</table>
Technical Progress

Completed the design, manufacture and assembly of ISO container (standard dimensions) capable of storing ~600 kg H₂ @ 3600 psi.

- Designed to meet industry standard transporting dimensions
- Completed stress analysis on frame
- Performed DFMEA
- Performed HazID analysis
- Developed pressure relief system for fire protection

Completed Testing of ISO Container
- Dimensional
- Stacking
- Lifting – Top and bottom
- Inertia Test
- Impact Test
- Bonfire
Areas for Improvement

• Composite reinforcement is the most significant cost in the system
  – Lower cost of carbon fiber ($/strength)
  – Identify material with lower net cost ($/strength)
  – Identify lower cost resin system (raw material & manufacture)
  – Reduce carbon fiber safety factor (from 2.35 to 2.25 or 2.0)
    • Additional stress rupture testing to confirm acceptability
    • Combine stress rupture testing with cycling, impact damage to assess real-life conditions
    • Consider in-situ monitoring and/or NDE

• Reduce cost of manufacture
  – Sell more! (reduces overhead, but must balance supply with need)
  – Improve throughput (faster winding, cure, assembly)
Areas for Improvement

• Increase pressure to increase H₂ contents
  – Qualification testing is expensive
  – Test facilities are limited
  – Need to fully assess initial vs. operational costs

• Facilitate regulatory approvals
  – Some countries are slower to approve, or have barriers
    • e.g. ADR requires higher FS
  – No standards or regulations directly apply
    • Working with ISO, ASME, et al to develop
  – Need support from DOE, customers, regulators
Areas for Improvement

• Increase diameter to use single tank?
  – New liner manufacturing process required
  – High cost and risk involved
  – Reduces cost for plumbing, assembly
  – Increases space utilization (63% vs. 60%)
  – Redesign frame

• Develop special purpose (integrated) running gear/frame, with lower ground clearance and reduced interface, to permit more tanks (e.g. 5 or 6 of current size within height limit, instead of 4 tanks mounted 2x2)
Working Pressure Trade Study

- Increasing H₂ Density by Raising Working Pressure
  - 33 % Increase in Capacity at 15°C
    - .024 kg/L at 350 bar
    - .018 kg/L at 250 bar

- Practical Limit is 350 bar
  - Higher pressures exacerbates thick-wall effects and reduced strength translation
  - Availability of Plumbing Hardware
  - Availability of H₂ Compressors
  - Operation costs may offset initial costs, allow higher pressure limit
Module/Cylinder Cost Study

- Currently Meet $500 per kg H₂
  - 72% of Cost is Cylinders
  - 86% of Cylinder Costs is Composite
Summary

• Lincoln Composites has developed and produced composite tube trailers that are currently in service

• These tube trailers are a cost effective solution, based on established technology and a solid safety record, but there are opportunities to reduce cost and weight, and increase H₂ mass

• Areas for improvement have been identified