IV.D.10 Development of Improved Composite Pressure Vessels for Hydrogen Storage

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Fiscal Year (FY) 2012 Objectives

- Improve the performance characteristics, including weight, volumetric efficiency, and cost, of composite pressure vessels used to contain hydrogen in adsorbants.
- Evaluate design, materials, or manufacturing process improvements necessary for containing adsorbants.
- Demonstrate these improvements in prototype systems through fabrication, testing, and evaluation.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) System Weight and Volume
(B) System Cost
(G) Materials of Construction

Technical Targets

This project is conducting fundamental studies for the development of improved composite pressure vessels for hydrogen storage, and developing an optimized vessel for use by HSHCoE partners in demonstrating a functioning vehicle storage system using adsorbant materials. The targets apply to the storage system, of which the vessel is a part. Insights gained from these studies will be applied toward the design and manufacturing of hydrogen storage vessels that meet the following DOE hydrogen storage targets:

	2010	2017
• Gravimetric capacity:	>4.5%	>5.5%
• Volumetric capacity:	>0.028 kg H_2/L	>0.040 kg H_2/L
• Storage system cost:	to be determined	to be determined

FY 2012 Accomplishments

- Phase 1 improvements, which resulted in the following values for the pressure vessel itself, can be incorporated into Phase 2 and 3 components:
  - 11% lower weight
  - 4% greater volume
  - 10% lower cost
- Phase 2 lab test vessel has been designed to requirements established by HSECoE partners. A total of 21 lab test vessels were manufactured for testing and use by HSECoE partners.
- Cryogenic testing of liner and fiber materials to confirm selection and properties.

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Introduction

Lincoln Composites is conducting research to meet DOE 2010 and 2017 Hydrogen Storage goals for a storage system by identifying appropriate materials and design approaches for the composite container. At the same time, the pressure vessels must continue to maintain durability, operability and safety characteristics that already meet DOE guidelines for 2010 and 2017. There is a continuation of work with HSECoE partners to identify pressure vessel characteristics and opportunities for performance improvement. Lincoln Composites is working to develop high-pressure vessels as are required to enable tank design approaches to meet weight and volume goals and to allow adsorbant materials that operate at cryogenic temperatures to operate efficiently.

Approach

Lincoln Composites established a baseline design using HSECoE team operating criteria as a means to compare and evaluate potential improvements in design, materials and process to achieve cylinder performance improvements for weight, volume and cost. Lincoln Composites then down-selects the most promising engineering concepts to meet Go/No-Go requirements for moving forward. The design and materials improvements will be incorporated into pressure vessel designs to support HSECoE partner systems in phases 2 and 3.

The following areas are being researched and documented:

- Evaluation of alternate fiber reinforcement
- Evaluation of boss materials and designs
- Evaluation of resin toughening agents
- Evaluation of alternate liner materials
- Evaluation of damage vs. impact
- Evaluation of stress rupture characteristics
- Evaluation of in situ non-destructive examination methods to detect damage

Results

Phase 1 efforts resulted in projected improvements to the pressure vessel of 11% lower weight, 4% greater internal volume, and 10% lower cost. These were achieved by:

- Confirmation of higher strength boss material (weight reduction ≈3%).
- Qualification of alternate fiber reinforcements (cost reduction ≈5%).
- Reduction of carbon fiber safety factors (cost reduction ≈5%, weight reduction ≈4%, volume increase ≈2%).
- Use of thinner liner (weight reduction ≈4%, volume increase ≈2%).

The reduction in safety factor will result in a corresponding reduction in minimum burst pressure. However, reliability under stress rupture conditions, which the safety factor addresses, is still projected to be over 0.999999 for the life of the pressure vessel. The cyclic fatigue life of the composite and liner are significantly higher than required by standards, and will not be affected by changing fiber manufacturer or boss material, or by using a thinner liner. The proposed changes will not otherwise adversely affect performance.

A bench-top test vessel was designed, analyzed, and fabricated based on consensus input from HSECoE partners as follows:

Dimension	Value
Design Pressure	200 bar
Maximum Operating Pressure	250 bar
Minimum Operating Pressure	Vacuum, <1e-5 torr
Internal Liquid Volume (dimensional priority)	~6 Liters
Internal Liner Inside Diameter	16.6 cm (6.54 inches)
Vessel Outside Diameter	2:1 aspect ratio for a 6 Liter tank
Temperature Range	20 K to 373 K

Figure 1 shows a cross-section of the test vessel structural elements, along with stresses calculated using finite element analysis. Figure 2 shows a completed test vessel. A total of 21 test vessels have been manufactured to date. Three were burst to confirm the design, and three were used for cryogenic testing and leak testing. The remainder are available to HSECoE partners to support their activities.

A Type 3 design was evaluated that had the same internal dimensions as the Type 4 design, so that it could be used interchangeably with the Type 4 design. It was designed with a 316L stainless steel liner so that it could be welded and yet maintain strength. However, there was not an expression of interest in using it in Phase 2.

A Type 1 design was prepared with the same internal dimensions. It was designed to open in the center to allow assembly of internal components, but the weight of the design made it impractical.

Liner materials were investigated to determine suitability for cold temperature use. The baseline material, high-density polyethylene (HDPE), was compared with modified ethylene vinyl alcohol, HDPE with nano-additives, polyamide, and

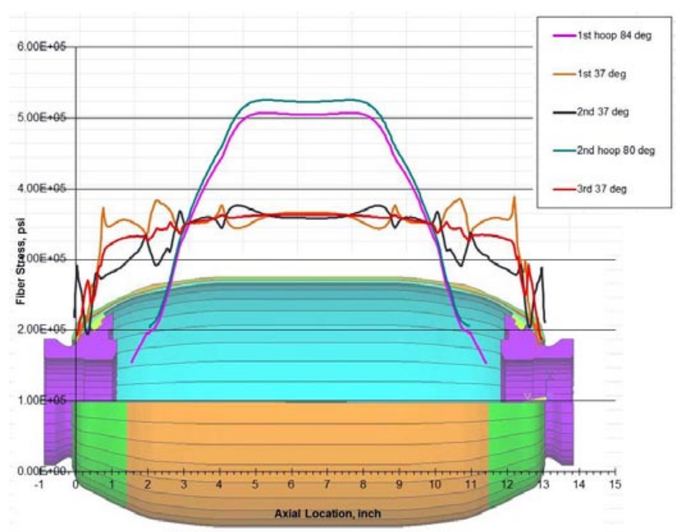

FIGURE 1. Test vessel cross-section and calculated stresses

FIGURE 2. HSECoE Phase 2 test vessel

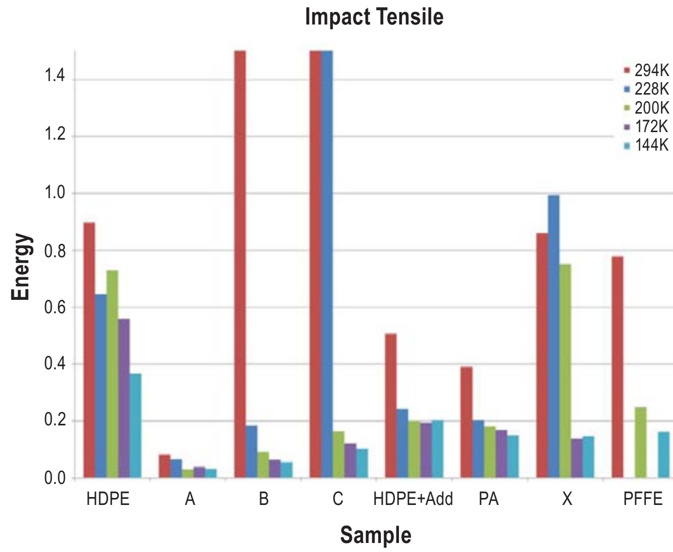

FIGURE 3. Liner material impact testing results

Teflon®. The HDPE material has shown to be the best suited of the materials tested, but additional evaluation is planned. Figure 3 shows impact test results.

Toray T700 will continue as the baseline reinforcing fiber, but two alternate fibers of similar strength have been identified. A prototype tank has been fabricated with T700 fiber and the baseline resin and is awaiting a burst test at cryogenic conditions, using liquid nitrogen as the pressurizing media, to confirm suitable performance at cryogenic temperatures. Testing of baseline epoxy resin material has confirmed its suitability for use at cryogenic temperatures. Testing of prototype and Phase 2 test vessels has confirmed basic suitability of the design and materials, but additional effort is planned for developing a more robust liner material.

Consideration was given to cylinder types moving forward into Phase 3. A Type 4 tank is the lightest weight, while a Type 1 is the heaviest. Type 1 tanks are generally less expensive than Type 3 and Type 4 tanks, although if stainless steel is required due to use at cryogenic temperatures, their cost would increase over the use of ferritic steels.

At lower pressures, and resultant thinner walls, Type 3 and Type 4 tanks may need additional reinforcement for durability, although this added fiber could be an inexpensive fiber such as glass. At cryogenic temperatures, some steel materials and polymer materials are brittle. Aluminum and composite materials are less affected. Thermal coefficient of expansion differences between a liner and composite must be considered when evaluating stresses.

The ability to install internal components is a consideration in the tank design. Earlier in Phase 2, consideration was given to a larger diameter opening, with components inserted after cylinder manufacture. However, current plans include the use of full diameter pucks or cylinders of sorbent materials, which must be considered in the vessel design and manufacture.

A Type 4 tank could have the components installed inside the liner initially, then it would be welded together, and the tank wound and cured. Cure temperature would be below the activation temperature of the sorbent material. Activation of the sorbent material would be done after tank manufacture is completed. The activation temperature of the sorbent material is not expected to adversely affect the tank.

A Type 1 tank would need to be designed to be joined after the sorbent material is installed. There are issues with accomplishing this. A conventional weld in an aluminum alloy would degrade the strength, and heat treatment is not an option. Friction stirred welding is being investigated as an option. Welding of stainless steel might be possible, but the resulting part would be expensive and heavy.

Conclusions and Future Directions

- Significant improvements in the cost, weight, and volumetric performance have been identified.
- Basic suitability for cryogenic service has been demonstrated for the baseline design and materials.
- Additional research is indicated to identify a more robust liner material for a Type 4 vessel. A Type 1 vessel may be considered as an option in Phase 3 to allow all other system components to be demonstrated while the Type 4 liner.
- Research and development will be continued for system design and optimization, including:
  - Insulation evaluation
  - Permeation and outgassing at temperature
  - Evaluation of component installation within the pressure vessel
  - Evaluation of pressure relief devices
  - Evaluation of qualification test requirements

- Continuing effort will be made to address the best options for the pressure vessel for Phase 3, including the means to assemble internal components, and will consider parallel solutions to balance performance with risk.

Special Recognitions & Awards/Patents Issued

1. Filing of a patent application on a thermal insulation shell system for composite pressure vessel is being evaluated.

FY 2012 Publications/Presentations

1. 2012 DOE Hydrogen Program Annual Merit Review, May 15, 2012