III.7 Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery

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Fiscal Year (FY) 2011 Objectives

The objective of this project is to design and develop the most effective bulk hauling and storage solution for hydrogen in terms of:

- Cost
- Safety
- Weight
- Volumetric Efficiency

Technical Barriers

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

(F) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs
(G) Storage Tank Materials and Costs

Technical Targets

This project has focused primarily on the design and qualification of a 3,600 psi pressure vessel and International Organization for Standardization (ISO) frame system to yield a storage capacity solution of approximately 8,500 L of water. Second phase is to perform and qualify same size container at higher pressures.

TABLE 1. Progress towards Meeting Technical Targets for Hydrogen Storage

Characteristic	Units	2010 Target	2015 Target	Status	Comments
Storage Costs	\$/kg	\$500	\$300	\$675-\$750	5,000 psi tank is expected to lower the cost
Volumetric Capacity	kg/liter	0.030	0.035	0.018	Estimated: 5,000 psi = >0 .024 kg/liter 8,300 psi = >0.035 kg/liter
Delivery Capacity, Trailer	kg	700	1,100	600	Estimated: 5,000 psi = >800 kg 8,300 psi = >1,150 kg

Accomplishments

- Successful completion of design and qualification of a 3,600 psi pressure vessel.
  - Qualification testing included:
    - Hydrostatic Burst
    - Ambient Pressure Cycle Test
    - Leak Before Burst Test
    - Penetration Test
    - Environmental Test
    - Flaw Tolerance Test
    - High Temperature Creep Test
    - Accelerated Stress Rupture Test
    - Extreme Temperature Cycle Test
    - Natural Gas Cycle Test with Blow-down
- Successful completion of design and qualification of an ISO frame capable of holding four 3,600 psi pressure vessels with a combined capacity of 600 kg of hydrogen. In addition to the structure, a system for loading, unloading, and pressure relief have been designed and implemented.
  - Qualification testing included:
    - Stress Analysis
    - Dimensional Analysis
    - Stacking
    - Lifting – Top and Bottom
    - Inertia Testing
    - Impact Testing
    - Bonfire Testing
- Successful completion of a trade study was achieved with respect to use and utilization of 5,000 psi pressure vessels.

- Factors used in the study:
  - Number of Pressure Vessels per Assembly
  - Working Pressure
  - Storage Temperature
  - Module/Cylinder Cost
  - Stress Ratio – reduce weight and cost by lower carbon fiber usage

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Introduction

Hydrogen holds the long-term potential to solve two critical problems related to energy use: energy security and climate control. The United States transportation sector is almost completely reliant on petroleum, over half of which is currently imported, and tailpipe emissions remain one of the country's key air quality concerns. Fuel cell vehicles operating on hydrogen produced from domestically available resources would dramatically decrease greenhouse gases and other emissions, while also reducing our dependence on oil from politically volatile regions of the world.

Successful commercialization of hydrogen fuel cell vehicles will depend upon the creation of a hydrogen delivery infrastructure that provides the same level of safety, ease, and functionality as the existing gasoline delivery infrastructure. Today, compressed hydrogen is shipped in tube trailers at pressures up to 3,000 psi (about 200 bar). However, the low hydrogen-carrying capacity of these tube trailers results in high delivery costs.

Hydrogen rail delivery is currently economically feasible only for cryogenic liquid hydrogen; however, almost no hydrogen is transported by rail. Reasons include the lack of timely scheduling and transport to avoid excessive hydrogen boil-off and the lack of rail cars capable of handling cryogenic liquid hydrogen. Hydrogen transport by barge faces similar issues in that few vessels are designed to handle the transport of hydrogen over inland waterways. Lincoln Composites' ISO Tank Assembly will not only provide a technically feasible method to transport compressed hydrogen over rail and water, but a more cost and weight efficient means as well (Figure 1).

FIGURE 1. Assembled ISO Container Without Outer Panels

Approach

In Phase 1 of this project, Lincoln Composites will design and qualify a large composite pressure vessel and ISO frame that can be used for storage and transport of compressed hydrogen over road, rail or water.

The baseline composite vessel will have a 3,600 psi service pressure, an outer diameter of 42.8 inches and a length of 38.3 feet. The weight of this tank will be approximately 2,485 kg. The internal volume is equal to 8,500 liters water capacity and will contain 150 kg of compressed hydrogen gas. The contained hydrogen will be approximately 6.0% of the tank weight (5.7% of the combined weight).

Four of these tanks will be mounted in a custom-designed ISO frame, resulting in an assembly with a combined capacity of 600 kg of hydrogen. Installing the compressed hydrogen vessels into an ISO frame offers a benefit of having one solution for both transportable and stationary storage. This decreases research and development costs as well as the amount of infrastructure and equipment needed for both applications.

The large size of the vessel also offers benefits. A limited number of large tanks is easier to package into the container and requires fewer valves and fittings. This results in higher system reliability and lower system cost. The larger diameter also means thicker tank walls, which will make the vessel more robust and damage tolerant.

Phase 2 of the project will be to evaluate using the same approximate sized vessel(s) and ISO frame at elevated pressures. The pressures that are targeted for scope are 5,000 psi and 8,300 psi. Basic design of the individual vessels will remain approximately the same size at the 5,000 psi pressure and minor changes may be needed for the higher pressure. Higher pressures are needed to accommodate goals of the project.

Results

Design and Manufacture of a 3,600 Psi Pressure Vessel

The design of the 3,600 psi pressure vessel architecture has been completed using finite element analysis to find a composite solution that resolves the internal pressure requirements and expected external loads. This design was translated into a manufacturing process that addresses the feasibility of vessel production. Several development units were fabricated and pressurized until burst to validate the proposed manufacturing process and design.

With the completed design and working manufacturing process, several additional vessels were fabricated and tested to address optimizing manufacturing issues and minimize production expenses. One of the units was fabricated and tested to ensure the highest risk associated with material availability could be addressed. By ensuring multiple sources of supplied materials, more leverage is available during procurement and lower production costs can be realized. Another vessel was fabricated to help establish confidence with migrating to a design having a higher margin of safety. Both of these vessels were subjected to a proof cycle and hydraulic burst test. The result of the testing met the expectations predicted by the design.

Qualification of 3,600 Psi Vessel

Due to the tanks geometry and construction, there are no published standards that can be used to directly qualify the product. There do exist, however, standards to qualify small pressure vessels of similar construction. These standards were reviewed for input to determine the appropriate requirements that would apply to a vessel of this geometry and construction and include:

- ISO 11439, gas cylinders – High Pressure Cylinders for the On-board Storage of Natural Gas as a Fuel for Automotive Vehicles
- ISO 11119-3, Gas Cylinders of Composite Construction (fully wrapped non-metallic liners)
- ANSI/CSA NGV2-2007, American National Standards for Natural Gas Vehicle Fuel Containers
- American Society of Mechanical Engineers (ASME) Code Case in Work/ASME BPV Project Team on Hydrogen Tanks and Section X

All qualification vessels have successfully been fabricated and completed through the following tests:

- Hydrostatic Burst
- Ambient Pressure Cycle Test
- Leak Before Burst Test
- Penetration Test
- Environmental Test
- Flaw Tolerance Test
- High Temperature Creep Test
- Accelerated Stress Rupture Test
- Extreme Temperature Cycle Test
- Natural Gas Cycle Test with Blow-down

Qualification of the ISO Frame

A complete assembly was constructed including ISO frame, four pressure vessels, and all relevant plumbing including pressure relief system. The following tests were performed on the entire assembly:

- Stress Analysis
- Dimensional Analysis
- Stacking
- Lifting – Top and Bottom
- Inertia Testing
- Impact Testing
- Bonfire Testing

American Bureau of Shipping has successfully approved the entire ISO assembly for production including, pressure vessels, ISO frame and subsequent valves, fittings and pressure relief system.

Trade Study for a 5,000 Psi Pressure Vessel

A trade study were undertaken to evaluate potential targets that would increase utilization storage design that best meet or exceed DOE targets. Lincoln Composites existing Titan Module was used as the baseline for the studies and a gap audit was conducted.

Design Baseline

- Intermodal ISO 668 1A Frame
- Four Type 4 Pressure Vessels
  - 250 bar Working Pressure
  - Carbon Fiber, 2.35 Stress Ratio

Gap Audit

- Increase Capacity (kg of hydrogen per liter)
  - Increase pressure and/or utilization
  - From 0.018 kg to 0.03 kg of hydrogen per liter
  - From 616 kg to 700 kg hydrogen capacity at 15°C
- Decrease Cost ($ per kg hydrogen)
  - From $500 per kg to $452 per kg hydrogen

Cylinder size was identified as a potential candidate for increase capacity through the increase of utilization of space. The study compared Lincoln Composites current four vessel configuration with a single large diameter vessel. Space utilization for the current Titan assembly is roughly 60% in volume while replacing it with a single, large tank would increase the utilization to 63%. However, when looking at the sheer size of a single tank, the thickness of a liner to manufacture this tank would not be very efficient and will have its limitations; i.e. pipe extrusion, and injection molding of the domes.

Lincoln Composites also looked at different scenarios of packing of pressure vessels within the current ISO frame. First scenario was to add an additional vessel down the center of the existing four vessels. This would increase the utilization of space to 68% from 60%, but the manufacturing of a small diameter tank that would fit in the available space would be difficult to achieve. This is due to the length/diameter (L/D) ratio. When this number becomes large, the tanks begin to bend due to the weight and decreased strength of the liner. Straightness is a key factor when trying to place the vessels next to each other within the frame.

This also increases the cost of the plumbing of the system. Second scenario is eight cylinders packed in a 3x2x3 matrix within the existing ISO frame. This arrangement would actually reduce the utilization from 60% to 56%. Lastly, Lincoln Composites performed a study to determine the potential to have many smaller cylinders packed within the frame assembly. Ninety-one smaller cylinders could be packed vertically with the frame. Again, the L/D ratio would increase and thus affect straightness and winding stability. If this were done, utilization would increase from 60% to 68%. However, the additional cost of plumbing this configuration would increase as well as the complexity of servicing the cylinders.

A third factor that was investigated through the study was to look at raising working pressure to increase compressed hydrogen density. By raising working pressure from 3,600 (250 bar) to 5,000 psi (350 bar) we could potentially see an increase of 33% in capacity at 15°C. Higher concentrations could be achieved at higher pressures, however cost increases need to be considered. As can be seen in Figures 2 and 3, the practical limit is 5,000 psi (350 bar). These costs are driven by several factors, i.e. higher pressures exacerbate thick-wall effects and reduced strength translation, the availability of high pressure plumbing hardware and the availability of hydrogen compressors.

Storage temperature was also investigated as a means to increase hydrogen density. As can be seen in Figure 4, with a decrease in storage temperature to -40°C, the current 3,600 psi tank could potentially see an increase of 33% in hydrogen density. With respect to a 5,000 psi tank, reducing the storage to the same temperature, -40°C, has the potential to increase hydrogen density by 61%. However, cold storage adds cost to the system.

Lincoln Composites also looked at full module costs as well as costs to manufacture pressure vessels for the Titan product line. The breakdown of costs associated with a full bulk hauling module and individual pressure vessels are as follows:

- Module
  - Pressure vessels make up approximately 72% of the total cost.
  - Frame and hardware make up approximately 28% of the total cost.
- Pressure vessel
  - End bosses make up approximately 3% of the total cost.
  - High-density polyethylene (HDPE) liner makes up approximately 11% of the total cost.
  - Composite material makes up approximately 86% of the total cost.

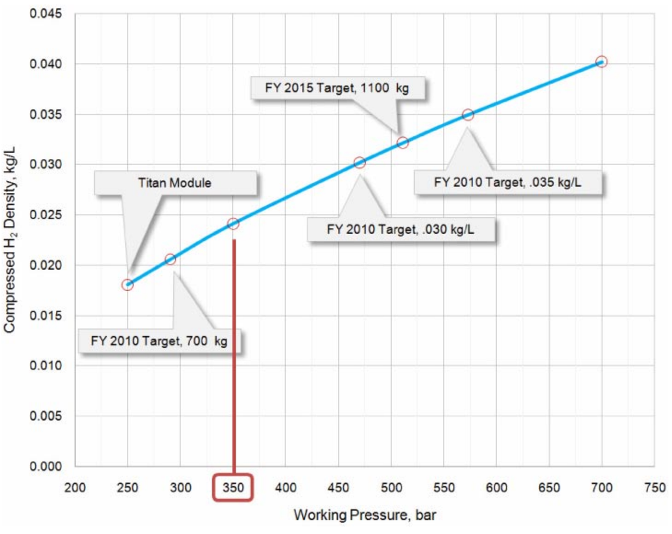

FIGURE 2. Working Pressure vs. Compressed Hydrogen (kg/L)

As part of the cost factor associated with this study, Lincoln Composites evaluated scenarios to reduce costs in

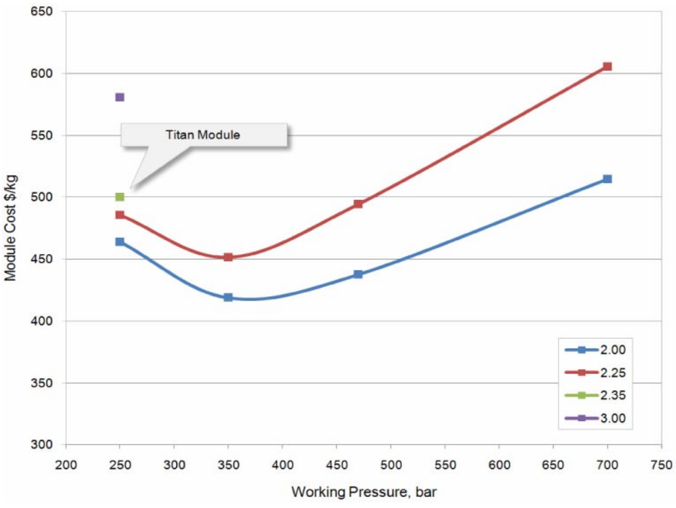

FIGURE 3. Working Pressure vs. Module Cost ($/kg)

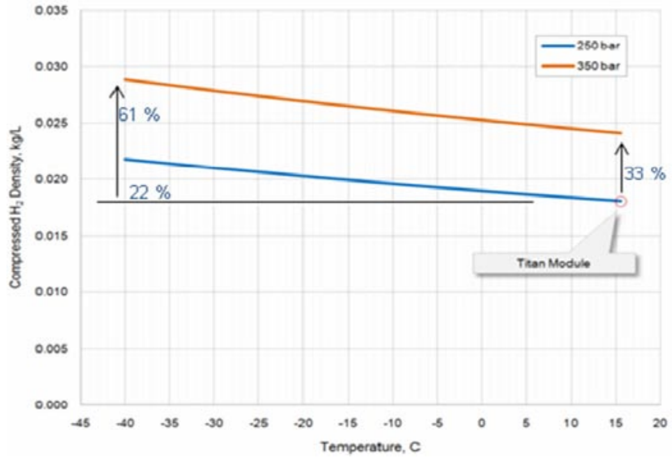

FIGURE 4. Temperature vs. Compressed Hydrogen Density (kg/L)

both the liners and the composite materials. Liner costs are associated with HDPE tubes/domes and the steel end bosses. Current construction and design of the liner shows that we are presently at minimum thickness/diameter ratio and any changes would result in difficulties in liner fabrication and filament winding of the vessel. The end bosses are constrained by the current mounting scheme and cost savings would be minimal if changes were made. As for the composite costs, the carbon fiber that is currently being used in the design contributes the lowest stress ratio of allowable fibers at 2.35. Current fiber possesses the greatest strength per unit cost. There are higher strength carbon fibers in existence but would have a 2-4 times increase in cost for a 15-40% increase in strength.

The last factor evaluated was that of reduction of stress ratio. By reducing the stress ratio, one could in turn lower the amount of carbon needed in the assembly of the pressure vessels and thus lower the cost of fiber used.

- Current Titan stress ratio is 2.35 based on compressed natural gas requirements
- ASME H2 allows for a 2.25 stress ratio
- 2.00 stress ratio is considered safe

Conclusions and Future Directions

Proposed objectives for Phase 1 of this project were completed in the fourth quarter of 2009. This includes successful completion of a large 3,600 psi pressure vessel able to contain 8,500 liter water capacity. The successful qualification of an entire assembly into an ISO container was also completed. Lincoln Composites will continue to evaluate cost reductions in design of the vessel as well as in the manufacturing processes. Pursuant of a higher pressure vessel is underway and will continue.

Trade studies have been completed for a increased service pressure of our current 3,600 psi Titan assembly. Based on the findings of this study, the logical next step is as follows:

- 5,000 psi pressure vessel design
- 2.25 stress ratio design will fit current Titan frame
- Will see an increase from 0.018 to 0.024 kg of hydrogen per liter
- Will see a hydrogen capacity increase from 616 to 822 kg of hydrogen
- Cost per kg of hydrogen would decrease from $500 to $452
- Cold storage would add cost
- Adding cylinders to the assembly adds cost

Future work will involve the fabrication and testing of a 5,000 psi pressure vessel. This will show results more closely to the targets for hydrogen storage.

FY 2011 Publications/Presentations

1. 2011 DOE Hydrogen Program Annual Merit Review, May 10, 2011.