III.15 Design and Development of High Pressure Hydrogen Storage Tank for Storage and Gaseous Truck Delivery

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Contract Number: DE-FG36-08GO18062

Project Start Date: July 1, 2008
Projected End Date: June 1, 2011

Project Objective

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 Hydrogen Delivery section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(C) Cost
(F) Transport Storage Costs

Technical Targets

This project will focus on the design and qualification of a 3,600 psi tank and an International Organization for Standardization (ISO) frame system in the first year to yield a storage capacity solution of approximately 8,500 L of water. The technical targets of the project are presented in Table 1.

TABLE 1. Technical Targets

Hydrogen delivery Targets	ISO Container with four 3,600 psi tanks (Fiscal Year 2009 work scope)
$500/kg stored hydrogen by FY 2010	The current ISO assembly, with four tanks installed, can store approximately 600 kg of compressed hydrogen gas at 3,600 psi. It is estimated that the initial cost will be $675-750/kg of hydrogen depending on market conditions.
Volumetric capacity 0.03 kg/liter by FY 2010	The baseline tank has a capacity of 150 kg hydrogen in a volume of approximately 8,500 liters, achieving a performance of about 0.018 kg/liter. This performance measure can be increased to 0.024 kg/liter by increasing the service pressure to 5,000 psi.
Tube trailer delivery capacity 700 kg by FY 2010	The current ISO assembly, with four tanks installed, will contain about 600 kg of hydrogen. This can be increased to about 800 kg by increasing the service pressure to 5,000 psi.

Accomplishments

- Successful completion of design and partial qualification of a 3,600 psi tank. Qualification testing included:
  - Strength testing (burst and pressure cycling).
  - Environmental testing (exposure to environmental fluids, extreme temperatures, and high temperature creep).
  - Durability testing (flaw tolerance per ISO 11439 and penetration).
  - Other special tests (blow down, accelerated stress rupture, and leak-before-burst).
- Successful completion of design and partial qualification of ISO frame capable of holding four 3,600 psi tanks with a combined capacity of 600 kg of hydrogen. In addition to the structure, a system for loading, unloading, and pressure relief has been designed and implemented.

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Introduction

Hydrogen holds the long-term potential to solve two critical problems related to energy use: energy security and climate change. The U.S. 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.

Approach

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

The baseline composite tank 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 percent of the tank weight (5.7 percent 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. An ISO frame and tank mounting system will also be designed to accommodate up to four (4) of these tanks, as illustrated in the solid-model geometry shown in Figure 1.

Installing the compressed hydrogen tanks into an ISO frame offers a benefit of having one solution for both transportable and stationary tanks. This decreases research and development costs as well as the amount of infrastructure and equipment needed for both applications.

FIGURE 1. Solid-Model Geometry of the TITAN ISO Frame System

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

During the course of the project, Lincoln Composite will evaluate different tank dimensions, safety factors, service pressures, and other factors in order to optimize the performance of the tank related to the DOE project goals. The ISO mounting frame will also be designed to existing standards and the ISO assembly will be tested for compliance to rigorous transportation standards.

Results

Design and Manufacture of 3,600 psi Tank

The design of the 3,600 psi pressure vessel architecture has been completed using finite element analysis to find a composite solution that resolved the internal pressure requirements and expected external loads. This design was translated into a manufacturing process that addresses the feasibility of tank production. A significant challenge has been the scale up of our standard manufacturing processes and equipment, including the liner weld fixture shown in Figure 2. Several development design verification test (DVT) 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 tanks were fabricated and tested to address optimizing

FIGURE 2. Development of the Manufacturing Processes for the 3,600 psi TITAN Tank has Required Scale Up of All Manufacturing Processes and Equipment

manufacturing issues and minimizing 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 material, more leverage is available during procurement and lower production costs can be realized. Another unit was fabricated to help establish confidence with migrating to a design having a higher margin of safety. Both of these units were subjected to a proof cycle and hydraulic burst test. The results of the testing met the expectations predicted by design.

Two additional tanks were fabricated and subjected to a proofing cycle and successfully passed but are waiting further hydraulic burst testing. One of these tanks was fabricated to study the effects of allowing certain manufacturing perturbations into the process that would reduce production costs of the tanks. The other DVT unit was fabricated using a modified material configuration to test the feasibility of a higher performance vessel and to enhance its cosmetic appearance.

Qualification of 3,600 psi Tank

Due to the tank's geometry and construction there are no published standards that can be used to directly qualify the product to. 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)
- American National Standards Institute/Canadian Standards Association Natural Gas Vehicle 2-2007, 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

Some of the qualification tanks that were fabricated have successfully completed and passed their respective test requirements. These include two tanks that were hydraulically burst and another tank that was subjected to ballistic penetration. Several others have passed a proofing test and will be used to qualify the ISO frame hauling system and additional testing such as:

- Cycle testing (ambient, leak before burst, and extreme temperature).
- Flaw tolerance per ISO 11439.
- Blow-down.

Design and Manufacture of the ISO Frame

An ISO frame has been designed to hold four large hydrogen carrying pressure vessels. The frame was modeled in FEMAP (a computer aided design independent pre- and post-processor for engineering finite element analysis, marketed by Seimens) and analyzed with NX Nastran using 28 load cases, including all conditions described in specification ISO 1496-3. This effort was contracted out to a professional engineering firm and a documented stress analysis report has been delivered.

The ISO frame construction was constructed by a metal fabricator having experience with this size of structure and shipped to our facility in February 2009. Tank and plumbing installation was completed as well as the installation of a fire protection/pressure relief system. The completed assembly is shown in Figure 3. The

FIGURE 3. Final Assembly of TITAN ISO Frame System

American Bureau of Shipping has conducted a Hazard Identification Analysis study on the design concept and the identified risks have been mitigated.

Qualification of the ISO Frame

The ISO container was recently sent out for qualification testing with the following results:

- Structural testing completed.
- Rail impact test completed.
- Bonfire test is scheduled for August.

The ISO frame qualification test unit is shown leaving our manufacturing facility in Lincoln, NE in Figure 4. Upon completion of remaining qualification tests, the American Bureau of Shipping has agreed to certify the entire ISO container assembly including tanks and pressure relief system.

FIGURE 4. TITAN ISO Frame System Departs for Final Qualification Testing

Conclusions and Future Direction

Proposed objectives for the first budget period of this project are very close to being achieved. By the end of summer 2009, all qualification testing will have been completed. The results of the completed qualification testing are very promising. Additional testing done earlier has shown the feasibility of pursuing a 5,000 psi configuration to better meet the DOE future hydrogen storage goals.

The plan forward for completing the qualification of the 3,600 psi tank involves:

- Completion of sub-scale testing activity.
- Completion of sub-length cycle testing activity.
- Completion of full-scale cycle testing activity.

The plan forward for completing the qualification of the ISO frame involves completion of the bonfire test. Both qualification activities are expected to be completed by the end of summer 2009. Upon completion a Go/No-Go decision will be made to purse the development of the 5,000 psi tank design.