III.3 Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage

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- MegaStir Technologies, Provo, UT
- Victor Li Independent Consultant, Ann Arbor, MI

Project Start Date: October 1, 2010
Project End Date: Project continuation and direction determined annually by DOE

Fiscal Year (FY) 2011 Objectives

- Develop engineering designs and fabrication technology for cost-effective high-pressure hydrogen storage system for stationary applications. In particular, the stationary storage vessel will utilize:
  - Cost-effective commodity structural materials.
  - A systematic, integrated vessel design to mitigate hydrogen embrittlement associated with the use of high-strength steels for high-pressure hydrogen storage.
  - High-productivity and low-cost fabrication technology.
  - Application of embedded sensors to ensure the safe and reliable operation of the storage system.

Technical Barriers

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

(F) Gaseous Hydrogen Storage and Tube Trailer Delivery Cost

(G) Storage Tank Materials and Costs

Technical Targets

This project is to develop and demonstrate a cost-effective design of composite steel/concrete vessel for bulk high-pressure hydrogen storage and associated fabrication technology that can be adopted to meet different stationary storage needs such as those at refueling stations and renewable energy generation sites. Insights gained from this project will be applied toward the manufacturing of off-board gaseous hydrogen storage tanks that meet the following DOE 2015 hydrogen delivery targets:

- Storage Tank Purchased Capital Cost (\$/kg of H_2 stored): \$300 - Primary objective of this project.
- Volumetric Capacity (kg H_2/liter of storage volume): >0.035 - Secondary objective of this project.

FY 2011 Accomplishments

- Completed conceptual engineering design of the inner layered steel vessel for hydrogen storage capable of sustaining 5,000 psi design pressure based on industry standard American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel (BPV) Code - Section VIII. The conceptual designs for the outer reinforcement sleeve made of pre-stressed concrete and the interface between inner steel and outer concrete vessels will be completed by September/October 2011 timeframe.
- Preliminary cost estimate showed that the proposed design of composite steel/concrete vessel and fabrication technology have a sound basis for meeting the revised DOE cost target for off-board bulk storage. Improved cost modeling based on the conceptual engineering designs is expected to be completed by September/October 2011 timeframe.
- Efforts are ongoing for demonstrating technical proof-of-feasibility of key design concepts and construction technology including hydrogen embrittlement mitigation and friction stir welding of high-strength steels.

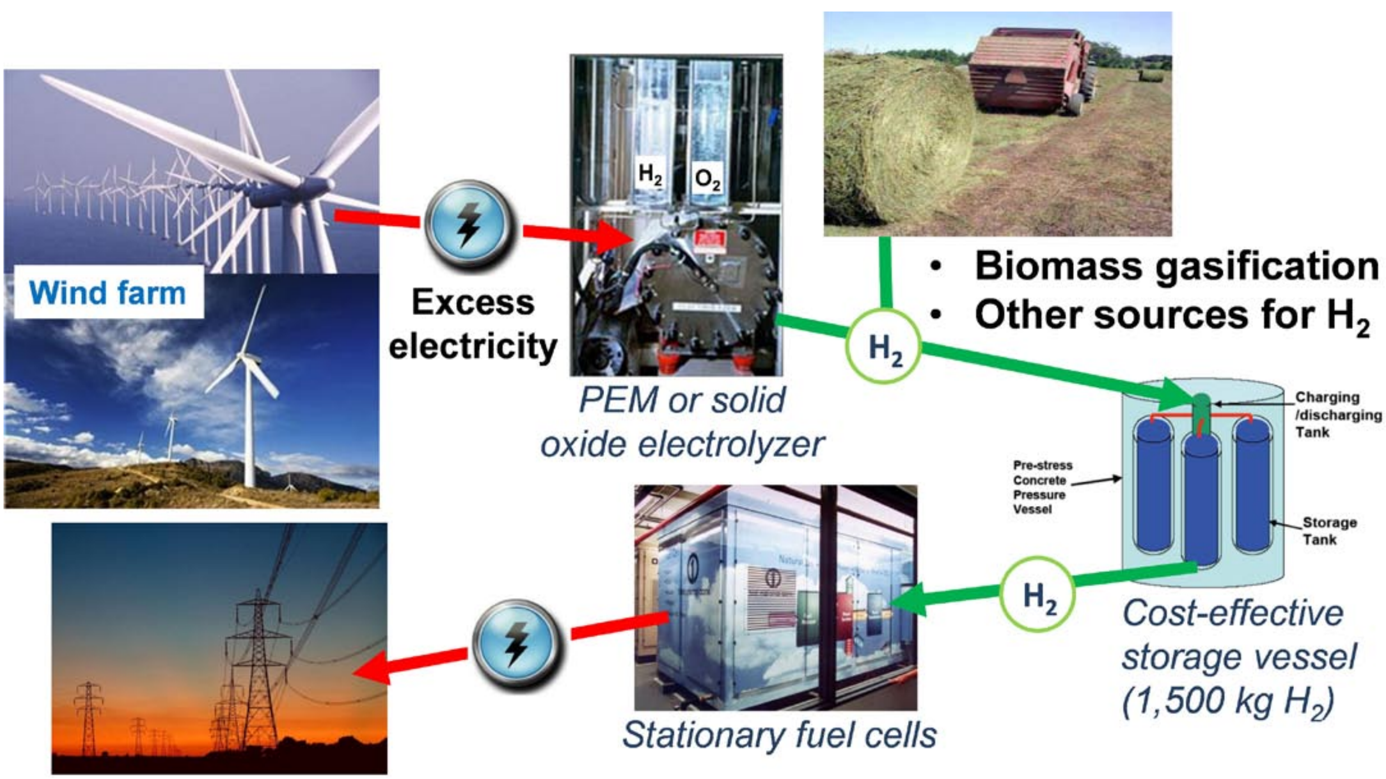
Introduction

Low-cost off-board bulk stationary storage of hydrogen is a critical element in the overall hydrogen production and delivery infrastructure. Stationary storage is needed at central production plants, geologic storage sites, renewable energy generation sites, terminals, and refueling stations. Stationary storage also provides the surge capacity to handle hourly, daily, and seasonal demand variations. Figure 1

FIGURE 1. Application of Stationary Hydrogen Storage Vessel At Refueling Station

illustrates a potential application of the cost-effective hydrogen storage vessel for refueling of hydrogen. The vessel is designed to store 1,500 kg of gaseous H_2, which is sufficient to refill about 267 passenger cars (based on a 5.6 kg H_2 tank per car [1]). Another potential application of the hydrogen storage vessel at renewable energy generation sites is shown in Figure 2. The hydrogen, produced from water electrolysis using excess electricity from wind farms and/or biomass gasification, will be stored in the vessel. The 1,500 kg of H_2 can be used to generate about 24,200 kWh [2] (or 3 MW for peak-load daytime) back into electrical grid, sufficient electricity to power 780 U.S. homes per day [3].

The size and volume of the stationary hydrogen storage are expected to vary considerably depending on the intended usage, the location and other economic and logistic considerations. For instance, the storage vessel at a renewable energy generation site may have a lower hydrogen pressure but much larger storage volume compared to that at a refueling station. Therefore, it is important the storage vessel is "scalable" (i.e., it can be readily scaled for different



PEM - proton exchange membrane

FIGURE 2. Another application of stationary hydrogen storage vessel at renewable energy generation site for utility-scale load leveling and peak shaving (in conjunction with fuel cells).

sizes and pressures). In this project, ORNL leads a diverse multidisciplinary team consisting of industry and academia to develop and demonstrate a cost-effective integrated steel/concrete high-pressure hydrogen storage vessel design and fabrication technology that could be adopted to meet different stationary high-pressure hydrogen storage needs. Safety and economics are two prevailing drivers behind the integrated hydrogen storage technology.

Approach

Figure 3 is a schematic drawing of the overall engineering concept of the high-pressure hydrogen storage vessel. It has a modular design with scalability and flexibility for meeting different stationary storage needs. The particular design shown in Figure 3 is a composite structure with four inner steel tanks that are reinforced by an outer pre-stressed concrete sleeve. Commodity materials such as structural steels and concretes are used for cost-effectiveness. It is noted that the project team led by ORNL is working closely with the DOE Delivery Tech Team. Alternative designs may be studied based on the directions set forth by DOE.

A key enabler for the overall composite storage vessel is the use of a layered steel vessel for the inner steel tank. The layered steel vessel technology is proven and has shown significant cost and safety advantages over the conventional single solid section steel vessel. In this project, new designs and fabrication technology will be developed for the layered steel-based hydrogen storage including: (1) novel vessel design to avoid hydrogen embrittlement of high-strength structural steels, and (2) advanced fabrication technology based on friction stir welding (FSW) for layered steels. Sensors will be embedded into both inner steel tanks and outer concrete sleeve to ensure safe and reliable operation. Steel tanks are self-contained and can be shut down individually for improved reliability and safety. Finally, recently developed high-performance concretes will be evaluated for the interface material between the steel tank and the concrete sleeve to ensure the structural compatibility between the two.

Results

There are three major activities in this first year (FY 2011) of the project: (1) preliminary cost estimate of the composite storage vessel, (2) preliminary design and engineering of key vessel components including steel tank, concrete, and interface between the two, and (3) technical proof-of-feasibility study of key design concepts and construction technology. The results from the first year of substantial development are discussed as follows.

Preliminary Cost Estimate of Composite Storage Vessel

Table 1 shows the preliminary rough-order-of-magnitude (ROM) cost estimate for three different design concepts. As shown in this table, the steel tank, though much cheaper than other materials such as carbon fiber composite tank, still represents a major cost item in the composite vessel. By shifting more structural loads from the inner steel tank to the outer pre-stressed concrete vessel, the required thickness for the steel tank is reduced. Even though the concrete vessel cost increases, the decrease in the steel tank cost (due to thinner wall) is sufficient to reduce the total cost of composite vessel. It is noted that the preliminary ROM cost estimate does not include the expected additional cost reduction attainable by the use of new steel vessel fabrication technology, new vessel design/engineering concepts, and ultra-high strength steels that are being pursued in the project. The ROM cost estimate does not account for engineering challenges and costs in high-strength concrete materials and integration of the inner steel vessel and the outer concrete containment. An improved cost analysis model is being developed which will take into account the detailed engineering and designs of key vessel components.

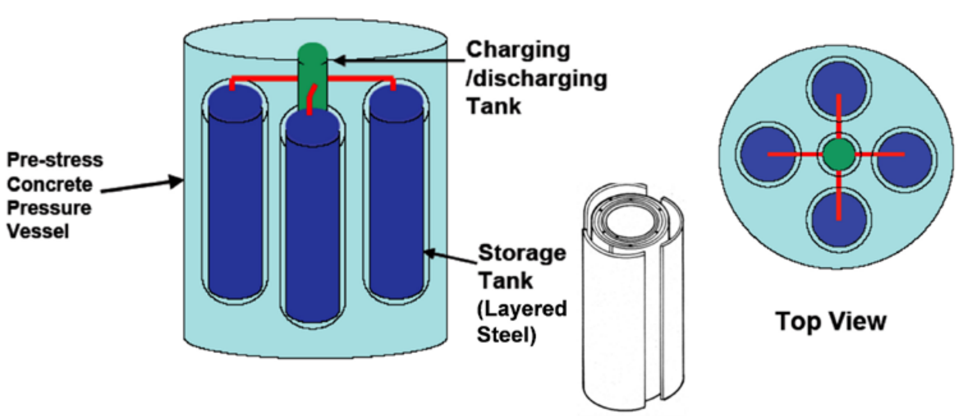


FIGURE 3. Schematic drawing of the overall engineering concept of the composite vessel for high-pressure hydrogen storage.

TABLE 1. Preliminary ROM Cost Estimate for Three Different Design Concepts of Stationary High-Pressure Hydrogen Storage Vessel *

	All Steel Layered Vessel				Composite Vessel with Concrete Carrying 50% Hoop Stress Only			Composite Vessel with Concrete Carrying 85% Hoop and Axial Stresses		
DOE Volumetric Capacity Target	2005 Status	2010 Target	2015 Target		2010 Target	2015 Target		2010 Target	2015 Target	
H_2 Pressure, psi	5000	7000	8700	10000	7000	8700	10000	7000	8700	10000
H_2 Weight, kg	1400	1820	2125	2340	1820	2125	2340	1820	2125	2340
Steel Vessel										
Wall thickness, in	7.7	11.0	14.0	16.4	5.3	6.6	7.7	1.5	1.9	2.2
Weight, lb	194,500	285,700	370,400	439,900	185,500	236,300	276,900	51,900	64,900	75,000
Steel Vessel Cost, $k	$933.7	$1,371.5	$1,777.7	$2,111.7	$895.7	$1,141.4	$1,337.4	$250.6	$313.7	$362.5
PCPV										
Wall thickness, in					24	24	24	48	48	48
Concrete, $k					$13.5	$13.7	$13.8	$48.5	$48.8	$49.0
Steel Tendon, $k					$109.8	$143.9	$171.5	$224.3	$284.2	$330.6
Rebar & Liner, $k					$61.0	$62.0	$62.8	$117.0	$117.7	$118.2
PCPV Cost, $k	$0	$0	$0	$0	$184.3	$219.6	$248.1	$389.8	$450.7	$497.8
Total Purchase Cost, $	$933.7	$1,371.5	$1,777.7	$2,111.7	$1,080.0	$1,361.0	$1,585.5	$640.4	$764.4	$860.3
Cost per kg H_2, $	***$667***	***$754***	***$837***	***$902***	***$593***	***$640***	***$678***	***$352***	***$360***	***$368***

* The basic premises in cost analysis include: (1) Reference vessel: a cylindrical vessel with semi-sphere heads, 12 ft. diameter and 21.7 ft. long (2,000 ft^3 storage volume), with piping attachment and maintenance access. (2) 50 ksi inner steel vessel design allowable stress (SA724 100 ksi grade high-strength steel) and 190 ksi steel tendon design stress (Grade 270 steel), per ASME Boiler and Pressure Vessel (BPV) Section VIII Division III design rules and material specification. (3) ASME BPV stress formulas to determine steel vessel wall thickness. (4) Layered steel vessel: steel plate cost at $2/lb, labor cost at $100/hr., and 6,000 hours to fabricate the reference vessel, estimated by a major steel vessel construction. (5) Pre-stressed concrete pressure vessel: material and construction cost for rebar, high-strength tendon, and high-strength concrete are $2.5/lb, $3.5/lb, and $400/cubic yard, respectively, based on 2007 steel and concrete market prices.

Design and Engineering of Key Vessel Components

The conceptual engineering design of the inner layered steel tank capable of sustaining 5,000 psi hydrogen pressure is developed based on industry standard ASME BPV Code - Section VIII. The layered steel tank consists of an inner thin liner with thin segmental cylinders wrapped around it to form the layered shells. The steel plate thickness is chosen to be 0.25 inch for ease of fabrication and to minimize the need for post-weld heat treatment. The concentric wrapped shells are welded to a single solid section steel head at each end. Special rules for welding, post-weld heat treatment and non-destructive examination required for layered steel tanks are included in the design. Such ASME code-based design is important for the industry acceptance and technology transfer and commercialization in a later stage of the project.

The conceptual designs for the outer reinforcement pre-stressed concrete pressure vessel and the interface between inner steel and outer concrete vessels are expected to be completed by the September/October 2011 timeframe. Structural analysis based on finite element modeling is being developed and used to aid the design of compatibility between steel and concrete vessels. Figure 4 shows preliminary results of stress distribution in a cross-section of the composite vessel at an internal hydrogen pressure of 5,000 psi. The predicted stress distribution is important to ensure the structure has enough capacity to sustain the design pressure.

Technical Proof-Of-Feasibility Study

The use of layered steels offers significant opportunities for further cost-reduction and safety and performance improvement. First, FSW has demonstrated to produce joint with superior mechanical strength when compared to conventional arc welding [4]. In the layered steel vessel construction, FSW can be used for the longitudinal seam weld of 0.25-in.-thick steel shells. Second, a novel design taking advantage of layered steel shells is being evaluated for mitigation of hydrogen embrittlement to high-strength structural steels. Finally, mechanical and chemical sensors can be embedded into both the steel and concrete vessels for monitoring structure health. In particular, state-of-the-art piezoelectric sensors are being studied for measuring strain/stress variations in the structure. These proof-of-concept studies are important to ensure the technical readiness of the proposed composite storage vessel.

Conclusions and Future Directions

From the above results gained in this first year of substantial development, it can be concluded: (1) the composite storage vessel utilizing commodity steel and concrete materials and advanced fabrication technology has a sound technical basis to meet the DOE revised cost target for off-board bulk storage, and (2) the preliminary engineering

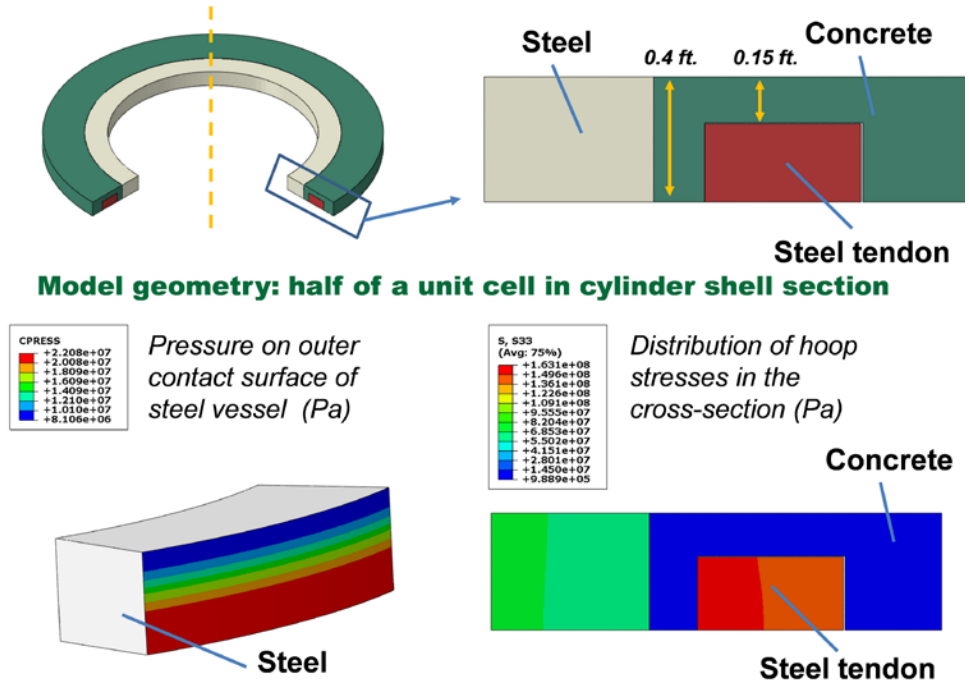


FIGURE 4. Preliminary results of finite element modeling for understanding stress distribution in the composite vessel.

design of inner layered steel vessel can sustain 5,000 psi hydrogen pressure based on relevant ASME BPV Code.

For the remainder of FY 2011, we plan to complete the preliminary designs of the outer pre-stressed concrete vessel and the steel/concrete interface. Detailed design and engineering analyses (including system cost), and mock-up vessel construction, testing and demonstration are planned in out-years.

Patents Issued

1. J. Wang, Z. Feng and W. Zhang: Conceptual Composite Tank Design for Stationary High-pressure Hydrogen Storage, ORNL Invention Disclosure No. 201102585, 2011.

FY 2011 Publications/Presentations

1. 2011 DOE Annual Merit Review, Fuel Cell Technologies Program, Washington, D.C., May 2011.

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1. M. Kromer, et al.: Analyses of Hydrogen Storage Materials and On-Board Systems, DOE FCT Program FY 2010 Annual Progress Report.

2. M.L. Perry and S. Kotso: A Back-up Power Solution with No Batteries, INTELEC 2004 Proceedings, pp. 210-217 (2004).

3. U.S. Energy Information Administration: How much electricity does an American home use in 2009, http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3.

4. Feng, Z. Steel, R. Packer, S. and David, S.A. 2009. “Friction Stir Welding of API Grade 65 Steel Pipes,” ASME PVP Conference, Prague, Czech Republic.