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

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Subcontractors:

- Global Engineering and Technology LLC, Camas, WA
- Ben C. Gerwick Inc., Oakland, CA
- MegaStir Technologies LLC, Provo, UT
- University of Michigan, Ann Arbor, MI

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

Fiscal Year (FY) 2012 Objectives

- Develop a high-fidelity cost modeling tool for composite pressure vessels designed based on relevant industry standards and codes
- Quantify the significant cost reduction attainable by composite vessel technology through the optimal use of steels and concretes and the optimization of vessel geometry
- Demonstrate a novel steel vessel manufacturing technology based on ORNL-patented multi-pass, multi-layer friction stir welding (MM-FSW) of thick steel section

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section (3.2) of the Fuel Cell Technologies (FCT) 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 aims at developing and demonstrating the novel design and fabrication technology for low-cost and high-safety composite steel/concrete pressure vessel for stationary gaseous hydrogen storage. The flexible and scalable composite vessel design can meet different stationary storage needs (e.g., capacity and pressure) at hydrogen fueling stations, renewable energy hydrogen production sites, and other non-transport storage sites. As shown in Table 1, the current generation composite vessel made using the existing design and manufacturing technology can readily exceed DOE's 2015 cost target. Moreover, with the successful development of advanced manufacturing technology such as the highly-automated friction stir welding process, the next generation vessel has a high potential to meet DOE's 2020 capital cost target.

TABLE 1. Progress towards Meeting Technical Targets for Stationary Gaseous H_2 Storage Tanks (for fueling sites, terminals, or other non-transport storage needs)

Pressure	DOE 2015 Target*	Current generation composite vessel	DOE 2020 Target*	Next generation composite vessel
345 bar (5,000 psi)	$884 per kg of H_2	$800 per kg of H_2	$735 per kg of H_2	$680 per kg of H_2

*DOE targets for 345 bar pressure were linearly interpolated between the targets at 160 and 430 bar (cost target data from the draft of 2011 FCT Program Technical Plan for Hydrogen Delivery, currently being finalized).

FY 2012 Accomplishments

- Designed a high-pressure composite vessel comprising inner layered steel tanks and outer reinforcement pre-stressed concrete for stationary gaseous hydrogen storage at an estimated capital cost about 10% below the relevant DOE technical target for 2015.
- Identified the pathways to achieve the DOE 2020 target through development of advanced vessel manufacturing technology and materials.
- Demonstrated the feasibility of MM-FSW for steel vessel fabrication by successfully joining a 15-mm-thick (0.6 in.) steel plate, which nearly tripled the thickness of steel weldable by the conventional FSW.

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Introduction

Off-board bulk stationary storage of hydrogen is a critical element in the overall hydrogen production and delivery infrastructure. Stationary storage is needed at fueling stations, renewable energy hydrogen production sites, central production plants, and terminals, etc. The capacity and hydrogen pressure of the stationary storage vessel 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 hydrogen fueling station may have a higher pressure but smaller storage capacity when compared to that at a renewable energy hydrogen production site. Therefore, it is important the storage vessel is flexible and scalable to meet different storage needs (i.e., capacity and pressure). Moreover, as it provides the surge capacity to handle hourly, daily, and seasonal demand variations, the stationary storage vessel endures repeated charging/discharging cycles. Therefore, the hydrogen embrittlement in structural materials, especially the accelerated crack growth due to fatigue cycling, needs to be mitigated to ensure the vessel safety.

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

Approach

A schematic drawing of the composite pressure vessel in hydrogen fueling station is illustrated in Figure 1, where the salient design features of the composite storage vessel technology are highlighted. The particular vessel design in this figure comprises four inner steel tanks and an outer reinforcement pre-stressed concrete sleeve. The shell section of each steel tank is a layered structure. The innermost layer directly exposed to the high-pressure hydrogen is made of an austenitic stainless steel (e.g., American Iron & Steel Institute 316L or 304L), which excels as a hydrogen embrittlement and permeation barrier. The other layers are made of high-strength low alloy steel (e.g., ASTM SA724), which costs about four times less than the stainless steel. Finally, the steel tanks are encased in the pre-stressed concrete sleeve, which bears the structural loads at an even lower cost when compared to structural steel. The optimal use of commodity materials (i.e., stainless steel, structural steel and concrete) is essential to the cost-effectiveness and safety of composite pressure vessel. The layered steel vessel technology is proven and accepted in industry standards and codes (e.g., American Society of Mechanical Engineers Boiler and Pressure Vessel Code). It has significant cost and safety advantages over the conventional single-section steel vessel. Moreover, the layered steel vessel is amiable to the advanced fabrication technology based on FSW for further reducing fabrication cost. Sensors will be embedded into both inner steel tanks and outer concrete sleeve to ensure the safe and reliable operation in field. The composite vessel shown in Figure 1 has the modular design with scalability and flexibility for meeting different storage pressure and capacity needs.

Results

The major tasks in FY 2012 include: (1) development of a high-fidelity cost modeling tool for composite pressure vessel and performing the cost optimization study using the model tool, (2) preliminary assessment of steel/concrete interface through finite element modeling of stress and displacement, and (3) demonstration of ORNL-patented MM-FSW for

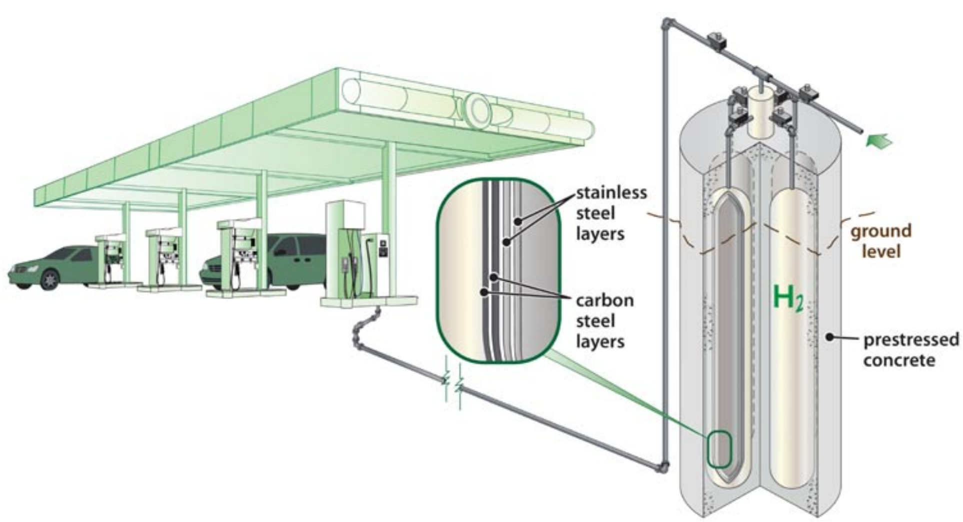

FIGURE 1. Schematic of a composite vessel comprising inner layered steel tanks and outer pre-stressed concrete confinement at hydrogen fueling station

joining of thick steel sections. The key results from this year's substantial development are as follows.

Composite vessel cost modeling and optimization: The baseline composite vessel is designed to contain 1,500 kg of H_2 per system, which is sufficient to refill around 260 fuel cell passenger cars (based on 5.6 kg H_2 tank per car). The design pressure is chosen at 345 bar (5,000 psi) to match the pressure of Type-III hydrogen tank used in fuel cell cars and forklift trucks. It is noted that due to its modular design, the storage vessel can be flexibly adopted for other pressure levels, i.e., low (160 bar), moderate (430 bar) and high (820 bar), and other storage volumes.

To obtain real-world representative cost estimate of composite vessel, ORNL partnered with Global Engineering and Technology and Ben C. Gerwick, two leading engineering design firms in the field of steel pressure vessels and pre-stressed concrete structures, respectively. The high-fidelity cost modeling tool was developed using the bottom-up cost estimate approach comprising the following steps. First, the composite vessel dimensions (e.g., thickness of steel and concrete walls) were calculated using the formula from relevant industry codes for the given user inputs (e.g., pressure, load carrying ratio between concrete and steel, and inner diameter). Second, a detailed, step-by-step manufacturing process flow was established for the composite vessel. Schematics of manufacturing steps for layered steel tank and pre-stressed concrete sleeve are illustrated in Figures 2(a) and 2(b), respectively. Finally, the component cost for each manufacturing step was calculated

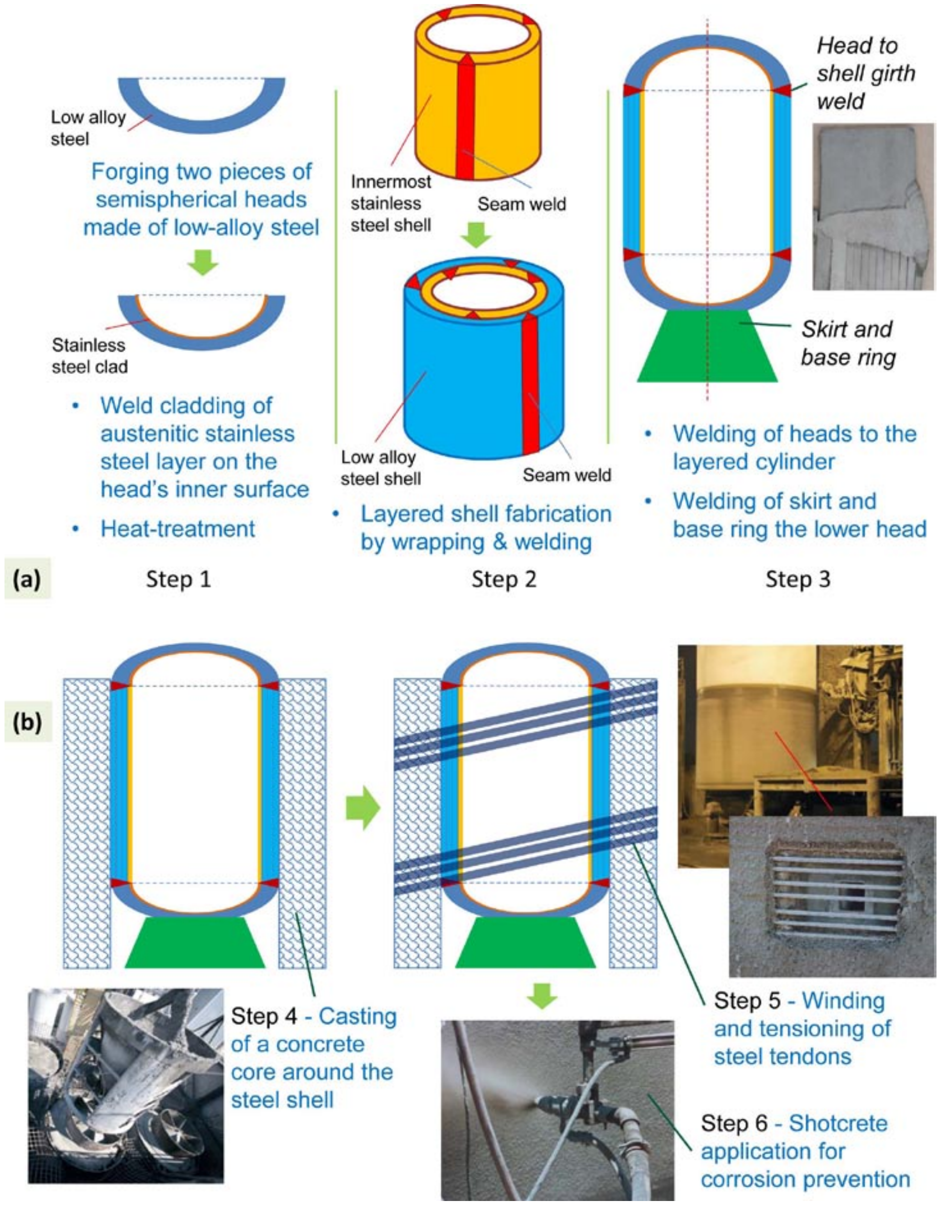

FIGURE 2. Schematics of manufacturing steps for (a) layered steel tank, and (b) pre-stressed concrete sleeve

by considering bill of materials and labor to obtain the total vessel cost.

Figure 3 compares the costs attainable through different composite vessel design and manufacturing technology to the DOE capital cost targets. The leftmost three columns correspond to DOE's latest cost targets obtained by linearly interpolation to 345 bar pressure. Base Case 1 given in column 4 represents the current industry status based on the conventional steel pressure vessel technology. This base case steel vessel, which includes a stainless steel liner as a hydrogen embrittlement and permeation barrier, has an estimated capital cost of \$1,350/kg of H_2. Columns 5 through 7 correspond to the group of composite vessels with 50%-50% load carrying ratio between steel and concrete (so-called Case 2). In particular, Baseline Case 2 (or simply Case 2) is the first design which is used to establish the detailed cost modeling tool. Built on the results of Case 2, a cost optimization study is performed to reach the "Current (generation) Case 2," which can be manufactured with the existing technology for an estimated cost of \$800/kg of H_2. Optimized Case 2 represents the next generation composite vessel where the cost reduction is achievable through further technology development including the automated MM-FSW. Finally, it is also studied Case 3 vessel with 30% steel and 70% concrete, which increases the usage of pre-stressed concrete to bear the structural loads. Case 3 does not seem to result in reduction in the total vessel cost since the needs for ultra-high strength concrete and additional longitudinal tensioning add significant cost that outweighs the cost saving due to the thinning of the steel tank.

Through the detailed cost modeling and optimization study, it is shown that the 50/50 composite vessel using the existing design and manufacturing technology can readily exceed DOE's 2015 cost target. Moreover, it is highly feasible for the composite vessel to meet DOE's 2020 cost target through the development of advanced vessel manufacturing technology and materials, as discussed in a later section.

It is noted the high-fidelity cost modeling tool for the steel/concrete composite vessel technology is currently being refined and finalized. The refinements include the following. First, a high-productivity electroslag strip cladding process is being considered for manufacturing of the stainless steel liner, which can significantly reduce the liner cost when compared to the conventional weld overlay process. Second, the cost savings achievable through the use of friction stir welding for layered steel shell manufacturing are being quantified based on published data from relevant literature. Finally, the refined cost modeling tool is being applied to study the new vessels for three pressure levels (160, 430 and 860 bar) relevant to the hydrogen production and delivery infrastructure. The final cost study results will be published in an ORNL report entitled "Manufacturing Cost Analysis of Novel Steel/Concrete Composite Vessel for Stationary Storage of High-Pressure Hydrogen."

<u>Assessment of steel/concrete interface:</u> Due to the different mechanical properties between steel and concrete, the steel/concrete interface is one of the most critical locations in a composite vessel. In collaboration with University of Michigan, a finite element analysis was performed to study the deformation compliance across the

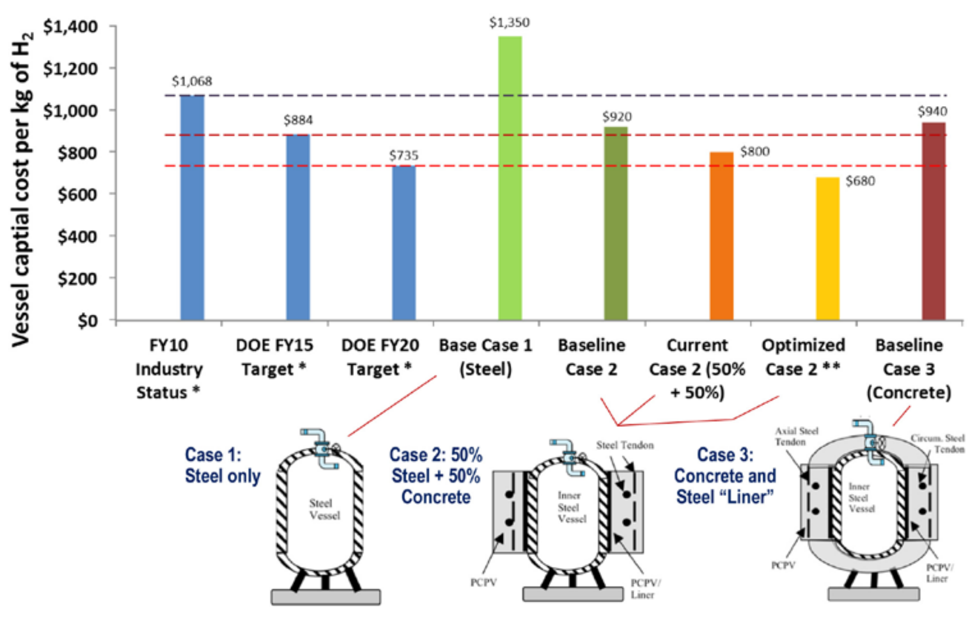

FIGURE 3. Comparison of the capital costs attainable through different composite vessel design and manufacturing technology to the DOE cost targets

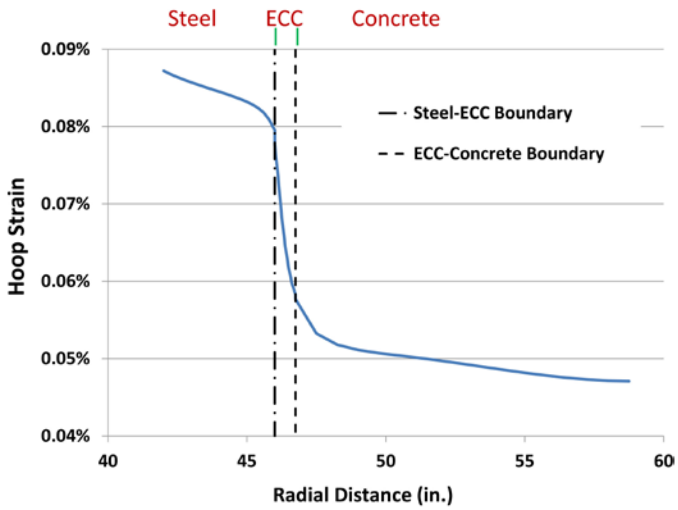

FIGURE 4. Finite element analysis results showing the hoop strain distribution across the steel/concrete interface, indicating a buffer layer of ECC can effectively reduce the tensile strain in the concrete material

steel/concrete interface. A ductile, engineered cementitious composite (ECC) [1] was used as a soft buffer layer between the steel and the concrete. Figure 4 shows the calculated hoop strain profile across the steel/concrete interface under the influence of both external pre-stressing and internal pressurization. As shown in this figure, the tensile strain decreased rapidly within the ECC layer, which limited the tensile strain exerted in the concrete due to internal pressurization. In other words, by utilizing the ductile ECC as soft buffer layer to absorb the majority of deformation, the concrete is exposed to much less tensile strain, thus significantly minimizing the risk of concrete brittle failure under tension.

Manufacturing technology: The detailed cost analysis in the previous task identified that a major pathway for further reducing the total composite vessel cost is the development of advanced welding process to displace the labor-intensive, conventional arc welding construction of steel shells. The highly-automated FSW process, being developed in this project, is expected to significantly reduce the labor cost while improving the weld quality at the same time. In FY 2012, the development effort was focused on the scale up of FSW for thick-section steel structures. The novel MM-FSW process (ORNL Patent US 7,762,447 B2) was successfully developed to weld 15-mm-thick (0.6 in.) pressure vessel steel plates, nearly tripling the thickness of steel that was weldable by the single-pass FSW [2]. Mechanical testing of the friction stir welded thick steel plate is ongoing. Moreover, the MM-FSW technology will be further developed to scale up to the expected wall thickness of the hydrogen storage steel tank.

Conclusions and Future Directions

- Through the detailed engineering calculations and cost optimization study, it is shown that the composite steel/concrete vessel can be fabricated using the existing technology for an estimated capital cost about 10% below the DOE 2015 target. Moreover, with the successful development of advanced manufacturing technology and materials, the next generation composite vessel has a high potential to meet DOE's 2020 capital cost target.
- The feasibility of MM-FSW for steel vessel fabrication is demonstrated by successfully joining a 15-mm-thick (0.6 in.) steel plate, nearly tripling the thickness of steel that can be welded by the single-pass FSW.
- Future directions in FY 2013 and subsequent years will be focused on the manufacturing and testing of mock-up composite storage vessel, which are crucial for enabling the near-term impact of the developed storage technology on high-pressure gaseous hydrogen storage market (especially stationary storage for hydrogen fueling station).

FY 2012 Publications/Presentations

1. W. Zhang *et al.*, "Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage," invited talk at Zhejiang University, China in Oct. 2011, hosted by Professor Jingyang (JY) Zheng.

2. W. Zhang *et al.*, DOE Hydrogen Delivery Tech Team (DTT) Meeting, Southfield, MI, March 2012.

3. W. Zhang *et al.*, 2012 DOE Annual Merit Review, Fuel Cell Technologies Program, Washington, DC, May 2011.

4. W. Zhang *et al.*, "Design Analysis of Composite Vessel for High-Pressure Hydrogen Stationary Storage," abstract accepted to the 2012 International Hydrogen Conference.

5. Y.C. Lim *et al.*, "Mechanical properties and microstructure characterization of multilayered multipass friction stir steel weld," abstract submitted to 2013 TMS Annual Meeting.

References

1. Li, V.C., "High-Ductility Concrete for Resilient Infrastructure", Journal of Advanced and High-Performance Materials, pp.16-21, 2011.

2. 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.