III.7 Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage

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- Ben C. Gerwick Inc., Oakland, CA
- MegaStir Technologies LLC, Provo, UT
- Kobe Steel, LTD., Japan

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Project End Date: Project continuation and direction determined annually by DOE

Overall Objectives

- To address the significant safety and cost challenges in high-pressure stationary hydrogen storage technology
- To develop and demonstrate a novel steel/concrete composite vessel (SCCV) design and fabrication technology for stationary hydrogen storage systems

Fiscal Year (FY) 2014 Objectives

- Validate that SCCVs can reduce the cost of stationary hydrogen storage and meet the DOE 2015 cost target of $1,200/kg stored at 860 bar
- Demonstrate friction stir welding scale-up manufacturing process for multiple-layer steels with wall thickness of 1.5 inch
- Design, engineer and manufacture a representative ¼-sized mock-up SCCV capable of storing 90 kg gaseous hydrogen at 430 bar, capturing all major features of SCCV design and fabricability with today's manufacturing technologies and code/standard requirements

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section (3.2) of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan:

(E) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Technical Targets

This project aims to develop and demonstrate the novel design and fabrication technology for low-cost and high-safety SCCVs 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 (FSW) process, the next generation vessel has a high potential to meet DOE's 2020 capital cost target. Details of the cost analysis are given in Zhang, et al [1].

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

Pressure	DOE 2015 Target	Current SCCV	DOE 2020 Target	Next generation SCCV
Low Pressure (160 bar) Purchased Capital Cost ($/kg of hydrogen stored)	850	681	700	652
Moderate Pressure (430 bar) Purchased Capital Cost ($/kg of hydrogen stored)	900	713	750	684
High Pressure (860 bar) Purchased Capital Cost ($/kg of hydrogen stored)	1,200	957	1,000	919

FY 2014 Accomplishments

- Validated that SCCVs can reduce the cost of stationary hydrogen storage by more than 15% and meet the DOE 2015 cost target of $1,200/kg-stored at 860 bar through detailed vessel design and supplier quotes.

- Completed the demonstration of friction stir welding scale up process for a multiple layer high strength steel with total thickness of 1.5 inch.
- Completed detailed engineering design and fabrication specifications for the ¼-sized mock-up composite SCCV capable of storing 90 kg gaseous hydrogen at 430 bar. Fabrication of the inner steel vessel is underway. Finalized procurement of concrete forming and pre-stressing. Made detailed plans on the follow up vessel testing and demonstration.

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INTRODUCTION

Low-cost infrastructure is critical to successful market penetration of hydrogen-based transportation technologies such as off-board bulk stationary hydrogen storage. Stationary storage is needed in many locations ranging from hydrogen production plants to refueling stations. The design capacity and 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 example, storage vessels at a hydrogen refueling station may have higher pressures but smaller storage capacity when compared to that at a renewable energy hydrogen production site. Therefore, it is important the make storage vessel design flexible and scalable in order to meet different storage needs. 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. Therefore, safety and economics are two prevailing drivers behind the composite hydrogen storage technology.

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 high-pressure steel/concrete composite storage vessel that can meet different stationary hydrogen storage needs.

APPROACH

A novel SCCV has been specifically designed and engineered for stationary high-pressure gaseous hydrogen storage applications. SCCV has several inherent features aimed at solving the two critical limitations and challenges of today's high-pressure hydrogen storage vessels—the high capital cost and the safety concerns of hydrogen embrittlement of high-strength steel vessels.

The basic concept of SCCV is illustrated in Figure 1. SCCV comprises four major innovations: (1) flexible modular design for storage stations for scalability to meet

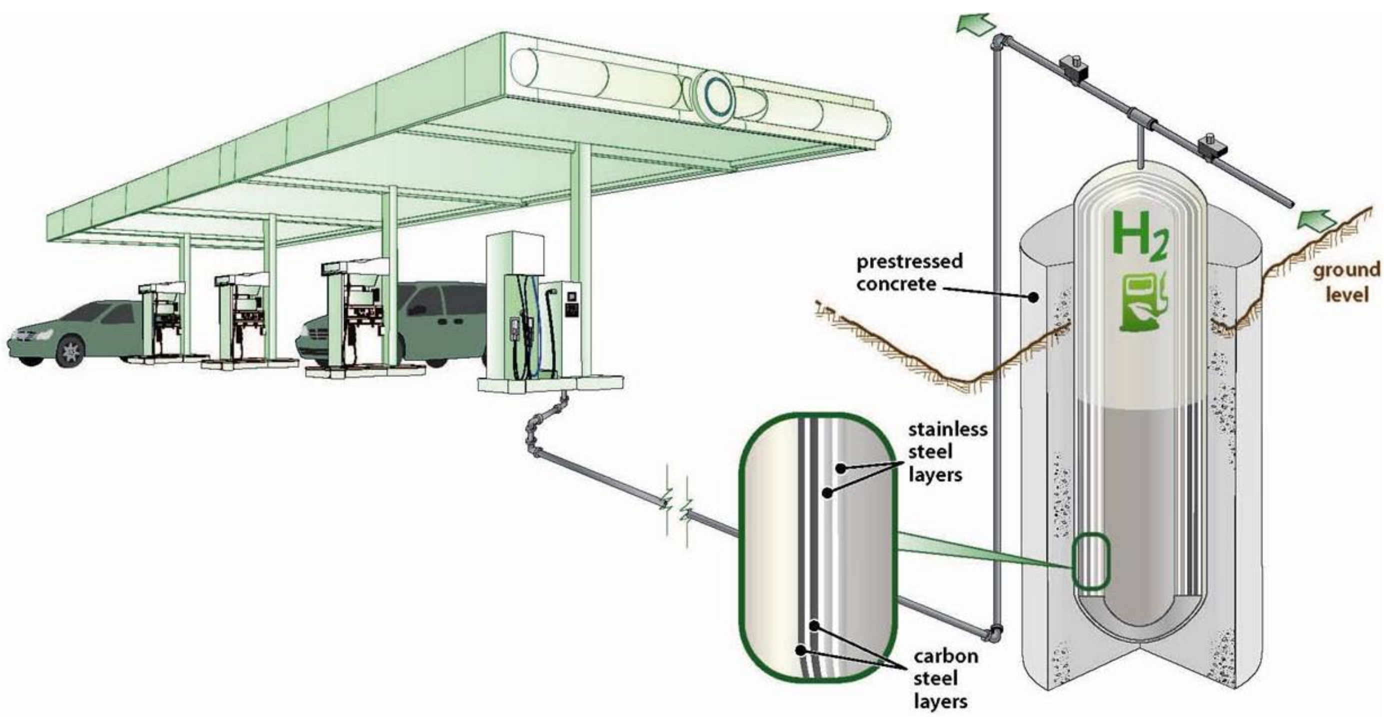

FIGURE 1. Schematic showing the design of a steel/concrete composite vessel comprising inner layered steel tanks and outer pre-stressed concrete confinement.

different storage pressure and capacity needs, flexibility for cost optimization, and system reliability and safety; (2) composite storage vessel design and construction with a inner steel vessel encased in a pre-stressed outer concrete reinforcement; (3) layered steel vessel wall and vent holes to solve the hydrogen embrittlement problem by design; and (4) integrated sensor system to monitor the structural integrity and operation status of the storage system. Together, these innovations form an integrated approach to make the SCCV cost competitive and inherently safe for stationary high-pressure hydrogen storage services. The inner steel vessel is a multi-layer design with strategically placed vent holes to prevent the intake and accumulation of hydrogen in the steel layers except the innermost layer. This effectively solves the hydrogen embrittlement problem by design and frees up the selection of steel for cost optimization. Furthermore, the novel steel/concrete composite vessel design allows for the stresses or the structural load from the high-pressure hydrogen to be shared between the inner steel vessel and the pre-stressed outer concrete reinforcement, thereby offering the flexibility to optimize the use of low-cost commodity materials (such as structural steels and concretes) and industry accepted fabrication technologies for cost reduction. For example, the layered steel vessel technology is proven and accepted in industry standards and codes (e.g., American Society of Mechanical Engineers [ASME] Boiler and Pressure Vessel Code). Moreover, the layered steel vessel is amiable to the advanced fabrication technology based on FSW for further reducing fabrication cost.

RESULTS

The major tasks in FY 2014 include (1) validate the SCCV design can reduce the cost of stationary hydrogen storage by more than 15% and meet the DOE 2015 cost target; (2) demonstrate ORNL-patented multi-pass, multi-layer (MM)-FSW for joining a multiple-layer ASME A516 Grade 70 steel to a total thickness of 1.5 inch; and (3) design and fabricate a ¼-size mock-up composite vessel capable of storing 90 kg gaseous hydrogen at 430 bar, while capturing all major features of SCCV design and fabricability with today's manufacturing technologies and code/standard requirements. The key results from this year's substantial development are as follows.

Validation on Cost Reduction of SCCV at 860 bar

The high-fidelity cost analysis tool developed in this project was used to optimize the design and engineering of the SCCV to achieve DOE's cost target. Since SCCVs can be fabricated with relatively mature technologies, it was possible to obtain cost figures for fabrication of SCCVs from commercial manufacturing vendors. A number of industry manufacturing vendors were surveyed, and a detailed cost breakdown of fabricating different parts of the SCCV structure was obtained under the assumption of moderate to high-volume production scenario. These cost figures were used as the basis for design and engineering optimization to meet the DOE cost target. A thorough study was performed to optimize the design and fabrication cost of SCCVs for hydrogen storage. The details of the cost analysis are summarized in an ORNL Technical Report [1].

The cost analysis results show that the 50/50 SCCV design is economically viable and technically feasible for storing compressed gaseous hydrogen. The design specifications were based on a 1,500 kg hydrogen station storage capacity design capable of refilling 250 to 300 cars per week, in moderate volume production (24 identical vessels per order). The unit cost breakdowns are listed in Table 1. As shown in this table, the steel vessel constitutes around 73% of the total SCCV cost. In other words, the pre-stressed concrete enclosure bears half of the total structural load at a cost that is only 37% of the steel vessel which bears the other half of the load. Hence, it is cost-effective to use the low-cost pre-stressed concrete enclosure to bear 50% of the structural load when compared to the current industry-standard steel-only pressure vessel.

In addition, further cost reduction can be achieved for the construction of the layered steel vessel. The detailed cost analysis shows that a major pathway for further reducing the total composite SCCV cost is the development of an advanced welding process to replace labor-intensive conventional arc welding of steel shells. ORNL has successfully developed a novel MM-FSW process (US Patent 7,762,447 B2) and high-strength steel plates fabricated by multi-pass FSW are demonstrated to show better or equivalent mechanical properties than the base metal. The highly automated FSW process is expected to significantly reduce labor costs while improving weld quality.

Table 1. Unit Cost Breakdowns for the 860-bar SCCV

Steel vessel (unit price $ per kg of stored hydrogen)	
Bill of materials	386
Labor (conventional arc welding)	251
Labor (FSW)	213
Consumables and others	33
Pre-stressed concrete enclosure (unit price $ per kg of stored hydrogen)	
Concrete	14
Rebar	4
Pre-stressing wire	269
Total SCCV unit cost ($ per kg of stored hydrogen)	
SCCV	957
SCCV with FSW	919

Note: The unit cost of SCCV utilizing FSW for layered steel shell manufacturing is projected by reducing the inner steel vessel manufacturing labor cost by 15%.

Figure 2 summarizes the projected total SCCV costs at 860-bar pressure from the detailed comparison of the

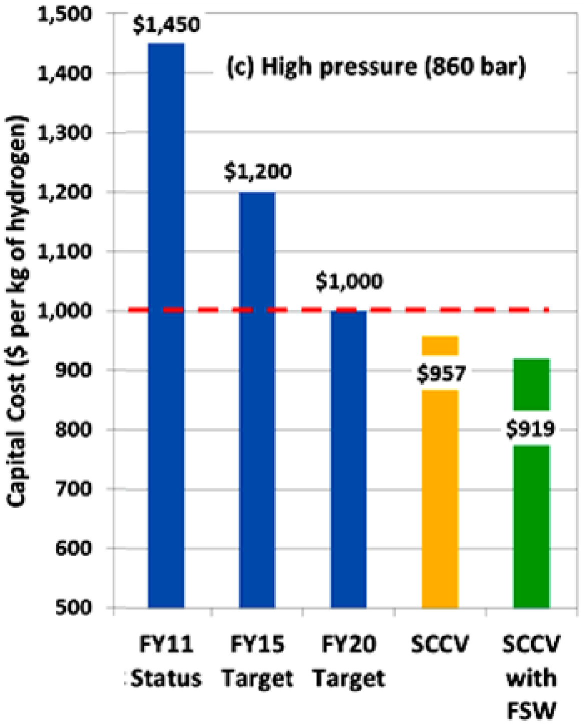

FIGURE 2. Comparison between SCCV unit costs and DOE technical targets for hydrogen pressures of 860 bar.

current cost status, DOE FY 2015 target, and DOE FY 2020 target. As shown in this figure, the projected cost of SCCV technology exceeds the DOE FY 2015 cost targets by about 20%, and potentially by 23% if FSW technology is commercialized and used. Furthermore, the SCCV technology exceeds the DOE FY 2020 cost targets by about 4%, and by 9% with the FSW technology.

Scale Up Demonstration of Friction Stir Welding Technology

In FY 2014, the feasibility of MM-FSW technique was successfully demonstrated on 15-mm thick three-layer pressure vessel steel (ASTM International technical specification 572 G50) plates and steel pipes [2]. This year, MM-FSW was further scaled up on 1.5-in (38.1-mm) thick, six-layer high-strength low-alloy steel (ASTM A516 Grade 70). The six-layer FSW was tested for transverse weld tensile and Charpy V-notch impact toughness as a function of temperature. Microstructure characterizations and digital image correlation technique were used during transverse weld tensile test to understand the local deformation and failure associated with the improvement in weld mechanical properties.

Consistent with our previous research on FSW of high-strength steels [2,3], the transverse weld tensile test revealed that the failure was in the base metal, far away from the FSW region (Figure 3), for defect-free welds produced

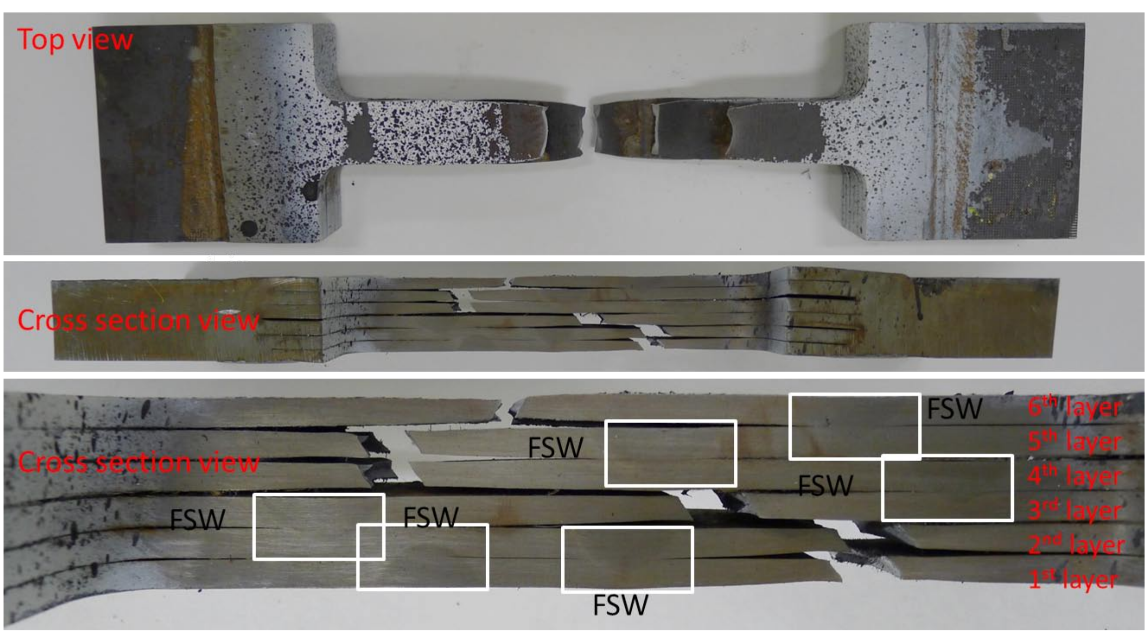

FIGURE 3. A six-layer MM-FSW sample after transverse tensile test. (a) top view image showing broken specimen. (b) Cross-sectional view of failed sample with each layer. Failure location for each layer was at the base metal. Note that a white box indicates friction stir weld (lightly etched with Nital solution) at each layer.

in this project (as determined by an X-ray non-destructive evaluation method). In addition, the Charpy V-notch impact toughness in both the stir zone and the heat affected zone of the friction stir welds are consistently higher than that of the base metal over the entire temperature range tested (-50 to 20°C).

Mock-Up SCCV Fabrication

A ¼-size mockup SCCV is under construction and expected to be completed in FY 2015 due to the relatively long leadtime (10 months) associated with the one-of-a-kind design. As shown in Figure 4, the mock-up vessel has all the essential features and functionality of the full-size SCCV. It contains the inner steel vessel and the outer pre-stressed concrete reinforcement containment. This mock-up vessel is designed to store 89 kg of hydrogen compressed to 430 bar (6,250 psi, or 43 MPa). The steel has a stainless steel inner layer as the hydrogen permeation barrier, hydrogen charging and discharging ports, and trunions for tank handling during the concrete construction and in-service installation. In addition, a manway on the top is added to the mock-up vessel, as it is an essential feature in the construction, inspection, and repair of the full-size steel vessel. The reinforcement skirt has a 6 inch thick concrete layer and five layers of pre-stressing wires.

The inner steel vessel will be built, inspected and hydro-tested in accordance to the ASME Boiler and Pressure Vessel Code Section VIII Division 2 (2013 Edition), and will be code stamped for high-pressure service, as expected for future commercial SCCV for high-pressure hydrogen storage. The pre-stressed concrete outer reinforcement is designed and constructed by ACI design allowables. The entire completed vessel will be hydro-static tested at 1.4 times the design pressure as part of code acceptance. A cyclic hydrogen

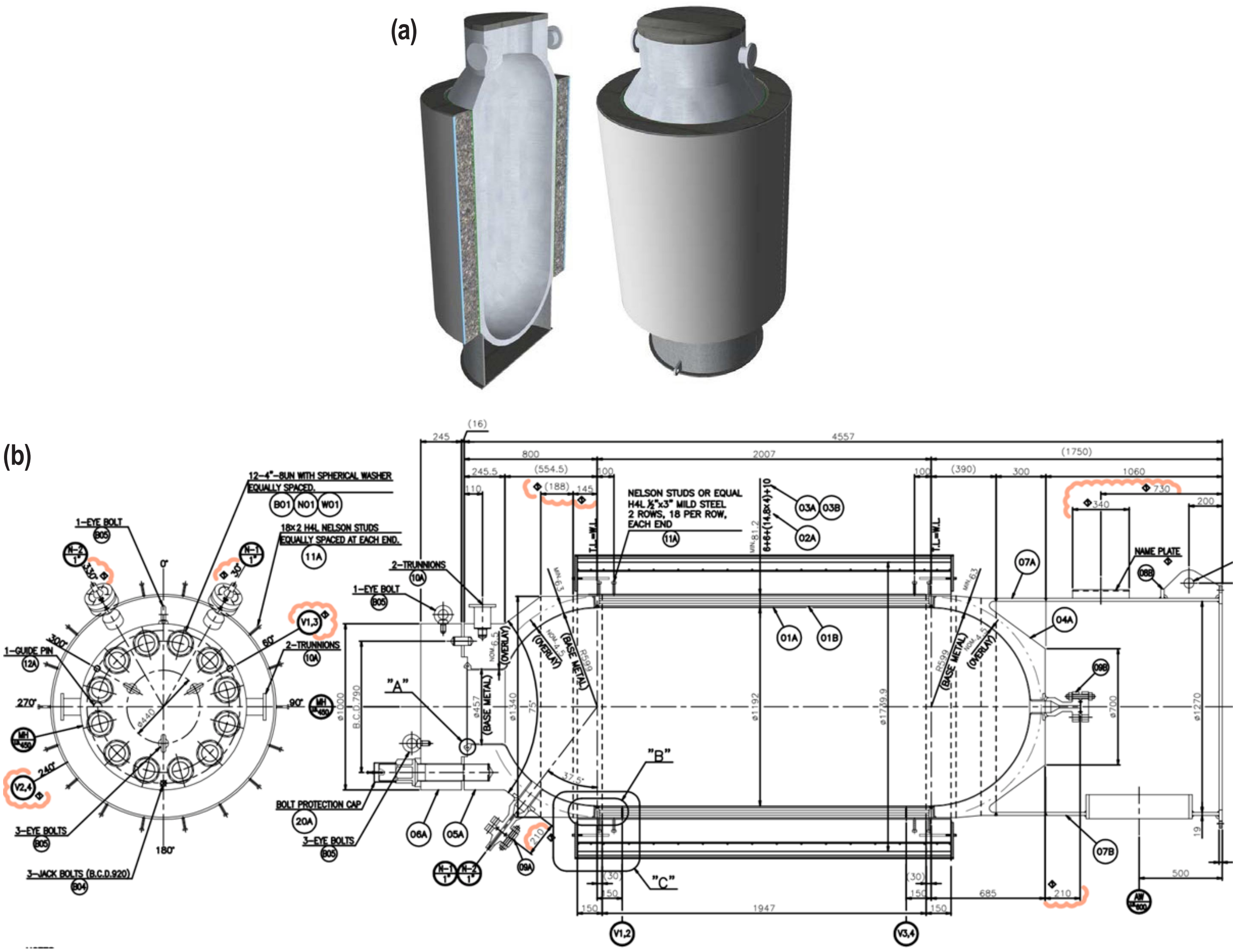

FIGURE 4. (a) Rendition of the mock-up design with all essential features of a SCCV for high-pressure hydrogen storage. (b) Detailed engineering drawing.

pressure loading test simulating hydrogen storage service conditions is planned to be completed.

CONCLUSIONS AND FUTURE DIRECTIONS

- The SCCV design was validated to reduce the cost of stationary hydrogen storage by more than 15% and meet the DOE 2015 cost target of $1,200/kg-stored at 860 bar. Further cost reduction concepts will be evaluated.
- The FSW scale-up process was demonstrated for a multiple layer high-strength steel with total thickness of 1.5 inch. This confirms the potential of using this technique as a future cost reduction element for hydrogen storage vessels.
- The fabrication of the ¼-sized mock-up SCCV capable of storing 90 kg gaseous hydrogen at 430 bar is ongoing.
- Testing of the mock-up SCCV under high-pressure hydrogen including long-term performance evaluation under cyclic hydrogen pressure loading is planned in FY 2015 to demonstrate both the constructability and performance of the SCCV for hydrogen storage.

FY 2014 PUBLICATIONS/PRESENTATIONS

1. Y.C. Lim, S. Sanderson, M. Mahoney, Y. Wang, and Z. Feng, "Mechanical properties and characterization of friction stir welded/root arc welded pipe steel," abstract accepted, 2014 MS&T conference.

2. Y. Wang, Y.C. Lim, F. Ren, W. Zhang, M. Jawad, F. Vossoughi and Z. Feng, 2014. "Steel-Concrete Composite Vessel for Stationary High-Pressure Hydrogen Storage," ASME 2014 12th Fuel Cell Science, Engineering & Technology Conference, Boston, MA, June 30 – July 2, 2014.

3. Y. Wang, Y.C. Lim, J-A Wang, L. Anovitz, W. Zhang, and Z. Feng, 2014. "Evaluation of Mechanical Property Testing Procedures and Techniques for Materials used for Hydrogen Storage and Distribution," ASME 2014 12th Fuel Cell Science, Engineering & Technology Conference, Boston, MA, June 30 – July 2, 2014.

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2. Y.C. Lim, S. Sanderson, M. Murray, X. Yu, D. Qiao, Y. Wang, W. Zhang, Z. Feng, "Characterization of Multilayered-Multipass Friction-Stir Weld on ASTM A572 G50 steel" in press, Welding Journal.

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