III.2 Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage

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- MegaStir Technologies LLC, Provo, UT
- Kobe Steel, LTD., Japan
- Hanson Pressure Pipe, Grand Prairie, TX
- Harris Thermal Transfer Products, Newberg, OR
- Temple University, Philadelphia, PA

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

Overall Objectives

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

Fiscal Year (FY) 2015 Objectives

- Demonstrate and validate the entire SCCV design concept and manufacturability using today's industry-scale manufacturing technologies that are accepted by relevant code/standard requirements
- Complete an SCCV prototype mockup capable of storing 90 kg gaseous hydrogen at 430 bar, which captures all major features of SCCV design and manufacturing requirements
- Complete hydrostatic test at 616 bar (1.43 times the design pressure, 430 bar) of the mockup SCCV to demonstrate both the constructability and performance of the SCCV per American Society of Mechanical Engineers (ASME) boiler and pressure vessel (BPV) code requirement
- Complete the initial phase of long term testing of the prototype SCCV performance under cyclic high-pressure hydrogen loading, simulative of hydrogen charging and discharging cycles of hydrogen refueling stations, at one to two cycles per day from 100 bar to 430 bar

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 (MYRDD) Plan (updated August 2015):

(E) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs

Technical Targets

This project aims at developing and demonstrating SCCVs as low-cost, safe means of stationary storage for gaseous hydrogen storage. SCCVs are scalable to different pressures and capacities, and can therefore satisfy a variety of applications 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 exceeds the DOE cost targets in place when the project began [1].

TABLE 1. Progress Towards Meeting Technical Targets for Stationary Gaseous H_2 Storage Tanks (for Fueling Sites, Terminals, or Other Nontransport Storage Needs)

Pressure	DOE 2015 Status	Current SCCV (2015)	DOE 2020 Target
Low Pressure (160 bar) Purchased Capital Cost ($/kg of H_2 stored)	$850	$681	$500
Moderate Pressure (430 bar) Purchased Capital Cost ($/kg of H_2 stored)	$1,100	$713	$600
High Pressure (860 bar) Purchased Capital Cost ($/kg of H_2 stored)	N/A	$957	N/A
High Pressure (925 bar) Purchased Capital Cost ($/kg of H_2 stored)	$2,000	N/A	$600

Note: Cost analysis of SCCV was based on the pressure levels from a previous DOE MYRDD Plan.

FY 2015 Accomplishments

- Successfully passed a major milestone of the project: an SCCV mockup capable of storing 90 kg gaseous hydrogen at 430 bar has been designed, fabricated, and tested for hydrogen storage per relevant codes and standards
- Demonstrated and validated the SCCV operation and manufacturability using today's industry-scale manufacturing technologies that are accepted by relevant code/standard requirements
- Completed hydrostatic test at 616 bar (1.43 times the design pressure, 430 bar) of the mockup SCCV to validate both the constructability and performance of the SCCV per ASME BPV code requirement

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INTRODUCTION

Low-cost infrastructure, such as off-board bulk stationary hydrogen storage, is critical to successful market penetration of hydrogen-based transportation technologies. 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 those at a renewable energy hydrogen production site. Therefore, it is important to develop vessel designs that are scalable to different pressures and capacities. Moreover, since storage vessels provide the surge capacity to handle hourly, daily, and seasonal demand variations, they endure repeated charging/discharging cycles. Thus, the hydrogen embrittlement in structural materials, especially the accelerated crack growth due to fatigue cycling, needs to be mitigated to ensure the vessel safety. 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 (HE) of high-strength steel vessels.

The basic concept of SCCV is illustrated in Figure 1. SCCV comprises four major innovations: (1) flexible modular design that can be scaled to meet different pressure and capacity needs, as well as different manufacturing scenarios; (2) composite design that combines an inner steel vessel with a pre-stressed outer concrete reinforcement; (3) layered steel vessel wall and vent holes to solve the hydrogen embrittlement (HE) problem by design; and (4) integrated sensor system to monitor the structural integrity and operation status of the storage system. Together, these innovations make the SCCV cost-competitive and inherently safe for stationary high-pressure hydrogen storage services. The inner steel vessel is composed of multiple layers with strategically placed vent holes to prevent the intake and accumulation of hydrogen in the steel layers except the innermost layer. Since the innermost layer is the only one to face significant volumes of hydrogen, it is the only layer made of stainless steel. This layered design thereby minimizes steel vessel cost while ensuring resistance to HE. 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., ASME BPV code). Moreover, the layered steel vessel has potential for further cost reduction through advanced fabrication technologies, such as friction stir welding.

RESULTS

The primary focus in FY 2015 was to demonstrate and validate the entire SCCV design concept manufacturability and operation using today's industry-scale manufacturing technologies accepted by relevant code/standard requirements. This included the following major tasks: (1) complete the design, engineering, and construction of an SCCV prototype mockup capable of storing 90 kg gaseous hydrogen at 430 bar, which captures all major features of SCCV design and manufacturing requirements by April 30, 2015; (2) complete a hydrostatic test at 616 bar (1.43 times the design pressure, 430 bar) of the mockup SCCV to validate the performance of the SCCV per ASME BPV code requirement; and (3) complete the initial phase of long-term testing of the prototype SCCV performance under cyclic high-pressure hydrogen loading, simulative of the expected hydrogen charging and discharging cycles at hydrogen refueling stations, 1–2 cycles per day from 100 bar to 430 bar.

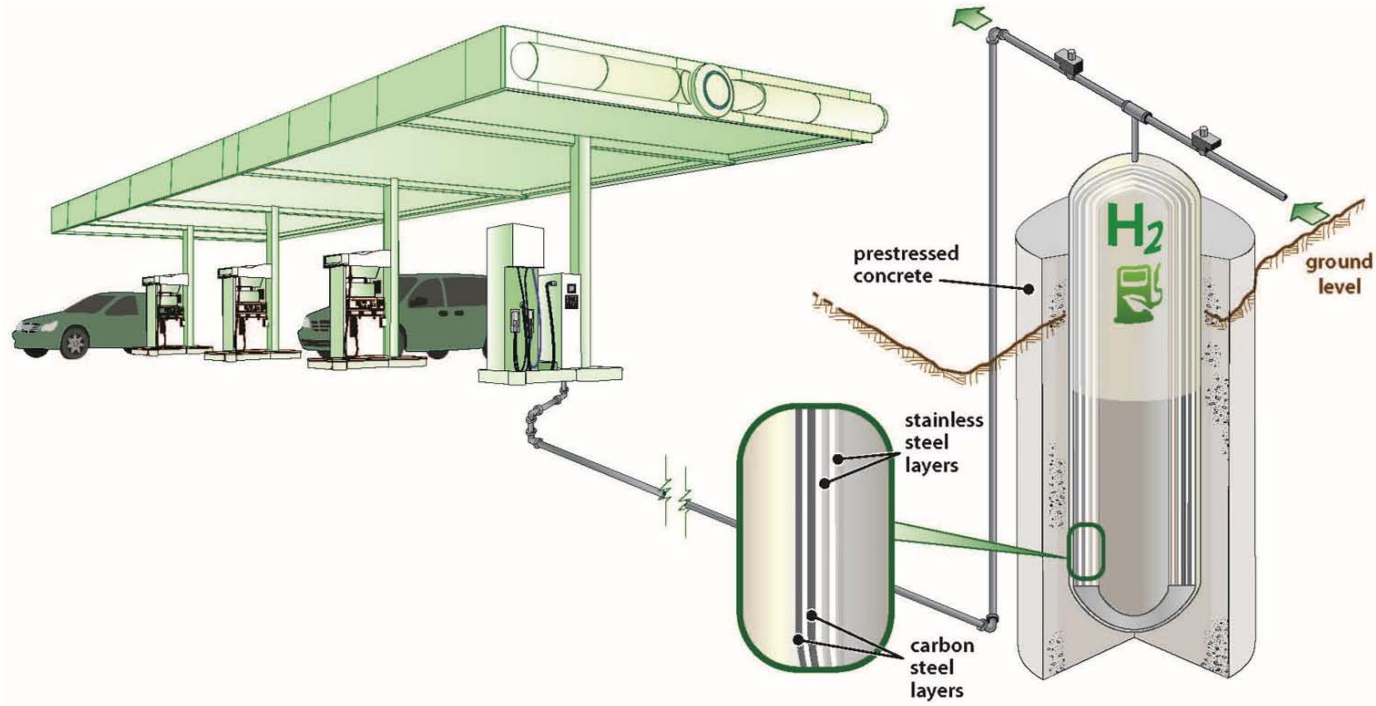

FIGURE 1. Schematic showing the design of a steel/concrete composite vessel comprising inner layered steel tanks and outer prestressed concrete confinement

Mockup SCCV Design and Engineering

A ¼ size mockup SCCV was designed, engineered, and constructed. Extensive finite element computations were carried out in the design and engineering of the mockup SCCV to realize the novel SCCV design concept while assuring relevant codes compliance and feasibility of fabrication using today's industry-scale manufacturing capability. Figure 2(a) shows the finite element model used in the design and engineering of the SCCV mockup. Figure 2(b) shows the hoop stress distribution in the concrete after pre-stress was applied, at operation pressure and at the hydrostatic test pressure. The calculation results are also given in Table 2. All stresses in different parts of the mockup are below the code allowable stress levels for these components during pre-stressing and at operation pressure of 6,250 psi (430 bar) and hydro-testing pressure of 8,940 psi (616 bar).

The mockup 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. 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 mockup vessel, as it is an essential feature in the construction, inspection, and repair of the full-size steel vessel.

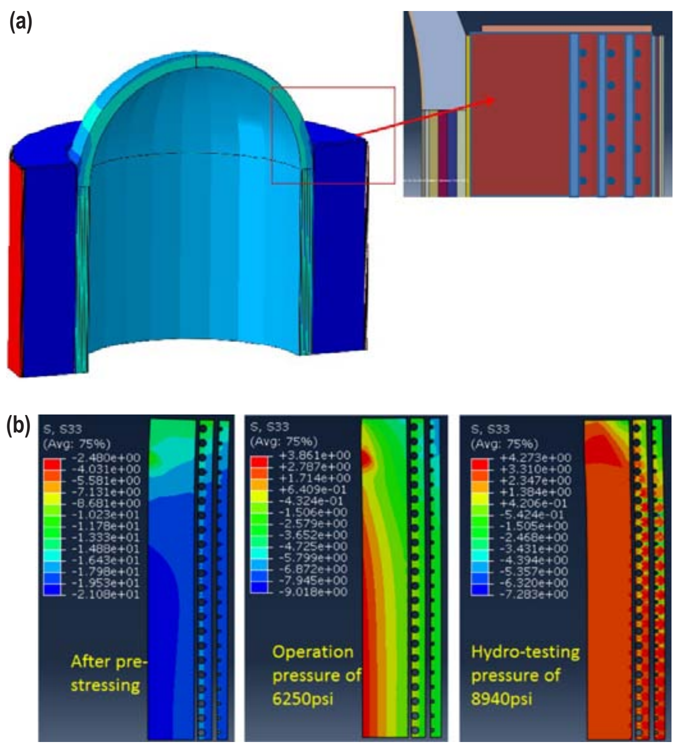

FIGURE 2. (a) Finite element model used to optimize the SCCV design; (b) Hoop stress distribution in the concrete after prestress applied, at operation pressure, and at the hydrostatic test pressure

TABLE 2. Hoop Stresses of the SCCV Steel Components (Code Allowable Stresses, σ_a, are in Parentheses)

Range of the Hoop Stresses		After prestressing, in ksi	6,250 psi operation pressure, in ksi	8,940 psi hydro-test pressure, in ksi
Inner steel vessel	Layered high strength steel shell (σ_a = 39.6 ksi)	-14 to -8	21 to 12	38 to 22
	Inner stainless liner (σ_a = 31 ksi, and -36 ksi for compression buckling)	-35.6 to -31.8	-1.5 to -9.1	7.8 to 0.5
Inner cage spiral rebar (σ_a = 32 ksi)		-15.6 to -10.8	1.4 to -3.0	9.5 to 0.7
Pre-stressing wire (σ_a = 227 ksi)		127 to 115	140 to 125	146 to 129

Mockup SCCV Construction

The inner steel vessel was constructed by Kobe Steel, per design specifications from the project. The inner steel vessel was built, inspected, and hydro-tested in accordance with the ASME BPV Code Section VIII Division 2 (2013 Edition) and was code-stamped for high-pressure services at 3,620 psi (without the pre-stressed concrete) before being shipped to add the pre-stressed concrete layer.

The outer concrete reinforcement was fabricated by Hanson Pressure Pipe. The concrete section is approximately 11 inches thick. It has three rebar cages, each consisting of vertical steel rebars and spiral steel rebars, as determined from the finite element modeling (FEM) analysis. These steel rebars were used to carry the tensile stresses from the service loading to prevent the concrete from cracking. In addition, a total of five layers of steel wire wrapping were used to pre-stress the concrete such that it is able to share 50% of the tension the vessel faces in service. Figure 3 shows the industry-scale wire wrapping process to apply the pre-stressing per SCCV design.

Mockup SCCV Testing

The completed SCCV mockup passed the hydrostatic test at 616 bar (8,940 psi), which is 1.43 times the 430 bar design pressure, thereby successfully validating both the constructability and performance of the SCCV per ASME BPV code requirement. An ASME certified inspector was on site during the hydrostatic test and certified that the entire hydrostatic test was in compliance with the ASME BPV testing requirement. The mockup was certified for pressure loading at the designed 430 bar (6,250 psi).

During both construction and testing of the mockup SCCV, strain gages and other sensors were strategically installed in various locations on the mockup to monitor and control the pre-stressing process of this first-of-its-kind SCCV design. The extensive use of the strain gages provided necessary experimental data to support and validate the design and engineering of SCCV. They also provided valuable insights to a number of variables in vessel manufacturing that influence the pre-stressing. These experiment data are critical for future technology transfer and commercialization of SCCV, especially related to key aspects in various stages of SCCV manufacturing. As one example, the strain variations during hydrostatic testing are presented in Figure 4. The actual strain gage readings during both pressurizing and depressurizing compared very well with the FEM design results. This validated our FEM-based design calculations. Furthermore, the strain gage readings confirmed that there was minimum relaxation of load carrying capacity

FIGURE 3. Wire wrapping during SCCV construction

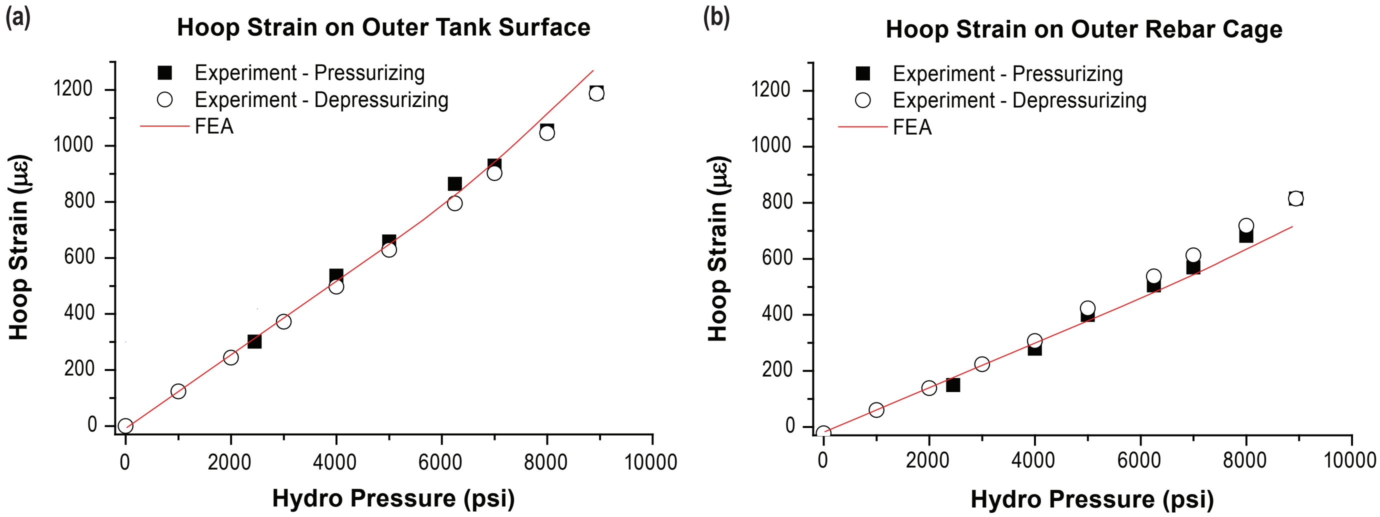

FIGURE 4. Comparison between experimentally measured and finite element analysis predicted strains during hydrostatic testing: (a) hoop strain on the outer surface of the steel vessel; (b) hoop strain on the outer rebar cage

of the vessel after the hydrostatic test. This is a critical experimental result that supports our design analysis and assumption that the concrete would sustain the peak tensile stress at code-required hydrostatic pressure level, which is 1.43 times the operating pressure, without damage.

CONCLUSIONS AND FUTURE DIRECTIONS

The project so far has achieved most of its major milestones and key project objectives:

- Demonstrated that the SCCV would meet or exceed the cost targets set forth in the DOE MYRDD Plan for all three different pressure levels for high-pressure gaseous hydrogen storage.
- Validated the technical basis for hydrogen mitigation by design through lab-scale experiments.
- Demonstrated the superior properties of multi-layer friction stir welds.
- Successfully designed, engineered, and constructed a mockup SCCV, which passed the hydrostatic testing, demonstrating and validating the entire SCCV design concept and manufacturability using today's industry-scale manufacturing technologies and relevant codes/standards.

Future planned activities include

- Completing the long-term testing of the mockup SCCV performance under cyclic hydrogen pressure loading, simulative of expected hydrogen charging and discharging cycles of hydrogen refueling stations, 1–2 cycles per day from 100 to 430 bar.
- Continuing with the lessons learnt in this project to further optimize all aspects of SCCV technology for additional major cost reduction in a follow-on project (Gen II SCCV).
- Technology commercialization.

FY 2015 PUBLICATIONS/PRESENTATIONS

1. Y.C. Lim, S. Sanderson, M. Mahoney, X. Yu, Y. Wang, and Z. Feng, 2014. "Characterization of Multilayered Multipass Friction Stir Weld on ASTM A572 G50 Steel," Welding Journal, vol. 93, 443-s.

REFERENCES

1. W. Zhang, F. Ren, Z. Feng, and J. Wang, "Manufacturing Cost Analysis of Novel Steel/Concrete Composite Vessel for Stationary Storage of High-Pressure Hydrogen," Oak Ridge National Laboratory Report, ORNL/TM-2013/113, Oak Ridge National Laboratory, Oak Ridge, TN, March 2013.