III.3 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) 2016 Objectives

- Establish the experimental procedure and instrumentation for long-term hydrogen cyclic testing of the SCCV prototype.
- Initiate and perform the long-term testing of the SCCV prototype under cyclic, high-pressure hydrogen loading, simulative of hydrogen charging and discharging cycles at hydrogen refueling stations (one to two cycles per day from 100–430 bar).

Technical Barriers

This project addresses the following technical barrier 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 Cost

Technical Targets

This project aims to develop and demonstrate SCCVs as a low-cost, safe means of stationary storage for gaseous hydrogen. 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 existing design and manufacturing technologies 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 Non-Transport Storage Needs)

Pressure	DOE 2015 Status*	Current SCCV	DOE 2020 Target*
Low Pressure (160 bar) Purchased Capital Cost ($/kg of H_2 stored)	$850	$681	$700
Moderate Pressure (430 bar) Purchased Capital Cost ($/kg of H_2 stored)	$900	$713	$750
High Pressure (860 bar) Purchased Capital Cost ($/kg of H_2 stored)	$1,200	$957	$1,000

*Per 2012 version of Multi-Year Research, Development, and Demonstration Plan in place when project began

FY 2016 Accomplishments

- Completed the modification and upgrade of the testing site capabilities to meet the requirements for the long term hydrogen cyclic testing of the demonstration SCCV.
- Automated data acquisition from strain gauges, and pressure and temperature sensors that monitor the vessel performance during cyclic loading.
- Completed the pre-test (including nitrogen purge and hydrogen purge), refined the operating procedure for long term hydrogen cyclic testing, and initiated hydrogen cyclic testing.
- Completed hydrogen impurity analysis of the supplied hydrogen gas and confirmed acceptable hydrogen purity level in the vessel after high purity hydrogen purge.

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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 and 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, Oak Ridge National Laboratory 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 SCCV technology 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 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 all 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 hydrogen embrittlement. 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 has potential for further cost reduction through advanced fabrication technologies, such as friction stir welding.

The prototype SCCV was subjected to two types of tests designed to validate the SCCV technology for high pressure hydrogen storage. First, the SCCV was subjected to hydrostatic testing at 8,950 psi (or 615 bar, 1.43 times of the 430 bar design pressure), to validate the constructability of the SCCV per ASME Boiler and Pressure Vessel Code requirement. In FY 2015, hydro-static test of the demonstration SCCV was successfully completed and both the constructability and performance of the SCCV were validated. Second, a long-term high hydrogen pressure cyclic testing was designed to confirm the suitability of the vessel under expected high pressure hydrogen charging and discharging operation condition, especially the effects of hydrogen embrittlement on structural steels in long-term operation with high pressure hydrogen. This second test is the primary focus in FY 2016.

RESULTS

The primary focus in FY 2016 was to evaluate the performance of the demonstration SCCV under high pressure hydrogen cyclic testing condition that could simulate a typical service condition of a stationary hydrogen storage vessel. The target is to have the vessel subject to cyclic hydrogen pressure loading from 2,000–6,000 psi (i.e., up to 96% of the maximum allowable operation pressure) for a total of 250 cycles to validate its performance for high-pressure gaseous hydrogen storage. It is expected that one to two pressure loading cycles will be carried out per day.

The existing testing facility was modified and upgraded for the high-pressure hydrogen cyclic testing. The demonstration SCCV was placed in a controlled access area restricted to personnel that have been trained in the testing procedure. The test area is readily accessible to the local fire department. The testing setup and the area meet related standards such as National Fire Protection Agency (NFPA) 55, ISA-12.12.01-2007, National Electrical Code NFPA 70 and ASME Boiler and Pressure Vessel Code Section VIII, Division 2 code. The fire marshal has visited the testing site and approved the hydrogen testing arrangement. Figure 1 shows arrangement of the hydrogen cyclic testing site. Multiple strain gauges, pressure sensors, and temperature sensors were placed on the vessel at various locations to provide the much needed experimental data for monitoring the integrity of the vessel under service condition. The test control and data acquisition were automated.

For safety reasons, the demonstration SCCV was filled with glass beads to reduce the hydrogen net volume for the cyclic testing. This reduced the effective volume to about 30% (i.e., 26.7 kg H_2 at 430 bar). The control system allows the hydrogen gas to be recycled to reduce testing cost and safety risk of discharging hydrogen to environment.

A detailed testing procedure was developed for testing of the SCCV. A leak test was performed to check the SCCV and associated piping utilizing nitrogen at pressure of 2,500 psi. After completion of the leak test, the vessel was subjected to a vacuum cycle and multiple step purges using nitrogen, low purity hydrogen and high purity hydrogen to ensure testing of the vessel using hydrogen gas that meets SAE J2719 requirements. Gas samples from the vessel and supplied hydrogen gas were collected and analyzed before and after the final purge steps. Unexpected high level of impurities was detected after the final purge step. After extensive chemical composition analysis and inspection of the testing system, the source of the impurities was later determined to be primarily from out-of-specification high purity hydrogen gas supply. The impurity issue of the supply gas has been addressed. Furthermore, analysis of the hydrogen gas in the demonstration vessel suggested there are minimum releases of oxygen and other impurities from the glass beads in the vessel, validating the appropriateness of using glass beads in lieu of hydrogen.

FIGURE 1. Arrangement of the testing site for hydrogen cyclic testing of the demonstration SCCV

After completion of the purging process and verification of the control and data acquisition system, the hydrogen cycle testing was initiated. However, unexpected leakages were detected while pumping hydrogen into the vessel. It was found that the vessel could not be pressurized above 2,200 psi. A leakage in the sealing gasket in the manway was identified to be the cause. It should be noted that the vessel was successfully pressurized to 9,000 psi during the hydrostatic testing before the hydrogen cyclic pressure test. The leakage is under investigation, and a key question is to determine whether or not it is a hydrogen specific issue or gasket installation issue. A detailed plan has been developed in order to identify and isolate the cause of the leak. The high-pressure hydrogen cyclic testing will resume as soon as this leakage issue is addressed.

CONCLUSIONS AND FUTURE DIRECTIONS

The project so far has achieved the following.

- Completed the test setup for the long term hydrogen cyclic testing of the demonstration SCCV.
- Established the procedures for hydrogen impurity analysis and for hydrogen cyclic testing of the demonstration SCCV.
- Initiated hydrogen cycle testing.

Future planned activities include:

- Determining the cause of the leakage and formulate a plan to resolve the issue accordingly.
- Completing the long-term testing of the demonstration 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 100–430 bar).
- Continuing with the lessons learned in this project to further optimize all aspects of SCCV technology for additional major cost reduction in a follow-up project (Generation II SCCV).
- Technology commercialization.

FY 2016 PUBLICATIONS/PRESENTATIONS

1. Zhili Feng, "Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage," 2016 DOE Hydrogen and Fuel Cells AMR, Washington, D.C., June 2016.

2. Yanli Wang, Maan Jawad, Fei Ren, Jian Chen, Yong Chae Lim, and Zhili Feng, "Steel-Concrete Composite Vessel for Stationary High-Pressure Hydrogen Storage." Proc. ASME 2016 Pressure

Vessels and Piping Conference, July 17–21, 2016, Vancouver, British Columbia, Canada, Paper No PVP2016-63371.

3. Yanli Wang, Fei Ren, Yong Chae Lim, Jian Chen, Maan Jawad and Zhili Feng, "Design and Testing of Steel-Concrete Composite Vessel for Stationary High-Pressure Hydrogen Storage." 2016 International Hydrogen Conference–Material Performance in Hydrogen Environments, Jackson Hole, WY, September 11–14, 2016.

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.