III.5 Steel Concrete Composite Vessel for 875 bar Stationary Hydrogen Storage

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- MegaStir Technologies LLC, Provo, UT
- POSCO, South Korea
- SustainX, Seabrook, NH
- Temple University, Philadelphia, PA
- WireTough Cylinders, Bristol, VA

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Project End Date: September 30, 2017

Overall Objectives

- Address the significant safety and cost challenges in high-pressure stationary hydrogen storage system.
- Develop and demonstrate the second generation (GEN II) steel/concrete composite vessel (SCCV) design and fabrication technology for stationary high pressure hydrogen storage at 875 bar.
- Reduce the purchased capital cost of GEN II SCCV for forecourt hydrogen refueling station to \$800/kg H_2 at 875 bar in 2017, and meet all other DOE funding opportunity announcement (FOA) requirements including material compatibility with hydrogen, projected service life of at least 30 years, scalability to 1,000 kg of storage, and versatility in meeting the footprint requirement of different forecourt hydrogen fueling stations including underground storage.

Fiscal Year (FY) 2016 Objectives

- Perform holistic design and engineering optimization toward achieving the project cost target of \$800/kg H_2 stored at 875 bar. Provide a detailed cost analysis report that validates the \$800/kg H_2 cost target, using a detailed bottom-up, high-fidelity cost analysis methodology.
- Complete the design and engineering of 875 bar storage demonstration vessel with all major features of GEN II SCCV technology optimized for cost reduction.

Technical Barriers

This project addresses the following technical barrier from the Hydrogen Delivery section 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 at developing GEN II SCCV that will be more cost-effective for forecourt hydrogen fueling station applications. Specific technical targets are:

- Meet or exceed the cost targets (<\$1,000/kg H_2) stored at pressures of 875 bar or greater as specified in DOE DE-FOA-0000821 under which this project was awarded.
- Demonstrate compatibility of design materials with hydrogen, and durability under pressure.
- Meet all performance requirements included in the DOE FOA 821 over a 30-year service life.
- Demonstrate scalability and footprint of the storage system for versatility in application.
- Construct and test a prototype demonstration vessel of sufficient size to adequately validate the technical concept, manufacturability and cost-effectiveness of the technology for forecourt high-pressure hydrogen storage scalable to >1,000 kg H_2.

FY 2016 Accomplishments

- Finalized the design features for the GEN II vessels and identified major areas of cost reduction for GEN II SCCV to meet the cost target of \$800/kg H_2.
- Completed baseline reference design for four different hydrogen storage capacities: 100 kg, 200 kg, 500 kg, and

1,000 kg. The team performed design and engineering optimization to develop the technical basis towards cost reduction below $800/kg H_2 at 875 bar.

- High-fidelity bottom-up cost analysis showed that the final GEN II reference designs with capacity from 100–1,000 kg H_2 at 875 bar could be produced for a cost in the range of $550–700/kg H_2 for a number of design, manufacturing, and capacity options using today's relevant American Society of Mechanical Engineers (ASME) Boiler and Pressure Cessel (BPV) code, high-strength steels that are currently accepted by ASME BPV code, and today's pressure vessel manufacturing practices.

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INTRODUCTION

In a previous DOE Fuel Cell Technologies Office project, a novel SCCV technology referred to as first generation (GEN I) SCCV in this report, has been specifically developed and demonstrated for stationary high-pressure gaseous hydrogen storage applications. The newly developed SCCV technology, GEN II SCCV, comprises four major innovations: (1) flexible and scalable modular design for different storage pressure and capacity needs, for cost optimization, and for system reliability and safety; (2) composite storage vessel design and construction with a pre-stressed inner steel vessel encased in an outer reinforcement; (3) the use of a hydrogen permeation barrier in a layered vessel structure 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 form an integrated approach to make the SCCV cost competitive and inherently safe for stationary high-pressure hydrogen storage services. The SCCV solved the two critical limitations and challenges of today's high-pressure hydrogen storage vessels: high capital cost, and the safety risk posed by HE in high-strength steels. The SCCV can be designed and constructed using mature and proven fabrication technologies acceptable by pertinent industrial codes and standards. Therefore, while the concept of SCCV is new, SCCV technology as a whole is relatively mature. The SCCV technology is expected to be commercialized for hydrogen fueling station applications in near future.

During the GEN I research, a number of design, materials and manufacturing options were identified that, upon further research and development, could lead to substantial cost reduction over the reference GEN I design. The GEN II project aimed to build upon the success of GEN I SCCV, and to optimize major aspects of the SCCV technology for further significant cost reduction for forecourt hydrogen fueling station applications.

APPROACH

A systematic approach is employed in this project to refine and optimize all major aspects of SCCV technology (design, engineering, materials, and fabrication) to achieve the DOE FOA cost target. The R&D in this project will effectively utilize the knowledge obtained in developing the GEN I SCCV, including the evaluation of the following of R&D areas for potential further cost reductions.

- Cost reduction by materials. High-pressure hydrogen vessels have in the past avoided the use of high-strength steels due to HE concerns. Our innovative approach to eliminate HE by design minimizes vessel exposure to hydrogen, thereby eliminating the potential HE issue[1]. High-strength steels can therefore be used for vessel construction without penalties in design allowable stress (static and fatigue) typically assumed with their use. Increase in the strength of steel used reduces the necessary vessel wall thickness and the associated fabrication cost. The GEN II design targeted a 35–60% increase in steel strength over GEN I; GEN 1 was composed of 50–75 ksi (SA-765 Grade IV and SA-724 Grade B) steel, while Gen II steel was 100–120 ksi yield strength. This allowed the design allowable stresses in the vessel to reach ~50 ksi in GEN II vs. 33 ksi in the GEN I design, per the ASME BPV code.
- Cost reduction by vessel design optimization. We applied the cost analysis methodology developed previously to further optimize the SCCV design for cost reduction. Options investigated included (a) optimizing the shape and dimension of the SCCV, (b) replacing the stainless steel inner liner with a lower cost hydrogen permeation barrier, and (c) optimizing the pre-stress level of the vessel. The design optimization considered the limits and constraints of today's manufacturing technologies and availability of materials; the manufacturing technologies chosen in the design optimization are available for such vessel fabrication per appropriate code requirements.
- Fabrication and sensor technologies. The following options were investigated: (a) remote non-contact vessel inspection and remote repair welding technologies, (b) application of friction stir welding, and (c) new wire wrapping technologies for pre-stressing.

RESULTS

The GEN II design has improved upon the success of GEN I SCCV. It not only kept the unique features of GEN I

[1] The SCCV comprises an inner liner surrounded by multiple layers of steel that each have mm-sized vent holes engraved within them. These vent holes allow any hydrogen that escapes the liner to escape the vessel. It is expected that these vent holes will therefore ensure that hydrogen is never in contact with the outer layers of steel (composed of high-strength steel alloys) long enough to cause embrittlement.

SCCV to mitigate the hydrogen embrittlement risk by design, but also incorporated a number of new design and manufacturing innovations developed in this project for cost reduction. These technology innovations formed the basis for cost optimization. A bottom-up, high-fidelity cost analysis methodology was used to determine the project cost of GEN II reference designs.

In order to investigate the scalability of the GEN II vessel technology, a set of *reference designs* has been selected for design optimization. These reference designs were studied for the following aspects:

- For cost optimization
- For detailed fabrication-construction engineering
- For high-volume manufacturing engineering
- For validation of technology scalability

Four initial reference designs were chosen: 100 kg, 200 kg, 500 kg, and 1,000 kg H_2 at 875 bar. In later stages of the design optimization, some intermittent capacities were also identified as they provided better material utilization and reduced manufacturing cost.

These reference designs were designed and analyzed in detail to ensure that they could be provided to vessel manufacturers for off-the-shelf production and order for refueling stations. These reference designs can be combined to meet a wide variety of capacity requirement of fueling stations.

The cost optimization of GEN II designs was systematically carried out in three different stages. Each stage served a different purpose during the course of the design iterations toward optimization. The designed details and cost analysis were progressed from simple to more comprehensive. The results from the early stage analysis served as the basis for more comprehensive design optimization for the later stage analysis. Stage I primarily focused on the effect of the vessel geometry (i.e., length vs. diameter of the vessel) on the cost. Stage II added the effects of different materials for the head, cylinder and the permeation barrier. Based on the findings from Stage I and Stage II, candidate reference designs for different hydrogen storage capacities were identified. In Stage III, a high fidelity, bottom-up cost analysis determined the projected costs of the reference designs from step-by-step cost analysis of vessel fabrication using fabrication flows recommended by U.S. domestic vessel manufacturers.

The final reference designs in Stage III cost analysis are summarized in Table 1. ASME BPV code accepted high strength steel SA-517 was used in cost analysis. SA-517 represented a middle point of steel prices surveyed in this project. The inner diameter of the vessel was set at nominal 30 inches based on the consideration of available material and manufacturing options. The scalability of the GEN II design was investigated with different vessel length for H_2 storage capacity ranging from 100 kg to 1,000 kg. Whereas the GEN II design was readily scalable to 1,000 kg or more of H_2 (for one vessel), 320 kg was regarded as a practical upper limit for most fueling station applications, due to weight limitations for the transportation of fabricated vessels to fueling station sites (80,000 lb including truck and freight would be the upper limit for trucking without significant cost penalty.)

For the final reference designs in Table 1, four different manufacturing options with a total of 24 design cases are analyzed in detail for the cost. These four options are extruded shell with overlaid head liner (ESOL), formed shell with overlaid head liner (FSOL), extruded shell with loose head liner (ESLL), and formed shell with loose head liner (FSLL). The projected costs are summarized in Figure 1, using the high-fidelity, bottom-up cost analysis methodology. For all design options, the unit costs of the vessel decrease as the storage capacity increases for storage capacity between 100 kg and 320 kg. The unit cost for the 500 kg storage capacities are high due to the cost penalty for transportation. Among the 24 design cases, 22 have a unit cost less than the \$800/kg H_2 target, and two were at \$810/kg H_2 and \$805/kg H_2, slightly over the cost target. More importantly, six cases had projected costs less than \$600/kg H_2 stored. The six cases with the lowest costs are those with capacities between 200 kg and 320 kg H_2.

The design and engineering for GEN II SCCV followed the design rules in ASME BPV code, Section VIII Division 2. The final reference designs in Table 1 also

TABLE 1. Design Parameters of Six GEN II SCCV using SA517-E High Strength Steel

Capacity (kg H_2)	100	167	200	270	320	500
Head/Shell Thickness (in)	2.125					
Inner Diameter (in)	30					
Layer of Wrap	5					
Outer Diameter* (in)	38.5					
Total Length (ft)	17	28	32.9	44	52.5	78.7
Total Weight* (lb)	20,400	33,500	40,000	53,750	63,700	98,700

* Including wire wrapping (~1 in thick) and protective (~1 in thick) layers

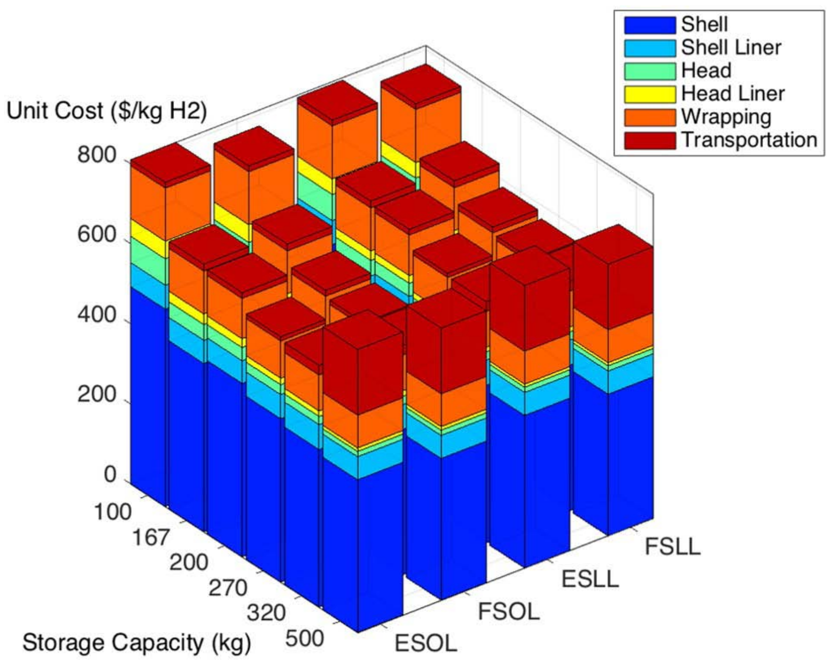

FIGURE 1. Unit storage costs ($/kg H2) of all GEN II SCCVs analyzed in the Stage III analysis

meet or exceed the 11,000 pressure cycles for the 30-year design life, which corresponds to the anticipated high-usage scenario: the vessel will be re-charged each day. The fatigue assessment was performed in accordance with Annex 3-F of Section VIII Division 2, using in-air fatigue design data and assuming maximum possible pressure changes in the vessel from 50 bar to the max design pressure of 875 bar in a cycle. The use of Division 2 design rules avoided uncertainties in assuming or specifying manufacturing related issues, such as the minimum manufacturing flaw size assumption required in Division 3 for more precise fatigue life prediction. The Division 2 analysis resulted in fatigue design lives of 78,877 cycles for the vessel head, 22,041 cycles for the vessel cylinder, and 12,681 cycles for the weld region. Detailed finite element model analysis of the final reference designs also identified that the nozzle region was problematic. Due to high stress concentrations at the inside corner of the original nozzle configuration, the design life was only 3,324 cycles. This necessitated nozzle design modification, to reduce the stress concentration. The modified nozzle design resulted in a design life of 50,230 cycles. The hydrogen permeation barrier liner was upgraded to stainless steel to ensure a high design life of 29,997 cycles.

CONCLUSIONS AND FUTURE DIRECTIONS

Through substantial engineering design work and economic analyses, project accomplishments in FY 2016 have included:

- Completed baseline reference design of GEN II SCCV for different hydrogen storage capabilities ranging from 100 kg to 1,000 kg.
- Performed holistic design and engineering optimization and achieved the $800/kg H_2 cost target using a bottom-up, high-fidelity cost analysis methodology.

Future Planned Activities for FY 2017:

- Complete the design and engineering of a GEN II SCCV mockup at 875 bar, and publish report detailing design and cost.

FY 2016 PUBLICATIONS/PRESENTATIONS

1. Zhili Feng, “Steel Concrete Composite Vessel for 875 bar Stationary Hydrogen Storage,” 2016 DOE Hydrogen and Fuel Cells AMR, Washington, D.C., June 2016.

2. Y. Wang, Z. Feng, Y.C. Lim, J. Chen, F. Ren, M. Jawad, and M. Kelly, “Cost Analysis of Hydrogen Storage Vessel at 875 bar,” ORNL/TM-2016/94, ORNL technical report, 2016.