III.8 Steel Concrete Composite Vessel for 875 Bar Stationary Hydrogen Storage

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- AccerlorMittal, East Chicago, IN
- Bevilacqua Knight Inc., Sacramento, CA
- Global Engineering and Technology LLC, Camas, WA
- Hanson Pressure Pipe, Grand Prairie, TX
- LightSail, Berkeley, CA
- MegaStir Technologies LLC, Provo, UT
- POSCO, South Korea
- SustainX, Seabrook, NH
- Temple University, Philadelphia, PA
- WireTough Cylinders, Bristol, VA

Project Start Date: October 1, 2014
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 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 projected service life of at least 30 yr, scalability to 1,000 kg of storage, and versatility in meeting the scalability and footprint requirement of different forecourt hydrogen fueling stations

Fiscal Year (FY) 2015 Objectives

- Select three candidate high strength structural steels with 100–120 ksi yield strength suitable for the inner steel vessel
- Identify two alternative hydrogen permeation barrier materials; confirm at least one barrier material having no more than 10% notch strength reduction in 2,000 psi hydrogen and a hydrogen leak rate of less than 50 kg/yr ($200/yr) for a reference 1,000 kg storage SCCV at 875 bar
- Identify alternative reinforcement technology with reduced cost over the reinforced concrete technology in first generation (GEN I) SCCV by 5%
- Identify options for SCCV design optimization for cost reduction with initial cost analysis

Technical Barriers

This project addresses the following technical barrier from the Hydrogen Delivery section in the Fuel Cell Technologies Office (FCTO) 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 the ***second generation*** SCCV that will be more cost effective for forecourt hydrogen fueling station applications. Specific technical targets are as follows.

- 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. Table 1 listed the FOA cost target and those from the most recent MYRDD plan (updated August 2015)
- Show compatibility of design materials with hydrogen and durability under pressure
- Meet all performance requirements included in the DOE FOA821 over a 30-year service life
- Construct and test a prototype system of sufficient size to adequately demonstrate the capability of the technology to be scaled to storage volumes of >1,000 kg H_2
- Scalability and footprint of the storage system for versatility in applications

TABLE 1. DOE MYRDD Technical Targets for Stationary Gaseous H_2 Storage Tanks, updated August 2015 (for Fueling Sites, Terminals, or Other Nontransport Storage Needs)

Pressure	DOE 2015 Status	GEN I SCCV (2015)	GEN II SCCV (2017)	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		$600
High Pressure (875 bar) (FOA821) Purchased Capital Cost ($/kg of H_2 stored)	N/A	$957	$800	$1,000
High Pressure (925 bar) Purchased Capital Cost ($/kg of H_2 stored)	$2,000	N/A		$600

N/A – not applicable

FY 2015 Accomplishments

- Working with steelmaking partners (ArcelorMittal and POSCO), selected five candidate high strength structural steels with 100–120 ksi yield strength suitable for the inner steel vessel
- Identified and experimentally confirmed a new hydrogen permeation barrier material having 5.3% notch strength reduction in hydrogen and a leak rate of less than 1 kg/yr ($2/yr) for a reference 1,000 kg SCCV at 875 bar
- Identified two new wire wrapping technologies which would considerably simplify the vessel reinforcement construction with estimated cost reduction by more than 5% over the GEN I SCCV
- Through initial design optimization, identified a number of reference design options with estimated cost that is potentially below the targeted $800/kg H_2 using the same materials as in the GEN I SCCV mockup, and potentially below $600 (the 2020 target) using higher strength steels investigated in this project

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INTRODUCTION

In a previous DOE FCTO project, a novel SCCV technology, referred to as 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 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 an inner steel vessel encased in a prestressed 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, the high capital cost and the safety concerns of HE of high strength steel vessels. The SCCV can be designed and constructed using mature and proven fabrication technologies acceptable by pertinent codes/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 2–4 yr.

This project aims at developing GEN II SCCV that will be even more cost effective for forecourt hydrogen fueling station applications. An exceptionally strong team has been assembled that is best suited for R&D and commercialization of the GEN II SCCV. The technical expertise and research capabilities of the team are "vertically integrated" to cover all aspects of the SCCV technology development, from forecourt hydrogen station requirements, material selecting and development, high-pressure vessel design, engineering and construction, materials joining, high pressure hydrogen testing, cost modeling, as well as application specific knowledge required for the proposed work.

APPROACH

A systematic approach is employed to refine and optimize all major aspects of SCCV technology (design, engineering, materials and fabrication) to achieve the proposed GEN II SCCV cost target. A representative prototype mockup, capturing all major features of SCCV technology, will be fabricated and tested for hydrogen service at 875 bar to demonstrate the technical viability and cost effectiveness of the GEN II SCCV technology for forecourt high pressure hydrogen storage. R&D in this project will effectively utilize the knowledge obtained in developing the GEN I SCCV, including the identification of a number of R&D areas with potentials for considerable further cost reduction. Potential cost reduction estimates for the different areas are summarized in Table 2. These areas are briefly described below.

- Cost reduction by materials: High-pressure hydrogen vessels have in the past avoided the use of ultra-high-strength steels due to HE concerns. Our innovative layered vessel design minimizes vessel exposure to hydrogen, thereby eliminating the potential for HE.

Ultra-high-strength steels can therefore be used in the vessel. Increase in strength reduces the vessel wall thickness and the associated fabrication cost.

- Cost reduction by vessel design optimization: We will apply the cost analysis methodology developed previously to further optimize the SCCV design for cost reduction. Options to be investigated include (a) optimizing the shape and dimension of the SCCV, (b) replacing the stainless steel (SS) inner liner with low cost materials as hydrogen permeation barrier, and (c) optimizing the prestress level of the vessel. The design optimization will consider the limits and constraints of today's manufacturing technologies and availability of materials.
- Fabrication and sensor technologies: The following options will be 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.

TABLE 2. Focused R&D Areas with Potentially Significant Cost Reductions (Reference Cost: DOE FOA Target $1,000 kg H_2 at 875 bar)

R&D Areas	Estimated Cost Reduction
Cost effective hydrogen permeation barrier	5%
Use of ultra-high-strength steels	15%
Cost effective prestressing technologies	5%
Friction stir welding scale up	10%
Novel sensor technologies	10%
Overall SCCV design optimization	15%
Total	60%

RESULTS

R&D in FY 2015 focused the following major milestones according to the project R&D plan.

Selection of Candidate Ultra-High-Strength Structural Steels

In the past, high pressure hydrogen vessels have avoided the use of ultra-high-strength steels due to HE concerns. The layered vessel design in SCCV eliminates HE by design. It therefore offers the opportunity to use ultra-high-strength steels for cost reduction through reduced wall thickness and the associated fabrication cost. This is an aspect that was unexplored in GEN I SCCV; steels used in the GEN I SCCV mockup were based on American Society of Mechanical Engineers (ASME) Boiler and Vessel Pressure Code (BVPC) approved steels for hydrogen services.

In this project, steels with yield strength level between 100 ksi and 120 ksi (690–830 MPa) were targeted. This represented an increase in strength of 35–60% over the SA-724B steel in GEN I SCCV.

We worked with our steelmaking team members (ArcelorMittal and POSCO, two largest steel producers in the world) to identify and select potentially qualified candidate steels. The selection of candidate steels was based on the consideration of their commercial viability (i.e., can be produced in commercial quantity), availability to the project, and meeting the cost reduction target of 15–30% from the current SCCV reference design through reduced wall thickness and the associated fabrication cost. Five candidate steels have been identified (Table 3). These steels will be down-selected based on further evaluation including weldability and weld properties of the steels, as planned.

TABLE 3. Mechanical Properties for Candidate Ultra-High-Strength Steels

	Candidate Steel A	Candidate Steel B	Candidate Steel C	Candidate Steel D	Candidate Steel E
σ_{ys}	100	120	Min. 100	101 ksi	127.6 ksi
σ_{ts}	100–130	--	Min. 115	113 ksi	142 ksi
Elongation	18%	--	16%	14%	<8%

Identification of Alternative Hydrogen Permeation Barrier Materials

GEN I SCCV design utilizes an austenitic SS liner to prevent hydrogen entering the subsequent high strength steel layers. However, austenitic SS is expensive. Cladding SS onto the layered steel vessel is also labor intensive and costly. The material and fabrication cost of the SS contribute to more than 10% of the total cost of the inner steel vessel for our reference GEN I SCCV design. For GEN II SCCV, low cost alternative materials were investigated as hydrogen permeation barrier.

The identification of hydrogen permeation barrier materials included extensive literature surveys of hydrogen permeability, diffusivity, and solubility for various potential materials. The leakage rate of each potential material was assessed based on the Fick's law for diffusion and the Sievert's law of hydrogen solubility as function of hydrogen pressure.

The leakage rate can be calculated following as:

$$Q = J \cdot A \cdot t$$

where Q is the leakage rate ($\frac{\text{kg}}{\text{year}}$), J the steady state flux of diffusion of hydrogen, A the surface area of pressure vessel, and t the time. In our analysis, a reference vessel containing 1,150 kg H_2 at 875 bar was assumed as shown in Figure 1. This reference vessel had a surface area of 65 m^2. The thickness of the hydrogen permeation barrier was assumed to be 6 mm. Hydrogen pressure of 875 bar was applied on one side of the hydrogen barrier layer, and 1 bar

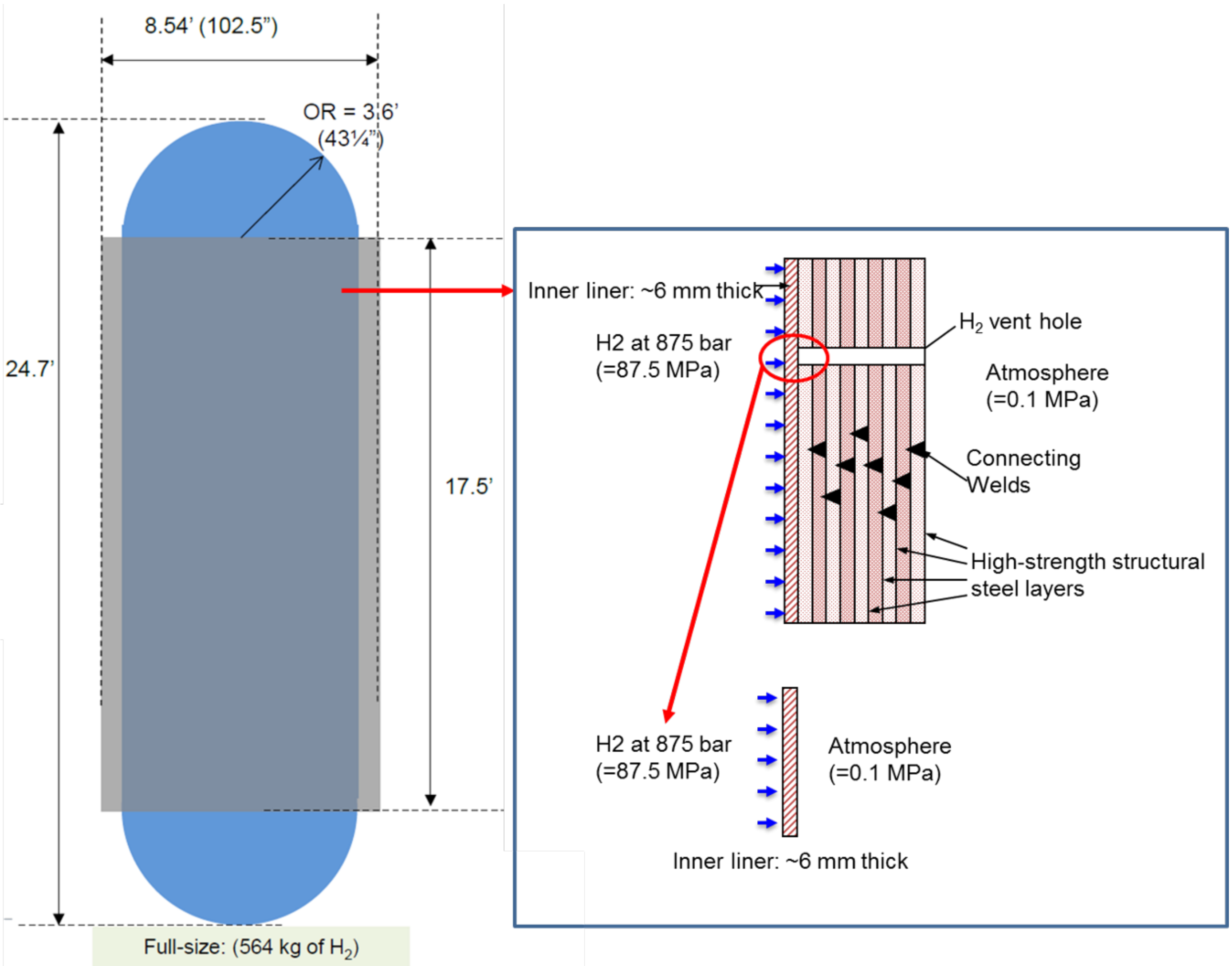

FIGURE 1. Schematics of the reference vessel containing 1,150 kg of H_2 at 875 bar for hydrogen permeation leak rate estimate. The dimensions are in feet.

was applied on the other side due to the presence of the vent holes.

The above leak rate analysis led to the identification of one low cost material with a leakage rate of 0.1–0.3 kg/yr, well below the target 50 kg/yr leak rate. (For reference, the stainless steel barrier has a leakage rate of approximately 1 x 10^{-5} kg/yr). The permeability of this material was experimentally measured at a test temperature up to 150°C. Calculations using the actual measurement data confirmed the above estimated leak rate. The newly identified material costs only a fraction of that of the stainless steel. Its use would also significantly reduce the fabrication cost compared to the current cladding process of stainless steel.

The low cost material identified above was also subjected to HE test. Notch tensile test in hydrogen at 2,000 psi confirmed that the material had an average of 5.3% reduction in notch tensile strength, suggesting excellent compatibility with hydrogen.

Two more materials are also identified as hydrogen permeation barrier. They are under further evaluation.

Design Optimization for Cost Reduction

A primary objective in this project is to develop a set of standard reference designs of different capacities that would meet the DOE cost target for refueling station. These reference designs would be systematically optimized for cost in this project. Such reference designs are intended for high volume off-the-shelf production with today's manufacturing capability of the project partners. It would minimize the capital investment and engineering cost by the manufacturers, which also eases the technology transfer and commercialization.

We have completed the initial, Level I, GEN II SCCV design optimization on five reference capacities (100, 200, 500 and 1,000 kg H_2 at 875 bar). As shown in Tables 4 and 5, this initial Level I design optimization suggested the possibility of meeting the $800/kg H_2 cost target with steels available in the ASME BPVC. With the use of ultra-high-strength steels that are commercially available but not yet accepted by code, it is possible to reduce the cost of the vessel to a level of $500/kg H_2.

The above initial GEN II SCCV designs will be used to guide the design optimization R&D in FY 2016. The designs and cost analysis will be further refined in FY 2016, with more detailed cost breakdown analysis for selected potentially low cost designs. Manufacturing capability constraints and fueling station requirements will need to be incorporated in the FY 2016 design optimization. It is expected that the final cost figures of the optimized designs would be different from the initial analysis performed in FY 2015.

TABLE 4. Initial Level I SCCV Design Optimization with Code Accepted Steels

($/kg H_2)	Tank capacity (kg)			
L/D ratio	**100**	**200**	**500**	**1,000**
1.67	982	959	945	936
5	816	801	765	745
10	756	747	715	697
40	750	762	674	670

L/D – Length to diameter ratio

TABLE 5. Initial Level I SCCV Design Optimization Using Ultra-High-Strength Steels with ASME BPVC Design Allowable of 50 ksi

	Tank capacity ($/kg H_2)			
Aspect ratio	**100**	**200**	**500**	**1,000**
1.67	667	651	637	630
5	551	542	540	539
10	560	510	518	500
40	507	527	509	501

CONCLUSIONS AND FUTURE DIRECTIONS

The project so far has achieved all the major milestones planned for FY 2015.

- Identified five candidate high strength structural steels with 100–120 ksi yield strength suitable for the inner steel vessel
- Identified and experimentally confirmed a new hydrogen permeation barrier material that has estimated leak rate of less than 1 kg/yr ($2/yr) for a reference 1,000 kg SCCV at 875 bar
- Identified two new wire wrapping technologies that may considerably simplify the vessel reinforcement construction
- Through initial design optimization, identified a number of reference design options with estimated cost that is potentially below the targeted $800/kg H_2 using the same materials as in the GEN I SCCV mockup, and potentially below $600 (the 2020 target) using higher strength steels investigated in this project

Future planned activities for FY 2016:

- Complete weldability evaluation and weld property testing of the new candidate high strength steels and down-select for inner steel vessel design and fabrication
- Complete the development of improved reinforcement technologies
- Complete the reference engineering and fabrication design of the reference designs that are optimized to meet the cost target
- Develop and demonstrate the remote sensor technology for vessel health monitoring and inspection