OAK RIDGE NATIONAL LABORATORY

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Manufacturing Cost Analysis of Novel Steel/Concrete Composite Vessel for Stationary Storage of High-Pressure Hydrogen

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Prepared by
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MANUFACTURING COST ANALYSIS OF NOVEL STEEL/CONCRETE COMPOSITE VESSEL FOR STATIONARY STORAGE OF HIGH-PRESSURE HYDROGEN

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EXECUTIVE SUMMARY

A novel, low-cost, high-pressure, steel/concrete composite vessel (SCCV) technology for stationary storage of compressed gaseous hydrogen (CGH_2) is currently under development at Oak Ridge National Laboratory (ORNL) sponsored by DOE's Fuel Cell Technologies (FCT) Program. The SCCV technology uses commodity materials including structural steels and concretes for achieving cost, durability and safety requirements. In particular, the hydrogen embrittlement of high-strength low-alloy steels, a major safety and durability issue for current industry-standard pressure vessel technology, is mitigated through the use of a unique layered steel shell structure.

This report presents the cost analysis results of the novel SCCV technology. A high-fidelity cost analysis tool is developed, based on a detailed, bottom-up approach which takes into account the material and labor costs involved in each of the vessel manufacturing steps. A thorough cost study is performed to understand the SCCV cost as a function of the key vessel design parameters, including hydrogen pressure, vessel dimensions, and load-carrying ratio. The major conclusions include:

- The SCCV technology can meet the technical/cost targets set forth by DOE's FCT Program for FY2015 and FY2020 for all three pressure levels (i.e., 160, 430 and 860 bar) relevant to the hydrogen production and delivery infrastructure.

- Further vessel cost reduction can benefit from the development of advanced vessel fabrication technologies such as the highly automated friction stir welding (FSW). The ORNL-patented multi-layer, multi-pass FSW can not only reduce the amount of labor needed for assembling and welding the layered steel vessel, but also make it possible to use even higher strength steels for further cost reductions and improvement of vessel structural integrity.

It is noted the cost analysis results demonstrate the significant cost advantage attainable by the SCCV technology for different pressure levels when compared to the industry-standard pressure vessel technology. The real-world performance data of SCCV under actual operating conditions is imperative for this new technology to be adopted by the hydrogen industry for stationary storage of CGH_2. Therefore, the key technology development effort in FY13 and subsequent years will be focused on the fabrication and testing of SCCV mock-ups. The static loading and fatigue data will be generated in rigorous testing of these mock-ups. Successful tests are crucial to enabling the near-term impact of the developed storage technology on the CGH_2 storage market, a critical component of the hydrogen production and delivery infrastructure. In particular, the SCCV has high potential for widespread deployment in hydrogen fueling stations.

1. INTRODUCTION

Off-board bulk stationary storage of hydrogen is a critical element in the overall hydrogen production and delivery infrastructure. Stationary storage is needed at locations such as fueling stations, renewable energy hydrogen production sites, central production plants, and terminals. The hydrogen pressure and capacity of the stationary storage vessels are expected to vary considerably, depending on the intended usage, the location and other economic and logistic considerations. For example, the existing hydrogen fueling stations for fuel cell cars in the United States dispense fuel at two pressure levels: H35 (35 MPa or 350 bar) and H70 (70 MPa or 700 bar) [1,2]. For ease of dispensing fuel, it is desirable for the stationary storage vessel to overmatch the dispensing pressure (e.g., storage vessels with 430 bar and 860 bar pressures for dispensing at H35 and H70, respectively). On the other hand, the stationary storage vessel at a renewable energy hydrogen production site or central production plant can be operated at a much lower pressure (e.g., 160 bar) and have a much larger capacity than that of the fueling station. Hence, it is important that the storage vessel design is flexible and scalable to meet different storage needs (i.e., pressure and capacity).

Among the various hydrogen storage technologies, the compressed gaseous hydrogen (CGH_2) storage in a stationary pressure vessel is the most widely used technology [3,4]. According to the recent data published by Fuel Cells 2000, 98% of the hydrogen fueling stations in the U.S. used CGH_2 [3]. Worldwide (excluding the stations in the U.S.), 84% of the hydrogen stations use CGH_2 [4]. However, there are two long-standing challenges that have limited further widespread deployment of CGH_2 pressure vessels: cost and safety. As shown in Table 1 below, today's industry-standard pressure vessel, which is based on the single-section steel vessel technology, is expensive (see FY 2011 Status). To meet the DOE's FY2020 targets, significant reduction of vessel cost is essential. 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, hydrogen embrittlement in structural steels, especially the accelerated crack growth due to fatigue cycling, must be mitigated to ensure vessel safety.

Table 1. U.S. DOE's technical targets for stationary gaseous hydrogen storage vessels (for fueling sites, terminals, or other non-transport storage needs)

Category	FY 2011 Status	FY 2015 Target	FY 2020 Target
Low Pressure (160 bar) Purchased Capital Cost ($/kg of H_2 stored)	$1,000	$850	$700
Moderate Pressure (430 bar) Purchased Capital Cost ($/kg of H_2 stored)	$1,100	$900	$750
High Pressure (860 bar) Purchased Capital Cost ($/kg of H_2 stored)	$1,450	$1,200	$1,000

Note: Cost target data from the FCT Program Technical Plan for Hydrogen Delivery updated September 2012 (http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/delivery.pdf).

As described in details elsewhere [5], ORNL has developed a novel, low-cost, high-pressure, steel/concrete composite vessel (SCCV) technology for stationary storage of CGH_2. Figure 1 is a schematic drawing of the SCCV design in a hydrogen fueling station. The particular SCCV design in this figure comprises inner steel vessels encased in an outer pre-stressed concrete sleeve. The shell section of the steel vessel is a layered structure. The innermost layer directly exposed to the high-pressure hydrogen is made of an austenitic stainless steel (e.g., AISI 316L or 304L), which excels as a hydrogen embrittlement and permeation barrier. The other layers are made of high-strength low-alloy structural steel (e.g., ASTM SA724), which is approximately 25 percent of the cost of stainless steel. Finally, the outer pre-stressed concrete sleeve used to bear the structural load costs even less when compared to structural steels. The salient features of this novel SCCV technology include:

- Use of commodity materials (e.g., structural steels and concretes) to cost-effectively bear the structural load exerted by the high-pressure hydrogen.
- Achieving safety and durability requirements by mitigating hydrogen embrittlement of high-strength low-alloy steels with a unique layered steel shell structure comprised of the hydrogen embrittlement and permeation resistance liner and strategically placed vent holes.
- Advanced multi-layer, multi-pass friction stir welding (FSW) process for automated manufacturing of the layered steel vessel.
- Flexibility and scalability for meeting different pressure and capacity requirements for various stationary hydrogen storage applications.

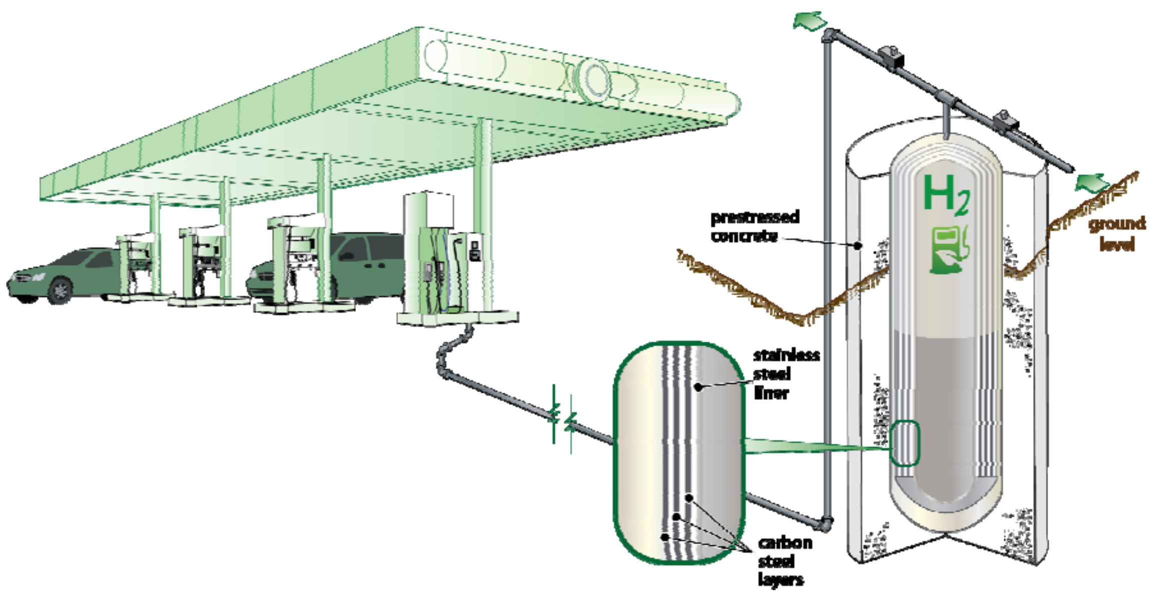

Fig. 1. Schematic of a novel SCCV design comprised of inner layered steel vessels and an outer pre-stressed concrete enclosure at a hydrogen fueling station.

This report presents the results of detailed cost analysis of the SCCV technology. It contains the following three major sections. First, the bottom-up cost estimation approach used in the detailed SCCV cost analysis is described. Second, the cost analysis results of SCCVs designed for three pressure levels (160, 430 and 860 bar) are discussed. It will be shown that the SCCV technology can meet the FY2020 technical targets set forth by DOE's FCT Program for all three pressure levels. Finally, future work will be described, including the manufacturing and testing of small-scale, mock-up vessel to demonstrate the performance and safety of the SCCV technology. Once successfully demonstrated, the SCCV technology has the potential for a high near-term impact on stationary gaseous hydrogen storage, a critical component of the hydrogen production and delivery infrastructure. In particular, the SCCV technology holds great promise for enabling widespread deployment in hydrogen fueling stations.

2. COST ANALYSIS APPROACH

The cost analysis procedure flowchart in Fig. 2 consists of two major steps. The first step shown at left in the flowchart is the engineering calculation using formulae (or closed-form equations) from relevant industry codes and standards such as ASME Boiler and Pressure Vessel (BPV) Code - Section VIII and American Concrete Institute (ACI) guidelines. The engineering calculation determines the vessel dimensions (e.g., steel thickness, concrete thickness, and layers of pre-stressing steel wires). These vessel dimensions are entered into a high-fidelity cost analysis model (shown at right in Fig. 2) to obtain the total manufacturing cost of the SCCV. Design optimization is then conducted for various design concepts to identify specific designs that meet the DOE cost targets. Domestic materials and manufacturing capability are considered in the development of these specific designs so that the cost-effective designs can be fabricated domestically with today's materials and manufacturing technology, or with near-term materials and/or manufacturing technology advancements such as friction stir welding technology.

2.1 ENGINEERING CALCULATION

The inputs to the engineering calculation include the inner diameter and length of the steel vessel and the hydrogen pressure, which together define the mass of stored hydrogen (i.e., storage capacity). Another input parameter is the load-carrying ratio between the steel vessel and the pre-stressed concrete enclosure. For instance, a 30/70 (steel/concrete) load-carrying ratio indicates a SCCV with the steel vessel carrying 30% of the structural load and the pre-stressed concrete carrying the remaining 70% of load. Once the user inputs are defined, a series of design allowable calculations are performed (shown at left in Fig. 2). Details of these calculations are described in the following sections.

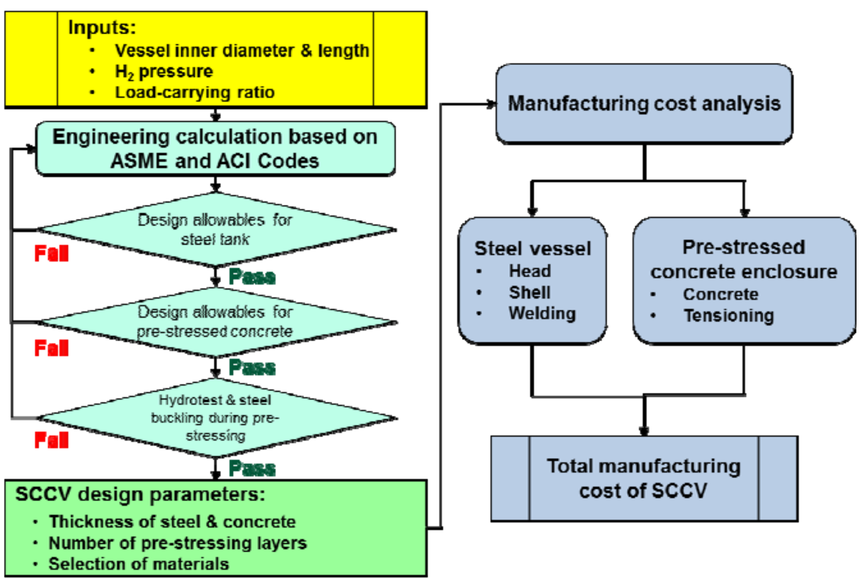

Fig. 2. Overview of cost analysis approach for SCCV.

2.1.1 Design Allowables for Steel Vessel

As shown in Fig. 2, the steel vessel thickness is calculated first. The thickness of hemispherical heads due to internal pressure is obtained from the ASME BPV Code - Section VIII-2 as:

$$t_h = R_i\left(e^{0.5P/S} - 1\right) \tag{1}$$

where t_h is the minimal head thickness, R_i is the inside radius, P is the internal hydrogen pressure, and S is the allowable stress of the specific steel.

For illustration purposes, the head thickness is calculated for a steel head with R_i = 39" and hydrogen pressure P = 430 bar (6250 psi). The selected material for head construction is SA537 with the following key mechanical properties:

- Ultimate tensile stress: 75 ksi
- Yield stress: 55 ksi
- Allowable stress (S) in VIII-2: 31.3 ksi

Using Eqn. (1), the head thickness t_h is calculated to be 4.09". For ease of manufacturing specification and extra safety margin, the head thickness is rounded up to the closest number in quarter-inch increments (i.e., 4.25" in this case).

Similarly, the thickness of the cylindrical steel shell can be obtained as:

$$t_s = R_i\left(e^{P/S} - 1\right) \tag{2}$$

where t_s is the shell thickness. For the above dimensions (R_i = 39" and P = 430 bar), the shell thickness t_s is calculated to be 8.62".

It is noted that the above example applies to a steel-only vessel. For the SCCV, where the outer pre-stressed concrete enclosure shares the structural load with the inner steel vessel, the steel thickness can be significantly reduced. For example, for a 50/50 (steel/concrete) load-carrying ratio, i.e., the steel vessel designed to carry 50% of the hydrogen pressure, substituting P = 215 bar (50% of the original pressure 430 bar) in Eqn. (2), the new steel shell thickness in the SCCV is only 4.09", a more than 50% reduction in thickness when compared to the steel-only vessel. As will be shown later, the cost savings of the SCCV technology result from thinning of steel vessel by using a pre-stressed concrete enclosure to bear the structural load.

2.1.2 Design Allowables for Pre-stressed Concrete

As shown in Fig. 2, once the steel vessel dimensions are calculated, the pre-stressed concrete dimensions are then determined. The concrete thickness is obtained based on the deformation compatibility of steel and concrete at their interface. The radial deflection, δ, of a cylindrical shell due to internal and external pressures is defined as:

$$\delta = \frac{R^2\left(P_i R_i^2 - P_o R_o^2\right)(1-2\nu) + \left(P_i - P_o\right)\left(R_i^2 R_o^2\right)(1+\nu)}{ER\left(R_o^2 - R_i^2\right)} \tag{3}$$

where R is the radius at any point in the cylinder, R_i is the cylinder inside radius, R_o is the cylinder outside radius, P_i is the inside pressure, P_o is the outside pressure, ν is the Poisson's ratio, and E is the elastic (Young's) modulus.

As illustrated in Fig. 3, the deformation compatibility at the steel/concrete interface under internal hydrogen pressure and external pre-stressing pressure is given as:

$$\delta_{so\_Pi} - \delta_{so\_Pf} = \delta_{ci\_Pf} - \delta_{ci\_Po} \tag{4}$$

where δ_{so_Pi} and δ_{so_Pf} are the deflections of the steel cylinder shell at its outside surface due to the internal pressure (P_i) and the interface pressure (P_f), respectively, and δ_{ci_Pf} and δ_{ci_Po} are the deflections of the concrete cylinder shell at its inside surface due to the interface pressure (P_f) and the external pressure (P_o), respectively. It is noted that the internal pressure (P_i) is the design pressure of stored CGH_2. The external pressure (P_o) that is applied onto the concrete outside surface depends on the specified load-carrying ratio. For instance, considering the example that P_i = 430 bar and the load-carrying ratio = 50/50 (steel/concrete), the external pressure P_o = 215 bar.

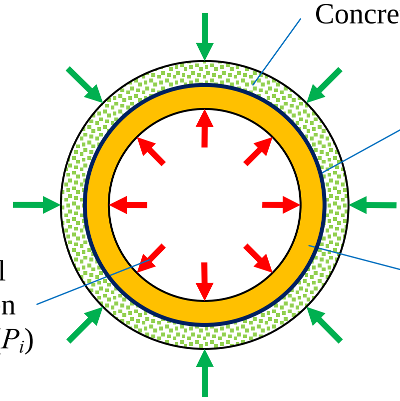

Fig. 3. Cross-section view of the SCCV cylindrical shell.

The interface pressure P_f can be calculated by substituting Eqn. (3) into Eqn. (4). With the knowledge of P_f, the circumferential (or hoop) stress in the concrete cylinder shell, σ_{c_θ}, is obtained as:

$$\sigma_{c\_\theta} = \frac{P_f R_2^2 - P_o R_3^2 + \left(P_f - P_o\right)\dfrac{R_2^2 R_3^2}{R^2}}{\left(R_3^2 - R_2^2\right)} \qquad (5)$$

where R_1 and R_2 are the inner radius and outer radius of the steel cylinder shell, respectively, and R_3 is the outer radius of the concrete cylinder shell. Using Eqn. (5), the concrete thickness is determined so that the highest circumferential stress (the most critical stress for vessel failure) in the concrete is less than the tensile strength of the specific concrete material (see Table 2). As shown in Table 2, two types of concrete materials are considered. The design allowable stresses for the light-weight concrete are much less than those for the ultra-high strength concrete. However, the cost of light-weight concrete is only twenty percent of that of ultra-high strength concrete.

Table 2. Comparison of two concrete materials for construction of pre-stressed concrete enclosure

Concrete material	Elastic modulus	Compressive strength	Tensile strength	Direct cost
Light-weight concrete	3.3×10^6 psi	8,000 psi	450 psi	$343/yd^3
Ultra-high strength concrete	8.0×10^6 psi	20,000 psi	1,000 psi	$1,714/yd^3

The circumferential stress in the steel cylinder shell, σ_{s_θ}, can be obtained similarly to Eqn. (5) as:

$$\sigma_{s\_\theta} = \frac{P_i R_1^2 - P_f R_2^2 + \left(P_i - P_f\right)\dfrac{R_1^2 R_2^2}{R^2}}{\left(R_2^2 - R_1^2\right)} \qquad (6)$$

Eqn. (6) is used to further ensure the steel vessel shell has a sufficient thickness so that the highest circumferential stress is less than the design allowable stress of the steel.

It is noted that the circumferential strength of concrete enclosure results mainly from the high-strength steel wires (or tendons) wrapped around the concrete outside surface. The concrete itself serves as a medium for uniformly transferring the tensioning (or external pressure) to the inner steel vessel and protecting the steel rebars, pre-stressing wires and tensioning rods from corrosion. The number of pre-stressing wire layers to achieve the specified external pressure, a critical vessel parameter, is determined using the following procedure. The required pre-stressing wire area per unit length in the cylinder direction, A_s, is calculated as:

$$A_s = \frac{P_o R_3}{f_{ew}} \tag{7}$$

where P_o and R_3 are the external pressure and the outer radius of concrete cylinder shell (as defined previously), and f_{ew} is the effective strength (or allowable stress) of the pre-stressing wire. The number of pre-stressing wire layers, N_s, is then determined from $N_s = A_s / A_w$, where A_w is the cross-section area of a single wire. In this study, the pre-stressing wire has f_{ew} = 150 ksi and A_w = 2.36 in^2.

In the longitudinal direction (i.e., vertical direction in Fig. 1), the strength of the concrete enclosure comes from the tensioning rods. The number of rods is determined by dividing the total required vertical stress by the allowable stress of individual rods as:

$$N_r = \frac{2(k-0.5)P_i \pi R_1^2}{f_{er} A_r} \tag{8}$$

where N_r is the number of tensioning rods, P_i is the internal hydrogen pressure, R_1 is the inner radius of the steel shell, f_{er} is the effective strength of the steel rod, A_r is the cross-section area of a single rod, and k is the load fraction carried by the concrete ($0.5 < k < 1$). In this study, the vertical tensioning steel rod has f_{er} = 78 ksi and A_r = 5.16 in^2. It is noted when the steel/concrete load-carrying ratio is 50/50, k = 0.5 and N_r = 0, indicating no longitudinal tensioning is needed.

2.1.3 Design Calculations for Hydrostatic Testing and Buckling

In Fig. 2, the final analysis in the engineering calculation is to ensure the following two conditions are satisfied during the fabrication and testing of an SCCV.

First, the inner steel shell must not buckle under the external pressure exerted by the pre-stressing wires. This is important because if the inner steel shell wall is too thin, the external pressure may crush the shell, resulting in failure due to steel shell buckling and separation between steel and concrete. Closed-form solutions from the ASME BPV Code [6,7] are used to determine if the steel shell thickness obtained in Section 2.1.1 is sufficient to avoid buckling.

Second, the vessel must pass the hydrostatic testing (or hydrotest) as required by ASME BPV Code. As described in Section 2.1.1, the steel shell thickness is determined using ASME BPV Code - Section VIII-2. Because of the built-in safety factors in the ASME Code, the steel shell will pass the hydrotest. Special consideration is given to the pre-stressed concrete enclosure to ensure that the maximum stresses incurred in the circumferential pre-stressing wires and the longitudinal tensioning rods do not exceed 90% of their respective yield strength during the hydrotest. Using Eqns. (7) and (8), the number of pre-stressing wire layers (N_s) and the number of longitudinal tensioning rods (N_r) are adjusted until they have sufficient capacity for at least 143% of the design pressure as required by ASME BPV Code - Section VIII-2 [8,9].

As indicated in Fig. 2, the steel thickness, concrete thickness, layers of pre-stressing wires and number of longitudinal tensioning rods are increased as needed to satisfy both the buckling and hydrotest conditions.

Through the series of engineering calculation outlined in Sections 2.1.1 through 2.1.3, the SCCV dimensions are fully defined. These dimensions are then entered into the high-fidelity cost model described in the next section to estimate the SCCV cost. The design-allowable calculation provides a quick method for determining the vessel dimensions with sufficient accuracy for cost modeling. It is noted that a finite element analysis (FEA)-based structural model is currently being developed for the mock-up pressure vessel that will be fabricated and tested later in the project.

2.2 HIGH-FIDELITY COST MODEL FOR SCCV

The SCCV cost is estimated based on the detailed, bottom-up approach which takes into account the material and labor costs involved in each of the vessel manufacturing steps. Moreover, the cost study only considers an SCCV that can be readily manufactured in existing domestic fabrication facilities without major capital equipment purchases/upgrades. In other words, the manufacturing technologies are commercially available in the U.S. at present or require only incremental/short-term development. For instance, the steel head, which is formed from a single steel plate, is limited to an upper thickness of 6”, the maximum thickness that can be handled in a typical U.S. head fabrication facility. Finally, a moderate production volume (24 identical vessels per order) is assumed in the cost study. Hence, the contingency in material and labor costs, which is typically considered for the small production volume of one or two vessels per order, is not included.

To obtain real-world representative cost estimate of SCCV, the cost analysis was performed in collaboration with Global Engineering and Technology LLC (Camas, WA) and Ben C. Gerwick Inc. (Oakland, CA), two leading engineering design firms in the field of steel pressure vessels and pre-stressed concrete structures, respectively. Figure 2 shows that the total SCCV cost comprises the steel cost and the pre-stressed concrete cost. Detailed cost modeling approaches for layered steel and concrete structures are described in the following sections.

2.2.1 Cost Estimate for Layered Steel Vessel

Figure 4 illustrates the manufacturing process flow for the layered steel vessel. The material and labor costs for each of the major manufacturing steps are determined first and then combined into the total cost of steel vessel. For illustration purpose, the following exemplary SCCV is considered:

- Hydrogen pressure: 430 bar
- Load-carrying ratio: 50/50 (steel/concrete)
- Steel vessel inner radius: 39”
- Length of steel cylinder shell: 17.5 ft.
- Steel vessel thickness: 4.25” (obtained using the procedure in Section 2.1.1)
- Capacity of storage CGH_2: 564 kg

In Fig. 4 below, the fabrication of a steel head involves two steps: (1) forming of a low-alloy steel plate, and (2) cladding of an austenitic stainless steel liner. For the low-alloy steel forming step, the first calculation is to determine the theoretical weight of a hemispherical head based on the inner radius (39”) and wall thickness (4.25”). The plate used for forming weighs more than the theoretical weight in order to ensure the formed head meets the specified thickness. Based on vendor quotes, the actual head weight is estimated to be 1.17 times the theoretical weight. The cost of a formed head is then estimated by multiplying the actual head weight by the unit price per pound of formed steel head from the vendor quotes. In short, the cost of a formed head is summarized as:

- Theoretical head weight = 13,122 lbs
- Actual head weight = 13,122 × 1.17 = 15,352 lbs
- Cost of formed head = 15,352 lbs × \$2.35/lb = \$36,078

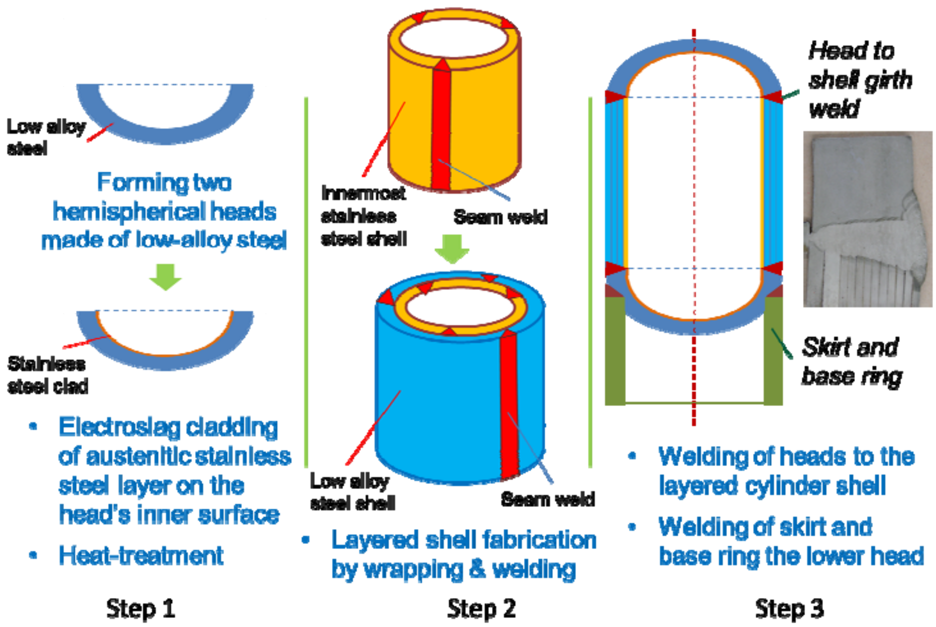

Fig. 4. Major manufacturing steps studied for steel vessel cost modeling.

The unit price of formed steel head based on the vendor quotes is plotted in Fig. 5 below. As expected, the thicker the steel head, the higher the unit price. The unit price curve shown in Fig. 5 is used for cost estimation of steel vessels with different thicknesses.

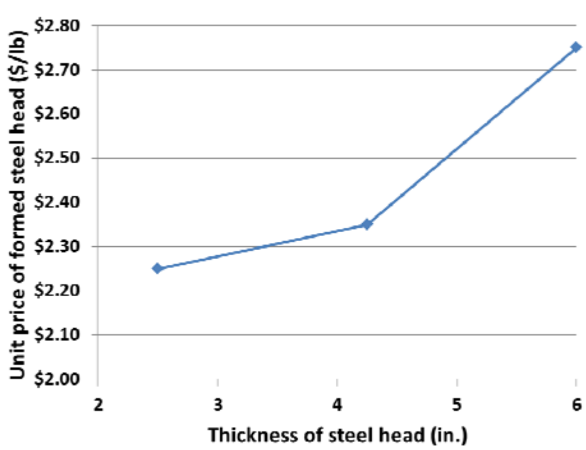

Fig. 5. Unit price of formed low-alloy steel head as a function of head thickness.

The second step in the steel head fabrication is the cladding of an austenitic stainless steel liner for use as protection against hydrogen embrittlement and permeation. A high-productive process, electroslag strip cladding [10], is used for the stainless steel liner cladding. Considering a stainless liner thickness of 0.177”, stainless steel strip price of \$6.57/lb, and cladding flux price of \$5.07/lb, the stainless steel clad price is estimated to be \$70.41/ft^2. The consumable cost for head liner cladding is then calculated by multiplying the inside surface area and the cladding price per unit area as:

- Inside area of head for cladding = 68.1 ft^2
- Cost of consumable for cladding = 68.1 ft^2 × \$70.41/ft^2 = \$4,793 per head

In addition, the labor hours needed for cladding can be estimated by dividing the stainless steel liner weight by the deposition rate of electroslag strip cladding. A deposition rate of 48.8 pounds per hour is chosen in order to minimize the dilution in the stainless steel liner due to melting of the substrate low-alloy steel [10]. In short, the labors hours for cladding are calculated as:

- Weight of 0.177”-thick stainless steel liner = 514 lbs
- Labor hours for cladding = 514 lbs / 48.8 lb/hr × 1.25 = 13 hours (Note: the factor 1.25 is used to account for the additional labor needed to rotate the head during cladding.)

Other labor related to the head fabrication includes 3 hours for sand blasting prior to cladding, and 11 hours for set-up of cladding. Hence, the total labor hours for cladding the stainless liner per head are estimated to be 27 hours.

Similar to the head cost estimation, the costs of other manufacturing steps of the steel shell are calculated. Table 3 summarizes the bill of materials and corresponding prices for the steel vessel. As shown in this table, the prices of two heads, one segment of layered low-alloy steel shell, and the shell stainless steel liner constitute the majority of the steel vessel material cost.

Table 3. Bill of materials and corresponding prices for the steel vessel

Item	Material	Weight	Unit price	Price
Two hemispherical heads	SA537	30,704 lbs	\$2.35/lb	\$72,155
Shell (low-alloy steel)	SA724	71,200 lbs	\$1.01/lb	\$72,062
Shell liner (stainless steel)	Roll-bonded 304L on SA516	7,872 lbs	\$2.38/lb	\$18,736
Base support subassembly:				
Skirt	SA516	6,774 lbs	\$1.00/lb	\$ 6,774
Base top ring and gussets	SA516	2,764 lbs	\$1.27/lb	\$ 3,499
Two nozzles (H_2 in and out)	SA336	576 lbs	\$4.00/lb	\$ 2,304
Misc. (paint, etc.)				\$ 1,840
			Total	\$177,370

Table 4 summarizes the labor hours for fabricating the steel vessel. These estimated labor hours are based on industry standard practice and past project experience of Global Engineering and Technology LLC. Assembling and welding the stainless steel liner and layered steel shell constitute the majority of the labor cost.

With the knowledge of bill of materials (Table 3) and labor hours (Table 4), the total cost for manufacturing the steel vessel is calculated and summarized in Table 5. Given that the steel vessel has a storage capacity of 564 kg of CGH_2, its cost is $539 per kg of stored hydrogen.

Table 4. Labor hours needed for fabrication the steel vessel

Item	Labor hours
Machining of two heads	12
Electroslag strip cladding of two heads	54
Heat treatment of two head sub-assemblies	18
Assembling and welding of stainless steel shell liner	223
Assembling and welding of low-alloy steel layers	610
Welding of skirt	135
Inspection, cleaning and testing	114
Transport (within the fabrication facility)	106
Others (installing nozzles, sandblasting, painting, etc.)	153
Total	1,425

Table 5. Manufacturing cost for the steel vessel with inner radius of 39", wall thickness of 4.25" and cylinder shell length of 17.5 ft

Item	Cost
Bill of materials (from Table 3)	$177,370
Labor (from Table 4 and with a labor rate of $75/hr)	$106,903
Consumables for cladding of head liner	$9,586
Welding consumables (e.g., rod and gas)	$9,200
Engineering and drafting	$1,000
Total	$304,059

It is noted that the Oak Ridge National Laboratory (ORNL) is developing an advanced multi-layer, multi-pass FSW of thick-layered steel structures. Once successfully developed, the highly automated FSW is expected to significantly reduce the amount of labor needed for assembling and welding layered shell. Moreover, FSW makes it possible to use even higher strength steels for further cost reductions and improvement of vessel structural integrity (e.g. minimum degradation of weld properties). In a recent study, ExxonMobil estimated that FSW offers about 25% and 7% construction cost savings for offshore and onshore construction, respectively [11]. In the present study, the projected cost for vessel fabricated with multi-layer, multi-pass FSW is obtained by assuming a 15% reduction in the labor hours for steel shell fabrication, a conservative assumption. For the above exemplary steel vessel, the labor cost shown in Table 5 is thus reduced to \$106,903 $\times$ 85% = \$90,868, with the use of multi-layer, multi-pass FSW. Correspondingly, the total steel vessel cost is decreased to \$510/kg of stored H_2.

2.2.2 Cost Estimate for Pre-stressed Concrete Enclosure

The major manufacturing steps for the pre-stressed concrete enclosure are illustrated in Fig. 6. The direct cost of the pre-stressed concrete is estimated based on the concrete wall height and thickness, the amount of circumferential pre-stressing wires, and the amount of longitudinal tensioning rods (for load-carrying ratios smaller than 50/50). Those concrete design parameters, determined from the engineering calculation detailed in Section 2.1, define the required amount of material for each concrete structure component (i.e., concrete, rebar and pre-stressing wire) in Table 6. The unit prices of these components are also listed in Table 6, which are obtained based on vendor quotes of labor, materials, and equipment use. With the knowledge of the amount of material for a component and the corresponding component unit price, the individual component costs are calculated and then added together to obtain the total direct cost of the concrete structure.

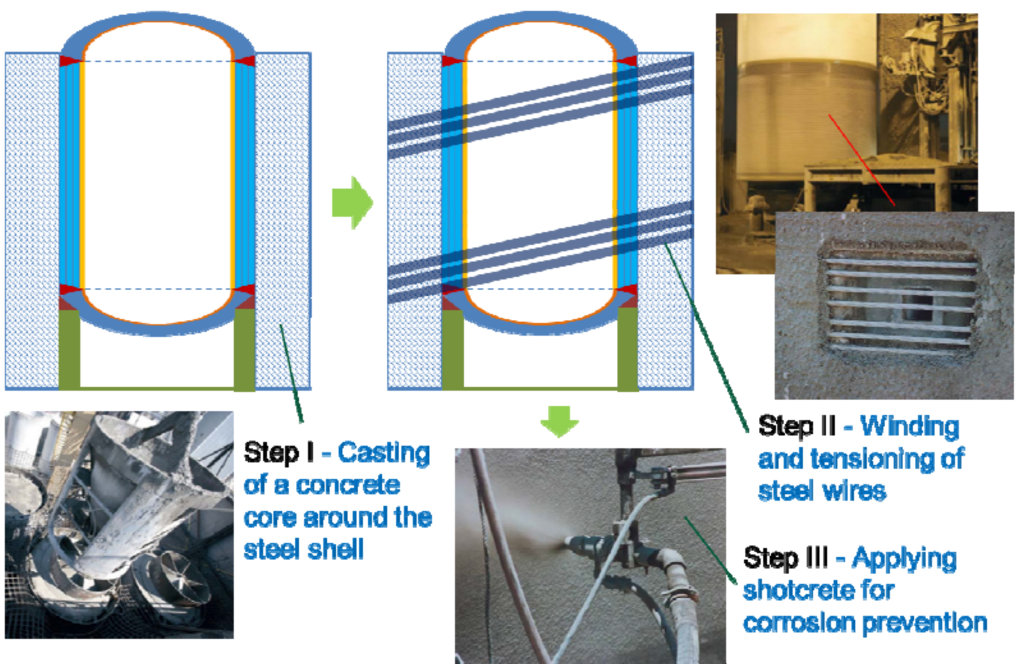

Fig. 6. Major manufacturing steps studied for pre-stressed concrete cost modeling.

Table 6. Direct unit prices of components for constructing the pre-stressed concrete enclosure

Item	Unit	Labor	Material	Equipment use	Subtotal
Light-weight concrete	yd^3	\$102	\$232	\$9	\$343/yd^3
Pre-stressing steel wire	lb	\$1.26	\$0.43	\$0.02	\$1.71/lb
Rebar	lb	\$0.37	\$0.40	N/A	\$0.77/lb

To illustrate the above procedure for concrete structure cost estimation, the same example used in Section 2.2.1 is used here, where the steel vessel has:

- Hydrogen pressure: 430 bar
- Load-carrying ratio: 50/50 (steel/concrete)
- Steel vessel inner radius: 39”
- Length of steel cylinder shell: 17.5 ft.
- Steel vessel thickness: 4.25”
- Capacity of storage CGH_2: 564 kg

Following the formula in Section 2.1.2, the pre-stressed concrete structure has:

- Concrete shell inner radius: 43.25”
- Concrete shell thickness: 8”
- Length of concrete shell: 17.5 ft.
- Rebar: 1% of concrete by volume
- Pre-stressing wire: 7 layers (cross-section area of a wire = 2.36 in^2)

It is noted that in this 50/50 design, no additional longitudinal tensioning is needed. Using the above dimensions, the amount of material for each component in Table 6 is calculated, and their direct costs are summarized in Table 7. Of the $51,083 total direct cost, about 29% is material and equipment cost and 70% is labor cost (see Fig. 7).

Table 7. Direct component costs of pre-stressed concrete structure with wall thickness of 8” and 7 layers of pre-stressing wires

Item	Amount	Unit Price	Direct cost
Concrete	11 yd^3	\$343/yd^3	$ 3,773
Pre-stressing steel wire	27,000 lb	$1.71/lb	$46,170
Rebar	1,500 lb	$0.77/lb	$ 1,140
		Total	$51,083

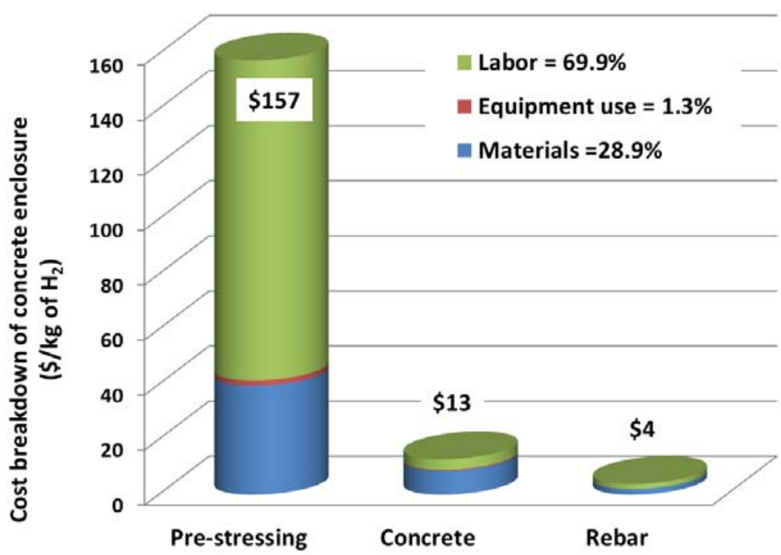

Fig. 7. Unit cost breakdown of the pre-stressed concrete structure, which has a storage capacity of 564 kg H_2 at 430 bar with a load-carrying ratio (steel/concrete) = 50/50.

From its past project experience, Ben C. Gerwick Inc. estimates the pre-stressed concrete fabricators’ contingency and profit are approximately 52% of the direct cost. Therefore the contract cost is

$51,083 × (1 + 0.52) = $77,646. In addition, 18.7% of escalation and 8% of site inspection and overhead (SIOH) costs are assessed on the contract cost to obtain the final cost. In other words, the final cost is calculated as $77,646 × (1 + 0.187 + 0.08) = $98,377. This final cost of pre-stressed concrete structure is equal to a unit cost of $174/kg of stored H_2, considering the storage capacity of 564 kg of H_2. The unit cost breakdown of concrete components is illustrated in Fig. 7.

3. COST ANALYSIS RESULTS AND DISCUSSION

Using the high-fidelity cost modeling tool described in Section 2, a thorough cost study is performed to understand the SCCV cost as a function of the key vessel design parameters: hydrogen pressure, vessel dimensions, and load-carrying ratio. The detailed cost analysis results are discussed below.

3.1 SCCV COST VS. PRESSURE

Figures 8 plots the SCCV costs at 160 bar (low-pressure), 430 bar (moderate pressure) and 860 bar (high-pressure), respectively. In each plot, the leftmost three columns correspond to the DOE technical targets at the given pressure (see Table 1). The fourth and fifth columns represent the estimated costs of SCCV manufactured with conventional arc welding and with automated FSW, respectively. As shown in this figure, <u>the SCCV technology can exceed the DOE's FY2020 technical targets by about 4% for all three pressure levels</u>. Moreover, with the successful development of advanced FSW, the SCCV fabricated using FSW can exceed the FY2020 technical targets by 8%.

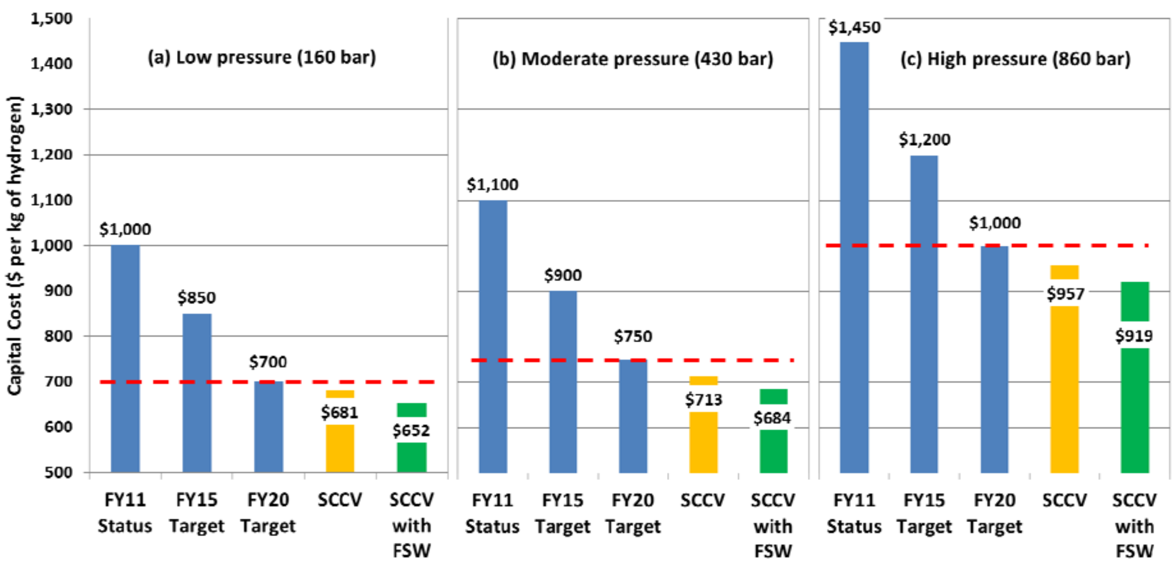

Fig. 8. Comparison between DOE's technical targets and SCCV costs for hydrogen pressure of (a) 160 bar, (b) 430 bar and (c) 860 bar. The SCCV technology can meet the DOE's FY2020 technical targets for all three pressure levels.

Key specifications of the three SCCVs in Fig. 8 are summarized in Table 8. The unit cost breakdowns for these three SCCVs are listed in Table 9. As shown in these tables, the material cost of steel vessel increases with the pressure, since thicker steel wall is needed for higher pressure. Correspondingly, the labor cost also rises with the increased material usage. For the pre-stressed concrete enclosure, the pre-stressing cost goes up significantly with the pressure due to the larger number of pre-stressing wire layers. For all three pressures, the steel vessel constitutes around 73% of the total SCCV cost. In other words, the pre-stressed concrete enclosure bears a 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. It is noted that the cost-effectiveness of pre-stressed concrete drops significantly when the load-carrying ratio for concrete is greater than 50%, as described in the next section.

Table 8. Key specifications of the three SCCVs in Fig. 8

Specification	**160-bar-vessel**	**430-bar-vessel**	**860-bar-vessel**
CGH_2 Pressure	16 MPa (2,350 psi)	43 MPa (6,250 psi)	86 MPa (12,500 psi)
Load-carrying ratio	50/50	50/50	50/50
Inner radius of steel vessel	62.5”	39”	27”
Steel vessel thickness	2.5”	4.25”	6”
Concrete thickness	21”	8”	8”
Number of pre-stressing wire layers	4	7	11
Steel shell height	17.5 ft.	17.5 ft.	17.5 ft.
Total vessel height	28.3 ft.	24.7 ft.	23 ft.
Storage capacity of CGH_2	707 kg	564 kg	416 kg

Table 9. Unit cost breakdowns for the three SCCVs in Fig. 8

Item	**160-bar-vessel**	**430-bar-vessel**	**860-bar-vessel**
Steel vessel (unit price \$ per kg of stored H_2)			
Bill of materials	\$268	\$314	\$386
Labor (conventional arc welding)	\$190	\$190	\$251
Labor (friction stir welding)	\$161	\$161	\$213
Consumables and others	\$50	\$35	\$33
Pre-stressed concrete enclosure (unit price \$ per kg of stored H_2)			
Concrete	\$42	\$13	\$14
Rebar	\$12	\$4	\$4
Pre-stressing wire	\$119	\$157	\$269
Total SCCV unit cost (\$ per kg of stored H_2)			
SCCV	\$681	\$713	\$957
SCCV with FSW	\$652	\$684	\$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%, as described in Section 2.2.1

As the steel vessel constitutes the majority of the SCCV cost, further vessel cost reductions can benefit from advanced FSW for layered steel shell fabrication that is currently under development at ORNL. As described earlier, the highly automated FSW not only reduces the amount of labor needed for assembling and welding the layered shell, but it also enables the use of even higher strength low-alloy steels for greater cost reductions and improvements of vessel structural integrity.

3.2 DEPENDENCE OF SCCV COST ON DIMENSIONS

In this section, the cost of a SCCV with 50/50 load-carrying ratio is studied as a function of vessel dimensions (i.e., vessel shell height and radius) at a constant hydrogen pressure. The moderate pressure of 430 bar is selected for the study, but the conclusions obtained are applicable to other pressures. In the following discussion, the reference vessel, shown in both Figs. 9(a) and 10(a), corresponds to the 430-bar SCCV with key specifications defined in Table 8.

Figures 9(a) and (b) show the unit cost comparison between the reference 430-bar SCCV with a shortened SCCV. Due to the shorter length, the SCCV in Fig. 9(b) has a CGH_2 storage capacity of 396 kg while that in Fig. 9(a) has a capacity of 564 kg. As the identical head (i.e., radius and thickness) is used for both steel vessels, the actual manufacturing cost of steel heads remains the same. However, since it stores much less H_2, the shortened vessel has a much higher unit cost ($/kg of stored H_2) for steel heads. Overall, the unit cost of the steel vessel increases from $539 to $629 per kg of stored H_2 as the vessel cylinder shell length (or height) is reduced from 17.5 to 11 ft. For the pre-stressed concrete enclosure, the steel shell area on which it is wrapped is reduced in the shortened vessel. As a result, the pre-stressed concrete cost goes down slightly to $156 per kg of stored H_2 for the shortened vessel shown in Fig. 9(b). Altogether, the rising steel vessel cost outweighs the dropping pre-stressed concrete cost, resulting in a net 10% increase in the total vessel unit cost as the vessel shell is shortened from 17.5 to 11 ft.

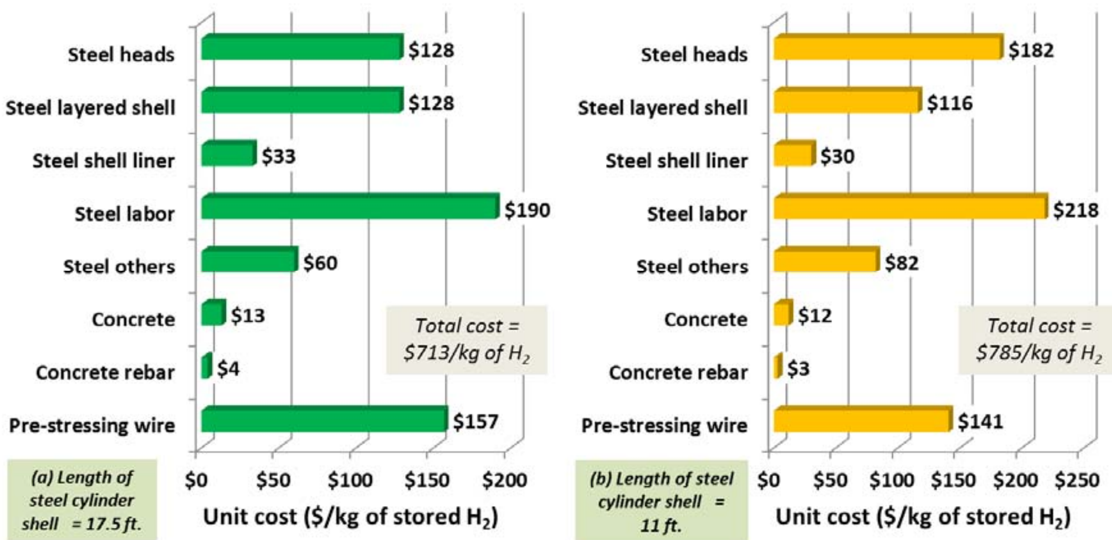

Fig. 9. Effect of vessel shell length (or height) on vessel unit cost: (a) Reference 430-bar SCCV with shell length of 17.5 ft, and (b) shortened SCCV with shell length of 11 ft

The dependence of SCCV cost on the inner radius of steel vessel is illustrated by the results shown in Fig. 10. As the inner radius decreases from 39 to 33.25 in, the storage capacity drops significantly, from 564 to 398 kg. In other words, a 15% drop in the steel vessel inner radius amplifies into a 29% decrease in the storage capacity (since the storage volume depends on the square of the radius). It is noticed that as the radius shrinks from 39" to 33.25", the steel wall thickness and the number of pre-stressing wire layers also decrease from 4.25" to 3.5" and 7 to 6 layers, respectively. However, as shown in Fig. 10, the drop in storage capacity outpaces the decrease in the manufacturing cost due to thinning of the steel vessel and the pre-stressing wire layers, resulting in an increase of 8.3% in the unit storage cost ($/per kg of stored H_2).

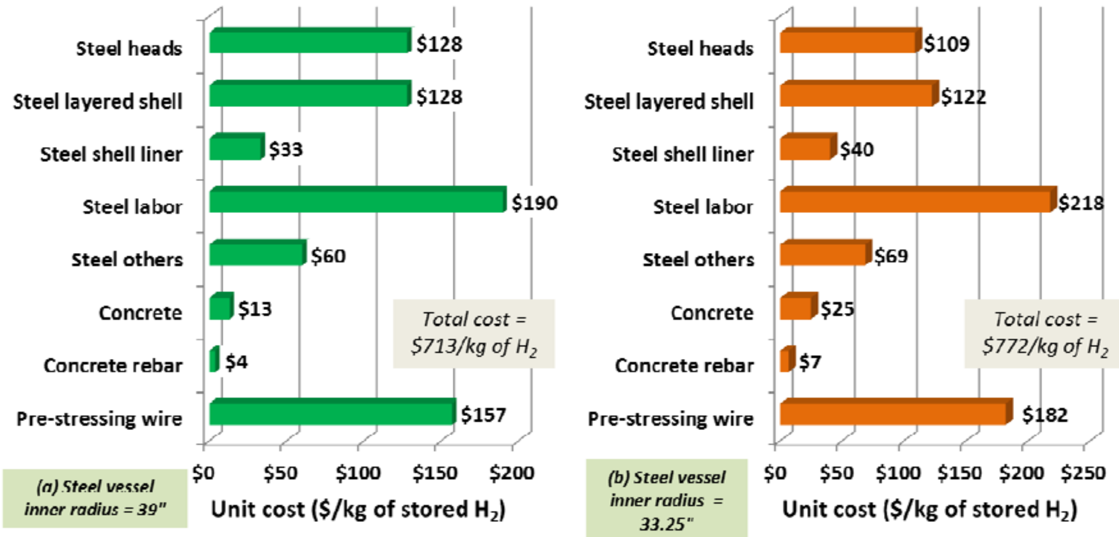

Fig. 10. Effect of steel vessel inner radius on vessel unit cost: (a) Reference 430-bar SCCV with inner radius of 39", and (b) smaller SCCV with inner radius of 33.25"

The cost comparisons in Figs. 9 and 10 favor SCCVs with larger inner radius and longer shell height for further lowering the total vessel unit cost. However, such reduction in SCCV unit cost by enlarging the vessel size is limited by the available vessel fabrication capacity. First, as discussed earlier, the steel head is limited to a maximum thickness of 6". Eqn. (1) indicates that such maximum thickness of steel wall can be quickly exhausted as the inner radius of steel vessel increases. Moreover, the SCCV with larger radius and thicker wall is heavier, which could pose a cost penalty when transporting the vessel from the fabrication location to hydrogen fueling or other storage sites. Second, due to the steel plate rolling capacity constraint, a single segment of steel shell is limited to the maximum length of 17.5 ft. If the steel shell length is greater than 17.5 ft, two segments of steel shell will have to be welded together, resulting in significant increase in welding and labor cost.

From the above analysis of the effect of vessel dimensions on SCCV unit cost, within the limits of vessel fabrication capacity, a SCCV with larger inner radius and longer shell height is desirable to reduce the vessel unit cost ($/per kg of stored H_2). It is noted that the actual manufacturing cost of a larger SCCV can be higher since the larger SCCV stores more CGH_2.

3.3 EFFECT OF LOAD-CARRYING RATIO ON SCCV COST

The cost analysis results in Sections 3.1 and 3.2 above are obtained for the SCCVs with a load-carrying ratio of 50/50. In this section, the effect of load-carrying ratio on the vessel cost is studied to explore the feasibility of further cost reduction by shifting a higher percentage of structural loads to the pre-stressed concrete enclosure.

Figure 11 compares the 50/50 SCCV design with the vessel design in which the pre-stressed concrete enclosure carries more than 50% of the structural loads (i.e., smaller load-carrying ratios such as 40/60, 30/70 or 0/100). As shown in Fig. 11(a), only the circumferential tensioning is used for the 50/50 vessel, as there is no need for longitudinal tensioning (see Eqn. (8)). This is because the longitudinal stress in the steel shell is half the circumferential stress. Hence, the steel vessel wall thickness, which is designed to carry 50% of the circumferential stress, is sufficient to bear the longitudinal stress. However, once the pre-stressed concrete enclosure carries more than 50% of the structural loads, the longitudinal tensioning becomes necessary. As will be shown next, the use of longitudinal tensioning and ultra-high strength concrete for smaller load-carrying ratios significantly increases the cost of the pre-stressed concrete enclosure, resulting in more expensive vessels than the 50/50 SCCVs.

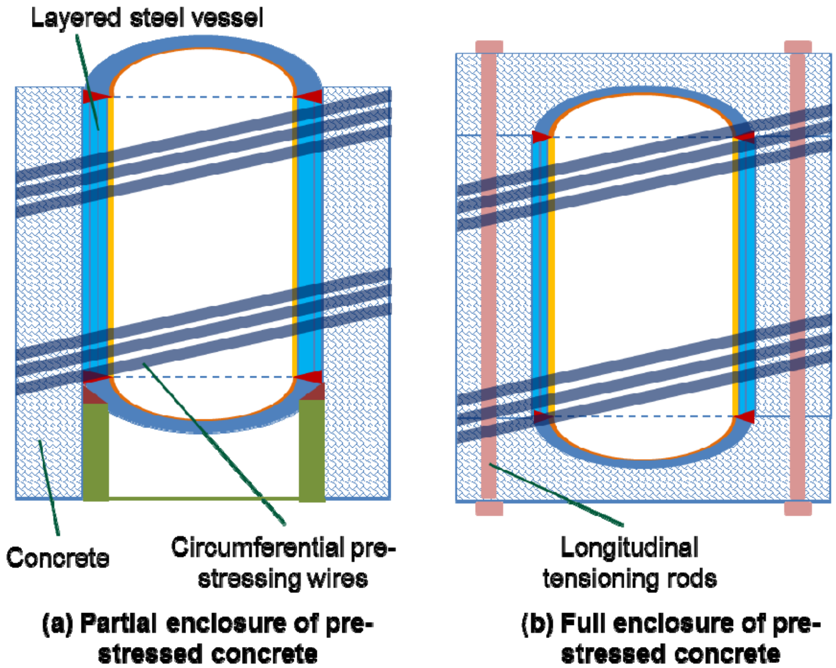

Fig. 11. SCCV designs with (a) 50/50 (steel/concrete) load-carrying ratio, and (b) smaller load-carrying ratios (e.g., 30/70).

The following cases are studied to understand the effect of load-carrying ratio on the vessel cost:

- Pressure: 160, 430 and 860 bar
- Steel vessel dimensions: inner radius = 36", and total height = 27.5 ft.
- Load-carrying ratio (steel/concrete): 50/50, 40/60 and 30/70

As described earlier, below the ratio of 50/50 (e.g. 40/60 and 30/70), a full pre-stressed concrete enclosure is required, such that both the steel head and shell are encapsulated (see Fig. 11(b)). The full enclosure uses both circumferential pre-stressing and longitudinal tensioning, thus requiring a larger amount of concrete and rebar than the partial enclosure for the 50/50 vessel. Moreover, unlike the partial enclosure which can utilize light-weight concrete, the full enclosure needs to use ultra-high strength concrete due to the higher pressure exerted to the concrete section. As shown in Table 2, ultra-high strength concrete comes at a premium price that is five times of the light-weight concrete price.

As shown in Table 10, the cost of pre-stressed concrete enclosure jumps up significantly as the load-carrying ratio is reduced below 50/50 due to use of longitudinal tensioning and ultra-high strength concrete. For the 160 bar pressure, the cost of 40/60 concrete enclosure itself (i.e., $981) is substantially higher than the corresponding DOE FY20 target (i.e., $700). For the 430 and 860 bar pressures, the cost of 40/60 concrete enclosure already constitutes 87% and 96% of the corresponding FY20 targets. Hence, it is projected that the total cost of SCCV (comprising both the pre-stressed concrete enclosure and the inner steel vessel) will be much higher than the FY20 targets at the 430 and 860 bar pressures.

Table 10. Estimated unit costs of pre-stressed concrete enclosure for different conditions

H_2 pressure	DOE FY20 target	Steel vessel radius	Steel vessel height	Load-carrying ratio		
				50/50	40/60	30/70
160 bar	$700	36”	27.5 ft	*$251*	$981	$1,063
430 bar	$750	36”	27.5 ft	*$205*	$656	$ 873
860 bar	$1,000	36”	27.5 ft	*$312*	$959	$1,434

Note: Estimated unit cost given as $ per kg of stored H_2.

The comparison of cost data for the 30/70 and 40/60 ratios in Table 10 indicates shifting the structural loads to a pre-stressed concrete enclosure beyond 50% would result in further increase in cost. A final example is for an extreme case where the pre-stressed concrete enclosure carries the entire structural loads (i.e. a load-carrying ratio of 0/100) at the 430 bar H_2 pressure. It is calculated that a 10”-thick concrete wall is needed, with 13 layers of pre-stressing wires. The unit cost of this 0/100 concrete enclosure is $1,147/kg of H_2, which is 53% above DOE’s FY2020 cost target even without including the cost of any liner as a hydrogen barrier. In other words, there does not seem to be any economic benefit in using the pre-stressed concrete enclosure to carry more than 50% of the structural loads. Moreover, the industry has limited experience and knowledge in constructing the full concrete enclosure for the high pressures considered here. Hence, the 50/50 SCCV design is determined to be both economically viable and technically feasible for storing CGH_2 at the needed high pressures (e.g., 160, 430 and 860 bar).

3.4 COST OF LINER MATERIAL

As described previously, an austenitic stainless steel clad liner is placed on the steel vessel’s inner surface as the hydrogen embrittlement and permeation barrier. The corrosion resistance property of austenitic stainless steel is expected to maintain its surface cleanness and not to contaminate the stored hydrogen even after a prolonged period of service. Moreover, the stainless steel clad, which is metallurgically bonded to the substrate carbon steel, has a strong tolerance to the temperature, stress and strain cycling common to the hydrogen fueling stationary storage. However, the performance of a stainless steel clad liner comes at a premium price: the liner costing about $101, $68, and $60/kg of stored H_2 for the 160-, 430- and 860-bar SCCVs in Fig. 8, respectively. In other words, the stainless steel liner (including both material and manufacturing) constitutes around 15%, 9.5% and 6.3% of the total cost of the 160-, 430- and 860-bar SCCVs, respectively. It is noted that the ratio of the liner cost over the total vessel cost is highest for the 160-bar SCCV, which has the thinnest steel wall due to the lowest hydrogen pressure among the three SCCVs. This ratio decreases quickly as the steel wall thickness increases.

The stainless steel liner is especially important for the carbon steel heads which experience significant tensile stress due to hydrogen pressure. For the steel cylinder in the 50/50 SCCV design, its inner surfaces are subject to compressive stresses or small tensile stresses due to the pre-stressing on the concrete outside surface. Therefore, it is possible that the cylinder section of the inner steel vessel does not require a hydrogen permeation barrier liner to avoid hydrogen embrittlement. However, such alternative design with austenitic stainless steel clad only for the heads can face some manufacturing issues such as welding of the stainless steel cladded head to the bare carbon steel cylinder. Considering the efficient and low-cost roll-bonding process used for cladding the austenitic stainless liner to the cylinder shell carbon steel, there does not seem to be any cost advantage to use the bare carbon steel cylinder without the stainless steel liner.

From the above discussion, it is evident that if a lower cost liner material with performance comparable to austenitic stainless steel can be developed, there could be a significant opportunity for further reduction of SCCV cost especially for vessels with relatively thin steel walls (e.g., about 2.5" to 3.5"). However, several challenges need to be addressed in order to develop the alternative liner material. First, for the stationary vessel with large storage capacity considered here, there can be a significant amount of heat generated due to pressurization of H_2. Second, the storage vessel experiences a significant stress and strain cycling due to repeated charging/discharging operations. Therefore, the alternative liner material must be able to sustain the combined thermal and stress cyclic loading during long term (10-30 years) service. Technical basis for use of alternative liner materials needs to be developed and demonstrated before they can be adopted for SCCV.

Finally, it is noted that the SCCV technology can be used for storing compressed natural gas (CNG) or a mixture of CNG and CGH_2. For such storage applications where the hydrogen embrittlement to carbon steel does not occur, the stainless steel liner may be not needed and the SCCV technology can be even more competitive to the industry-standard high-pressure storage technology.

4. SUMMARY AND CONCLUSIONS

A high-fidelity cost analysis tool is established for the novel, low-cost, high-pressure, steel/concrete composite vessel technology (SCCV) for stationary storage of CGH_2. The SCCV technology uses commodity materials such as structural steels and concretes to cost-effectively contain the structural loads exerted by the high-pressure hydrogen. The hydrogen embrittlement of high-strength steels, a major safety and durability issue for the industry-standard pressure vessel technology, is mitigated through the use of a unique layered-steel shell structure. The high-fidelity cost analysis tool for the SCCV is composed of two major steps. First, the SCCV dimensions are calculated using the guidelines from relevant industry codes and standards such as ASME BPV Code – Section VIII. A series of engineering calculation are performed to ensure the SCCV passes the standards' requirements including hydrostatic testing etc. Second, the SCCV cost is estimated based on the detailed, bottom-up approach which takes into account the material and labor costs involved in each of the vessel manufacturing steps. The cost analysis tool is established in collaboration with two leading engineering design firms (Global Engineering and Technology LLC and Ben C. Gerwick Inc.) with cost data obtained from vendor quotes, past project experience, and industry standard practice.

Using the high-fidelity cost modeling tool, a thorough cost study is performed to understand the SCCV cost as a function of the key vessel design parameters: hydrogen pressure, vessel dimensions, and load-carrying ratio. The following conclusions can be drawn:

- The SCCV technology can exceed the DOE's FY2020 technical targets by about 4% for all three pressure levels (e.g., 160, 430 and 860 bar) relevant to the hydrogen production and delivery infrastructure.

- For the conditions examined in this work, the SCCV unit cost (\$/kg of stored H_2) decreases slightly as the vessel inner radius is larger or the vessel shell length is longer. This is because the larger radius or longer shell length results in an increase in the storage capacity, which outpaces the rising manufacturing cost due to more material usage of steel, concrete and pre-stressing wires.

- The 50/50 SCCV design is determined to be both economically viable and technically feasible for storing CGH_2. On the other hand, further shifting structural loads to the pre-stressed concrete enclosure beyond 50% incurs a significant cost penalty due to the required use of both circumferential and longitudinal tensioning and ultra-high strength concrete.

- The layered steel vessel constitutes a majority of the total cost for 50/50 SCCV. Further vessel cost reduction can benefit from the development of highly automated friction stir welding (FSW). The Oak Ridge National Laboratory's patented multi-layer, multi-pass FSW can not only reduce the amount of labor needed for assembling and welding the layered steel shell, but also make it possible to use even higher strength low-alloy steels for further cost-reductions and improvement of structural integrity.

The cost analysis results demonstrate the significant cost advantage attainable by the SCCV technology for different pressure levels when compared to the industry-standard pressure vessel technology. However, the real-world performance data of SCCV is imperative for this new technology to be adopted by the hydrogen industry for stationary storage of CGH_2. Therefore, the key technology development effort in FY2013 and subsequent years will be focused on the fabrication and testing of SCCV mock-ups. The rigorous tests will include both static and low-frequency cyclic loading conditions (similar to pressure variations of a hydrogen refueling station) to confirm the integrity of the system for high-pressure hydrogen service. Such testing is essential to evaluate the technology in its entirety and provide the critical data/results required for future technology transfer and acceptance by ASME and other relevant standards and codes. The successful fabrication and tests of SCCV mock-ups are essential to enabling the near-term impact of the developed storage technology on the CGH_2 storage market, a critical component of the hydrogen production and delivery infrastructure. In particular, the SCCV has high potential for widespread deployment in hydrogen fueling stations.

5. AKNOWLEDGEMENTS

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