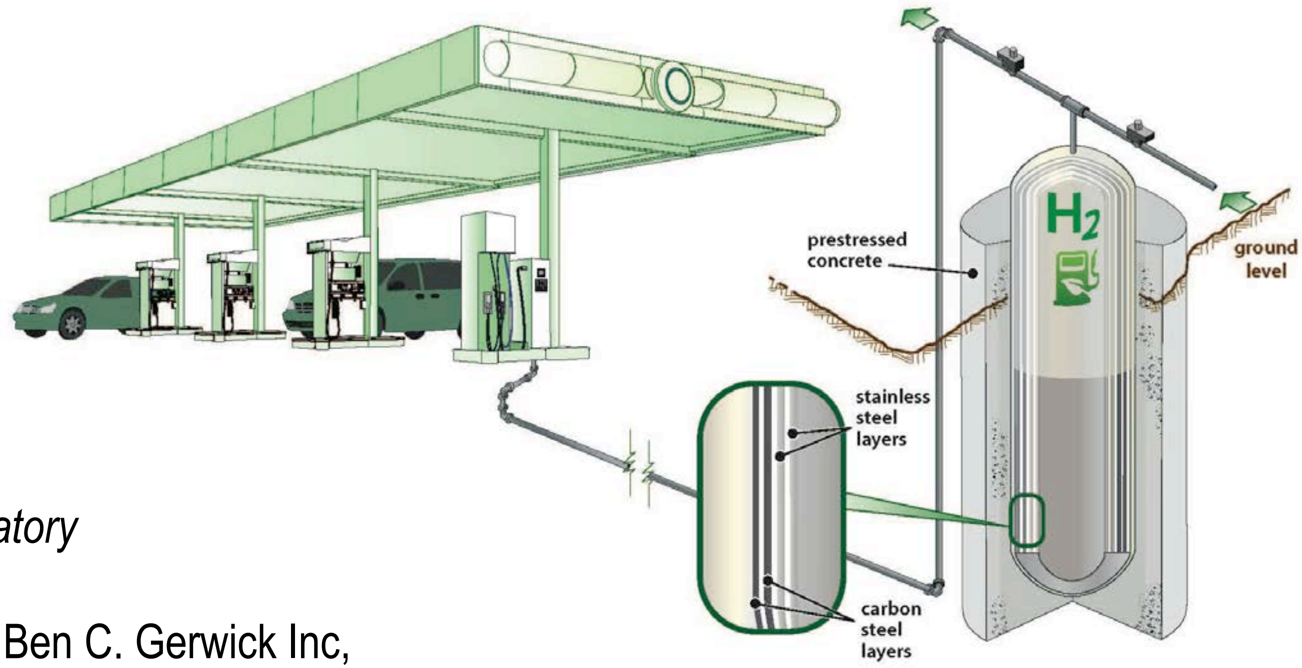
Steel Concrete Composite Vessel for 875 bar Stationary Hydrogen Storage



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Air Liquide, AccerlorMittal, Ben C. Gerwick Inc, BKi, Hanson Pressure Pipe, Global Engineering & Technology, LightSail, MegaStir Technologies, POSCO, Shell, SustainX, Temple University, WireTough Cylinders

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U.S. DEPARTMENT OF ENERGY

PD109

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Overview

Timeline

- Project start date: Oct. 2015
- Project end date: Sept. 2017*

* Project continuation and direction determined annually by DOE

Budget

- Total Project Budget: $2,897K
- Total Recipient Share: 30%
- Total Federal Share: 70%
- Total DOE Funds Spent: $147K

  * as of 3/31/2015

Barriers

- Barriers addressed
  - F. Gaseous hydrogen storage and tube trailer delivery cost
  - G. Storage tank materials and costs

Partners

- Partners *(receiving funding)*:
  Temple University, Wiretough Cylinders, Hanson Pressure Pipe, BKi
- Interactions / collaborations
  Air Liquide, AccerlorMittal,
  Ben C. Gerwick Inc,
  Global Engineering & Technology,
  LightSail, MegaStir Technologies,
  POSCO, SustainX,
- Project lead
  - Oak Ridge National Laboratory (ORNL)

Relevance – DE-FOA 821 Topic 3

The project goal is to develop and demonstrate low-cost, high-pressure hydrogen storage for use at a hydrogen fueling station.

- Meet the cost targets of <$1000/kg H_2 stored at pressures of 875 bar or greater.
- Show compatibility of design materials with hydrogen, and durability under partial pressure
- Meet all performance requirements included in the DOE MYRD&D 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 > 1000 kg of hydrogen.
- Scalability and footprint of the storage system for versatility in applications

** DOE FCT Multi-Year Plan updated 2-2013* http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

Project Objective

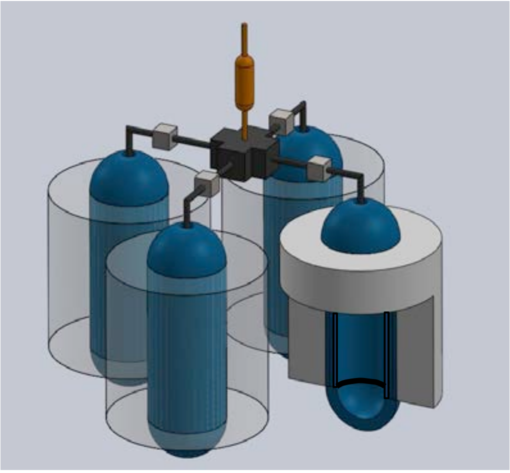
Develop the ***second-generation*** SCCV that will be more cost-effective for forecourt hydrogen fueling station applications.

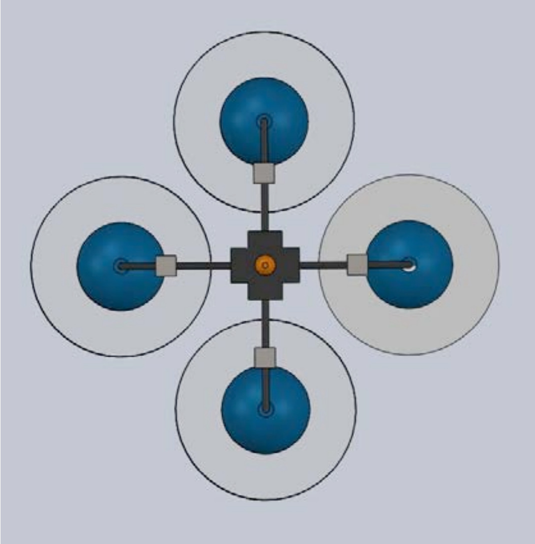
- Reduce the purchased capital cost of SCCV for forecourt hydrogen storage to **$800/kg H2** at 875 bar (i.e., 20% lower than DOE FOA's cost target), while meeting all other requirements including projected service life of at least 30 years and scalability to 1000 kg of storage set forth in FOA
- A representative prototype mockup, capturing all major features of SCCV technology, will be fabricated and tested for hydrogen service at 875 bar to validate the technical concept, manufacturability and cost-effectiveness of GEN II SCCV for forecourt high-pressure hydrogen storage.

SCCV Technology

SCCV technology integrates four major innovations to optimize cost, scalability, durability, and safety.

- Modular design
  - Flexibility for scalability
  - Flexibility for cost optimization
  - System reliability and safety
  - Individual vessels are self contained and monitored.
- Composite of steel and concrete to reduce cost
  - An inner multi-layered steel vessel encased in a pre-stressed outer concrete reinforcement, for load sharing (hoop stress)
  - Use of cost-effective commodity materials (concrete and steel)
- Novel inner steel vessel design that eliminates hydrogen embrittlement potential
- Advanced fabrication and sensor technologies for cost reduction and improved operation safety





SCCV Technology

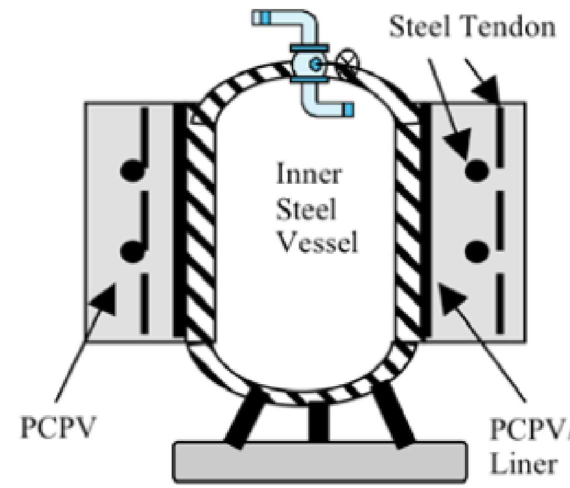
SCCV technology utilizes today's fabrication technologies to meet DOE cost targets and safety and performance requirements.

- Can be designed and constructed using mature and proven fabrication technologies accepted by pertinent codes/standards
  - Steel inner vessel designed and built per ASME Boiler and Pressure Vessel (BPV)
  - Outer concrete reinforcement per American Concrete Institute (ACI)
- Safety and performance:
  - Layered design: **Leak before burst** (for avoiding catastrophic failure)
  - Steels and concretes:
    - Mechanical properties (e.g., static, fatigue and creep) well established
    - Tolerant to third-party damage
  - Many decades of construction and operation experience (e.g., inspection, maintenance, repair etc.)
- Detailed cost analysis shows the first generation SCCV meets DOE's cost targets

Approach

The Gen II SCCV builds on the success of Gen I SCCV and optimize all major aspects of SCCV technology for significant cost reduction.

- GEN I SCCV
  - 50/50 concrete/steel design is the most cost effective in the current design
  - All major design concepts and industry scale manufacturability have been validated
- High cost areas identified for considerable *further* cost reduction
  - Hydrogen permeation barrier
  - Steel vessel design
  - Concrete reinforcement design
  - Novel sensor technologies



Case 2: 50% Steel + 50% Concrete

Pre-stressed concrete sleeve carrying 50% of hoop stress

Project Scope: Areas of Cost Reduction

The high-cost areas of the GEN I SCCV are being focused on for refinement of design, engineering, materials, and fabrication.

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

* Reference cost: GEN I SCCV ($957 Kg$H_2$ @ 860 bar), or DOE FOA Target $1000kg H2 @875 bar

Proposed target is 20% reduction

Approach: Cost Reduction by Materials

SCCV design enables use of ultra high-strength steels, which lower vessel cost.

- SCCV design minimizes vessel exposure to hydrogen, thereby eliminating the potential for hydrogen embrittlement. High-strength steels can therefore be used in the vessel. Use of high-strength steels reduces the vessel wall thickness and the associated fabrication cost.
  - A 35-60% increase in steel strength (i.e. from the reference 75 ksi (SA724 Gr B) to 100 – 120 ksi yield strength) would potentially result in a cost reduction by 15-30%

Approach: Cost Reduction by Vessel Design Optimization

Vessel cost will be optimized by re-analyzing materials, dimensions, and manufacturing considerations.

- We will apply the cost model methodology developed previously. Options to be investigated include :
  - Optimizing the shape and dimension of the SCCV
  - Replacing the stainless steel inner layer with low cost materials as hydrogen permeation barrier
  - Optimizing the pre-stress level of the concrete vessel
- Work with manufacturers to understand the limits and constraints of today's manufacturing technologies in SCCV optimization

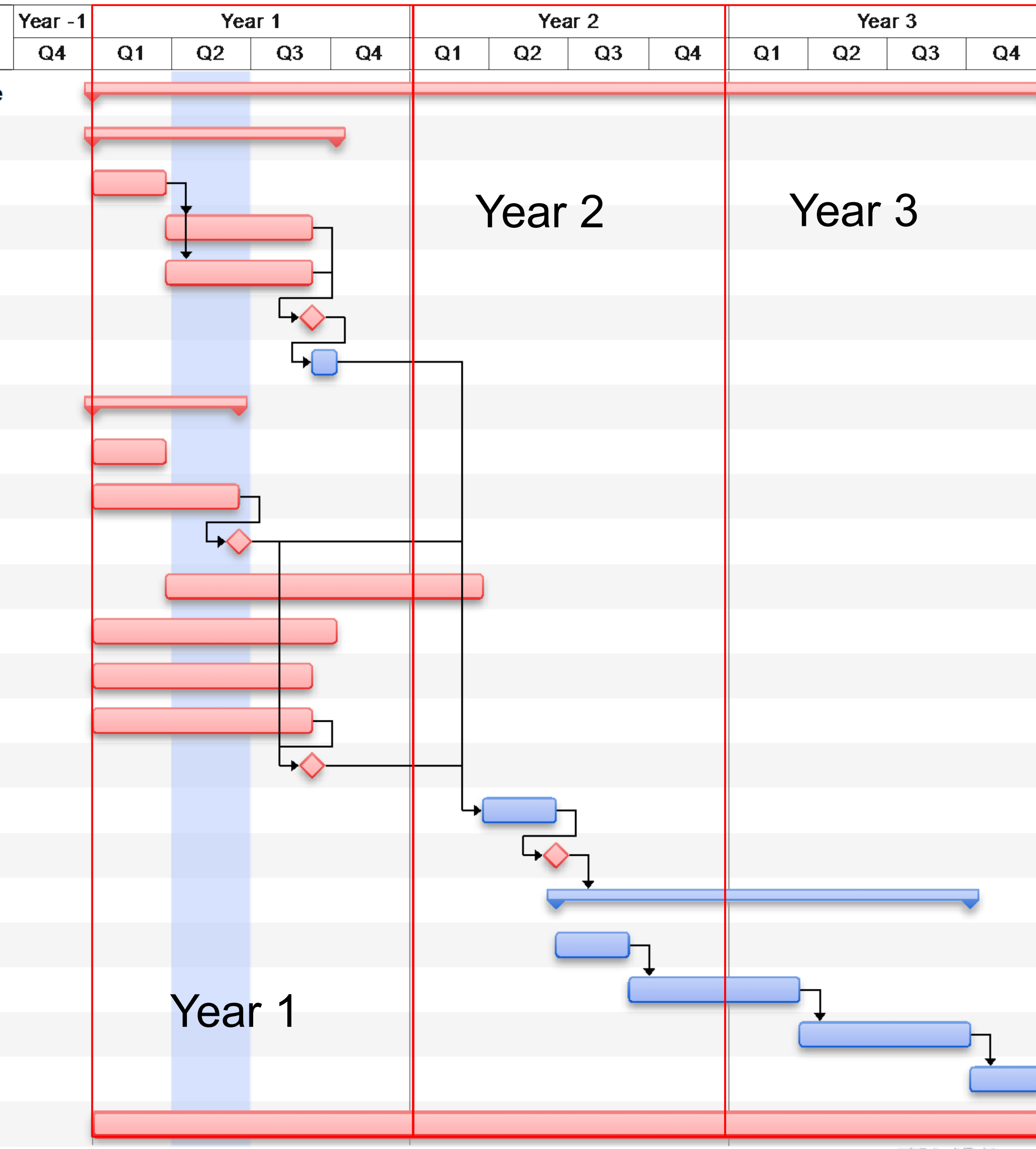
Approach: Fabrication and Sensor Technologies

Vessel cost will further reduced by development of new and improvement of vessel manufacturing and sensor technologies.

- The following options will be investigated:
  - Eliminating the use of manway by means of state-of-the-art non-contact vessel inspection and remote repair welding technology,
  - Application of friction stir welding, and
  - New wire winding techniques for pre-stressed concrete
  - New sensor technologies for vessel health monitoring and supporting cost reduction (repair and fabrication)

Project Schedule

#	Info	Title
0		**Gen II SCCV for Forecourt Hydrogen Storage**
1		**Ultra High Strength Steel**
2		Materials Selection
3		Welding and Weldability Evaluation
4		Hydrogen Compatibility Testing
5		Go/ No- Go on Steel
6		Steel Cost Model
7		**Low Hydrogen Permeation Liner**
8		Materials Selection
9		Hydrogen Compatability
10		Go/ No- Go on Steel Liner
11		**Friction Stir Welding**
16		**Alternative Pre- Stress Technology**
21		**Remote Sensors**
25		Remote Repair Welding
26		Eliminating Manway
27		Design Optimization
28		Meet Project Cost Target/ DOE Target
29		**Prototype Mockup**
30		Design/ Engineering
31		Construction
32		Testing
33		SCCV Technology Demo/ Transfer
34		Project management/ Reporting



FY2015 Milestones and Go/No Go Decisions

- Select three candidate high-strength structural steels with 100-120 ksi yield strength suitable for layered steel vessel. Identify two alternative hydrogen permeation barrier materials for inner liner for further testing. (Q1) Completed
- Go/No Go: Develop or identify at least one barrier material having no more than 10% notch strength reduction in hydrogen embrittlement and a leak rate of less than 50 kg/year ($200/year) for a reference 1000 kg storage SCCV at 875 bar. (Q2) Passed
- Demonstrate acceptable weldability of the new candidate high-strength structural steels selected (Q3) in progress
- Go/No Go: Demonstrate alternative reinforcement technology with reduced cost over conventional reinforced concrete technology by 5%. (9/30/2015) in progress

Accomplishment

High strength steels have been identified that meet the proposed property requirements and are available from our steelmaking team members.

	ArcelorMittal			POSCO	
	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% >

- Weldability and weld properties of these candidate steels are being evaluated

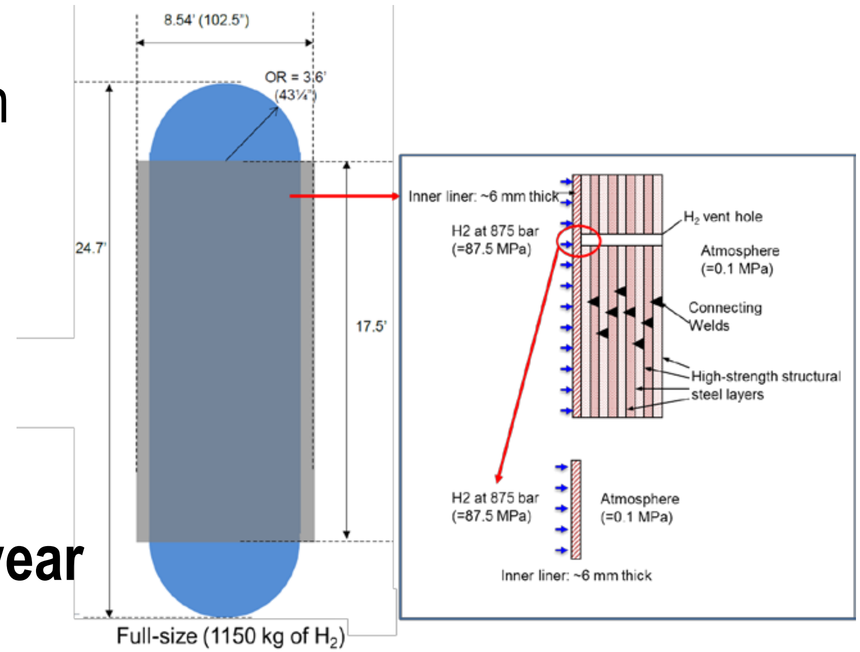
Accomplishment

Two types of low cost hydrogen permeation barrier materials have been identified.

- Target hydrogen leak rate: 50kg H_2/year for reference design (1150kg H_2 at 875 bar)
- Maximum allowable hydrogen permeation rate to meet the target:

$$1.56x10^{-8}\frac{mole}{m\cdot s\cdot\sqrt{MPa}}$$

- **The candidate barrier materials have permeations rate far less than 1kg H_2/year (50 time lower than proposed target)**
  - **Cost is about 10-20% of current stainless steel barrier**
  - **Much easier to fabricate**



Accomplishment

A set of standard reference designs has been selected for GEN II SCCV optimization.

- Intended for off-the-shelf production/order for re-fueling stations
  - One size doesn't fit all. Combination of reference designs to meet different capacity requirement of different fueling station.
  - Initial reference designs: 100, 200, 500 and 1000 kg H_2 at 875 Bar
- Basis for GEN II SCCV optimization
  - For cost optimization
  - For detailed fabrication-construction engineering
  - For high-volume manufacturing engineering
  - For validation of technology scalability

Accomplishment

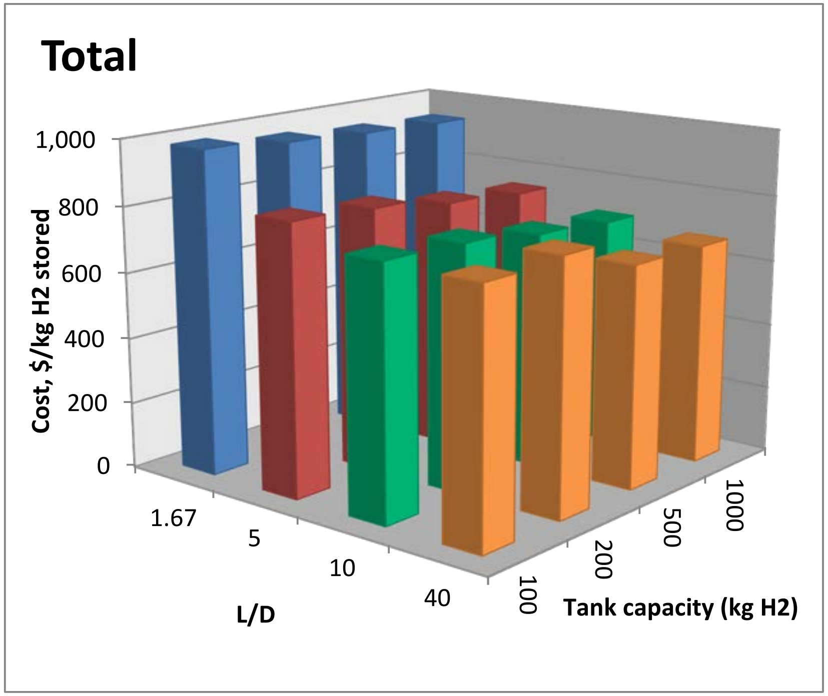
Completed the initial, Level 1, vessel design optimization that identified significant cost reduction options.

- Baseline Reference Design
  - Design of the composite vessels (GEN 1)
    - Inner Steel Vessel:
      - Head: SA-537-CL2 + 308L , Shell: Structural layers: SA-724B, H_2 permeation barrier: 1/8" SS 304
    - Pre-stressed Outer Concrete Reinforcement
      - Concrete, Rebar, Steel wrapping wire
  - Material properties and cost (GEN 1)

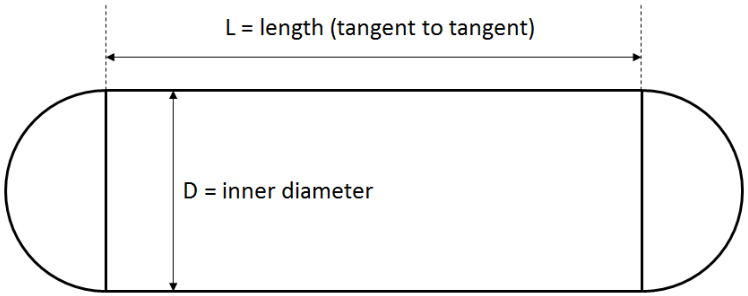
Material	σ_{allow} (ksi)	Material Cost ($/lb)	Note
SA-537-CL2	32.2	2.75	Head
SA-724B	39.5	1.01	Shell
SS 304/SA-516-70		2.38	H2 barrier
Wrapping wire	150	4	(including labor)
Concrete	0.2 (tension)	$800/yd^3	(including labor)
Rebar		1.8	(including labor)

Accomplishment: GEN I SCCV Cost (Baseline Reference)

Preliminary cost analysis results shows that the unit cost (per kg H2) decreases with increase in capacity and increase in L/D ratio.

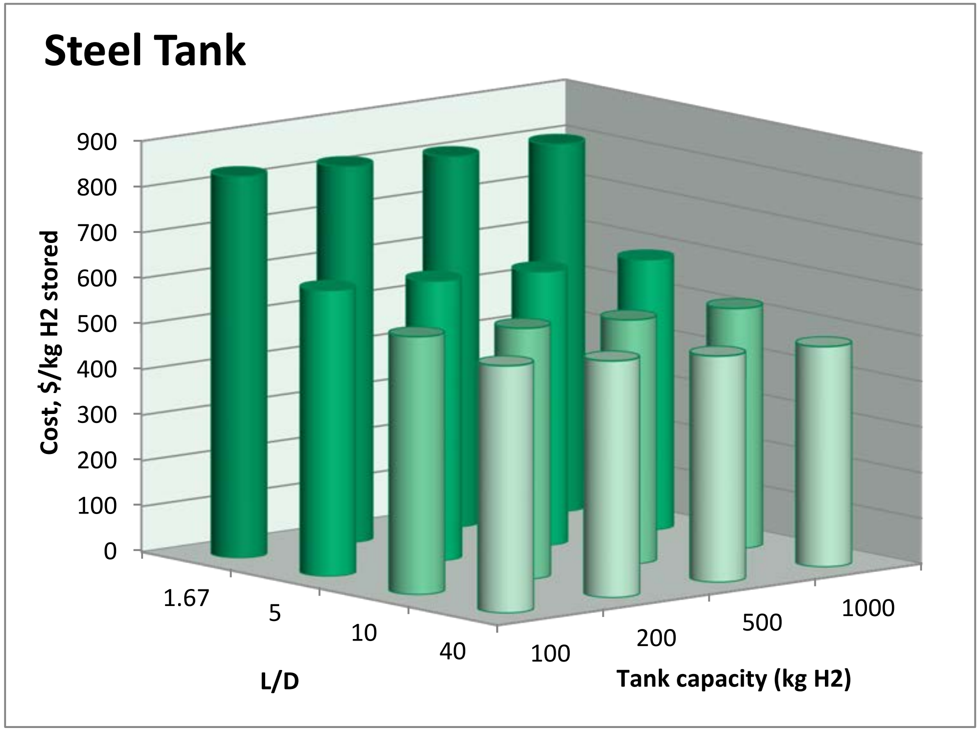


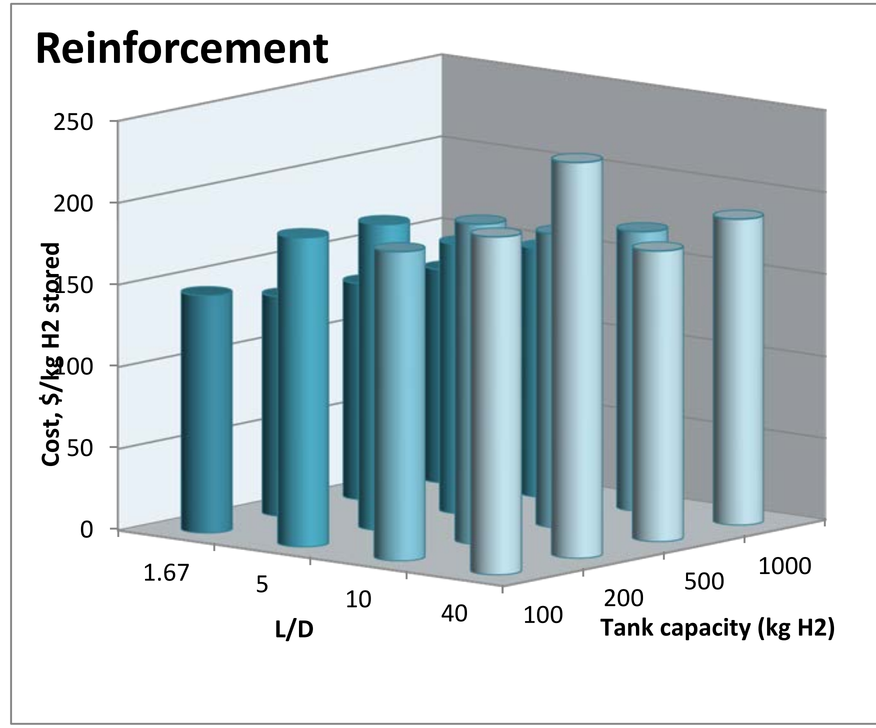
($/kg H2)	Tank capacity (kg)			
L/D ratio	**100**	**200**	**500**	**1000**
1.67	982	959	945	936
5	816	801	765	745
10	756	747	715	697
40	750	762	674	670



Accomplishment: GEN I SCCV Cost breakdown (Baseline Reference)

Preliminary cost breakdown results shows that the primary cost driver is the inner steel vessel.





($/kg H2)	Tank capacity (kg)			
L/D ratio	**100**	**200**	**500**	**1000**
1.67	837	825	813	806
5	627	614	601	593
10	566	551	535	526
40	543	520	497	483

($/kg H2)	Tank capacity (kg)			
L/D ratio	**100**	**200**	**500**	**1000**
1.67	145	134	132	130
5	189	187	165	152
10	189	196	180	171
40	207	242	178	187

Accomplishment: Initial Level 1 Cost Optimization (GEN II, Design B)

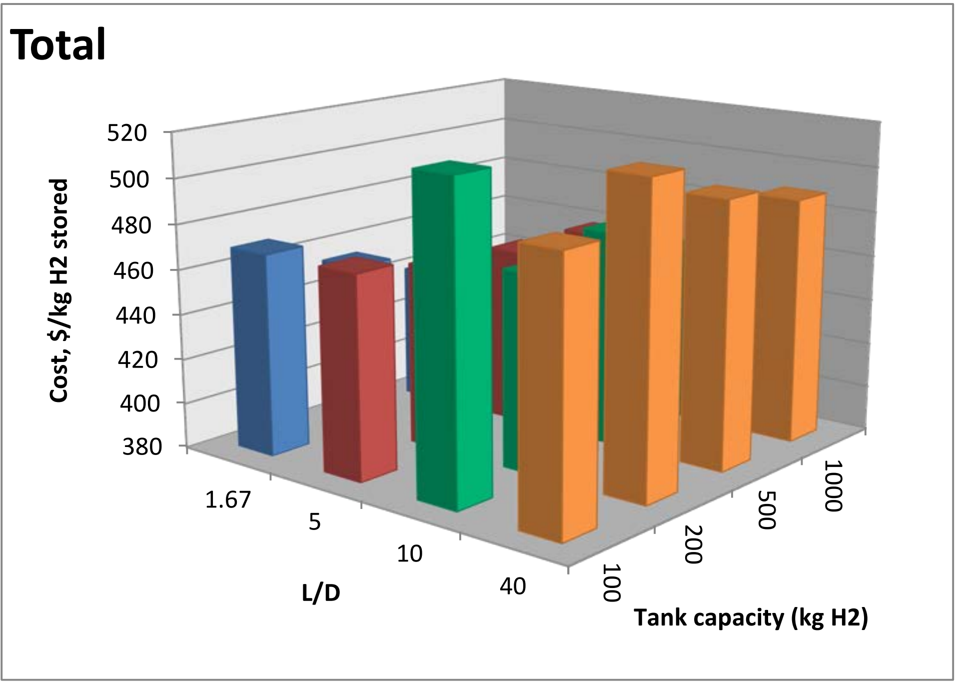
A new design using higher strength steels and low cost hydrogen permeation barrier material (Design B) suggested considerable cost reduction.

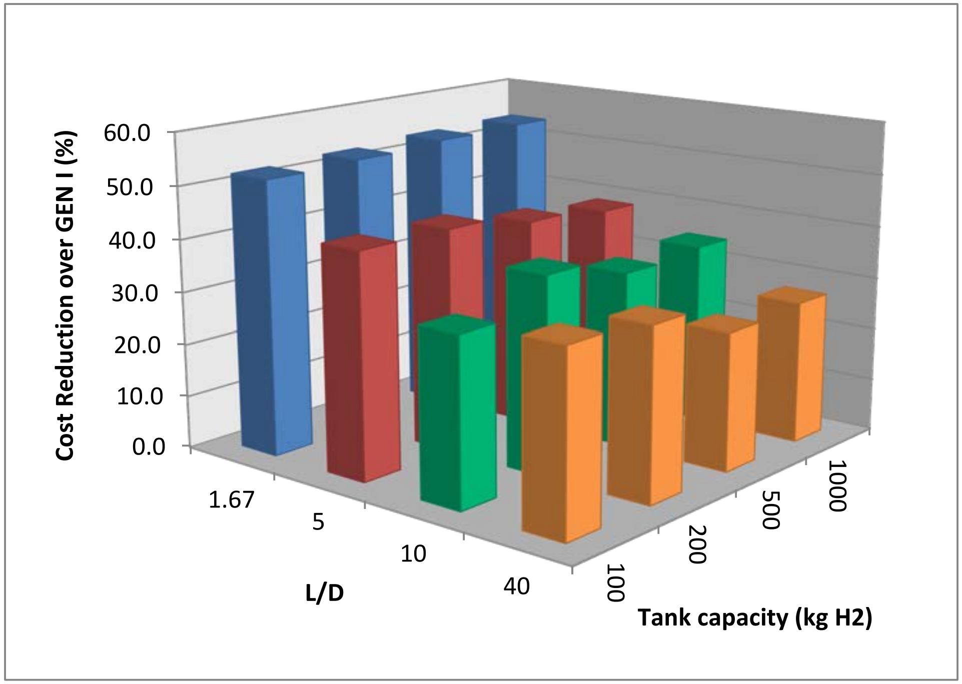
- Design of the composite vessels
  - Head:
    - Structural layers: high strength steel (proprietary)
    - Low cost H_2 permeation barrier (proprietary)
  - Shell
    - Structural layers: high strength steel (proprietary)
    - Low cost H_2 permeation barrier (proprietary)
  - Reinforcement
    - Steel wrapping wire only
- Material properties and cost

Material	σ_{allow} (ksi)	Material Cost ($/lb)	Note
HS Steel	50	1.11 (~ 10% higher than SA-724B)	Head + Shell
Low cost H2 permeation barrier		1	H2 barrier
Wrapping wire	150	4	(including labor)

Accomplishment: Initial Level 1 Cost Optimization: GEN II, Design B

Preliminary cost analysis suggested significant cost saving potential.



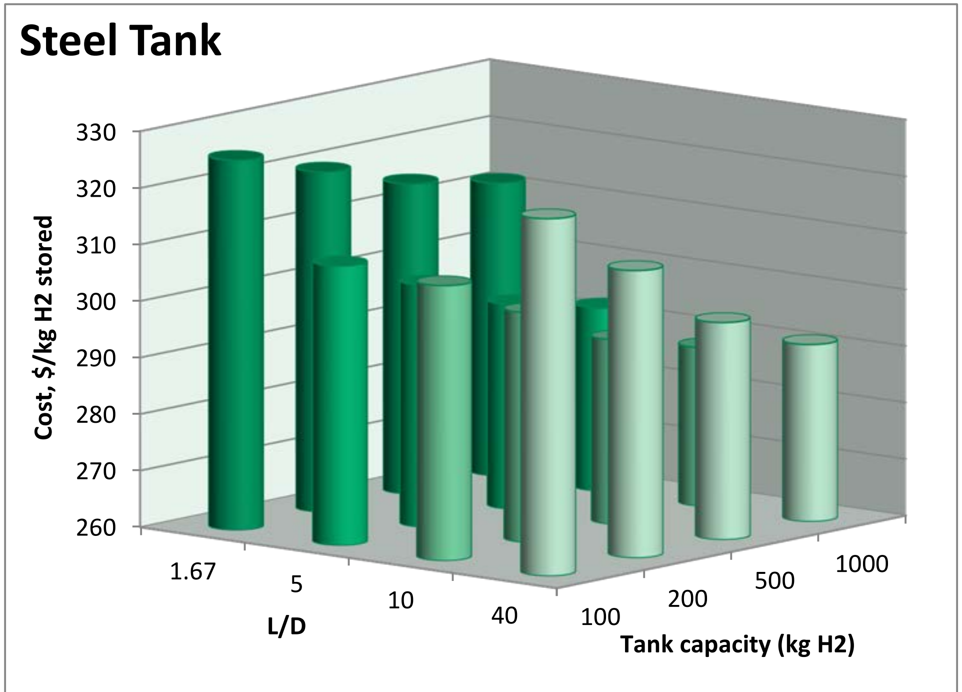


($/kg H2)	Tank capacity (kg)			
L/D ratio	**100**	**200**	**500**	**1000**
1.67	469	454	441	434
5	469	461	459	458
10	517	467	475	457
40	495	515	498	489

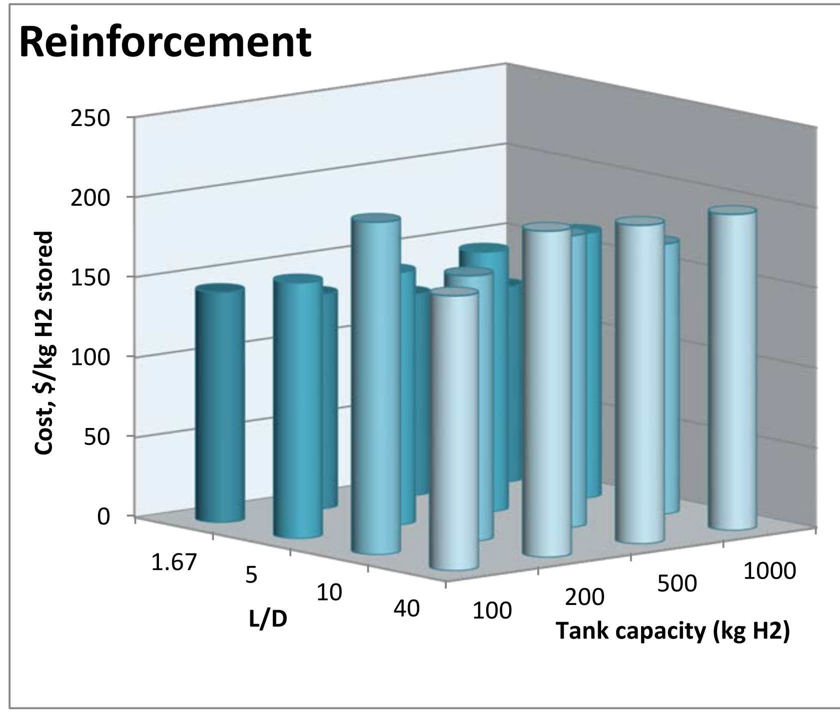
Cost saving %	Tank capacity (kg)			
L/D ratio	**100**	**200**	**500**	**1000**
1.67	52.2	52.6	53.4	53.7
5	42.5	42.5	40.1	38.5
10	31.6	37.5	33.5	34.5
40	34.0	32.4	26.2	27.1

Accomplishment: Initial Level 1 Cost Optimization for GEN II, Design B

Preliminary cost analysis suggested primary cost reduction from inner steel vessel.



($/kg H2)	Tank capacity (kg)			
L/D ratio	100	200	500	1000
1.67	325	320	315	312
5	309	303	296	292
10	309	301	293	288
40	323	311	298	291



($/kg H2)	Tank capacity (kg)			
L/D ratio	100	200	500	1000
1.67	144	134	126	122
5	160	158	162	166
10	208	166	182	169
40	172	204	199	198

Accomplishment: Initial Level 1 Cost Optimization

Preliminary cost analysis suggested that use of higher strength steels could provide the greatest cost reduction.

- Case Study: L/D = 1.67, 100kg

	GEN I ($)	GEN II-A($)	Relative change (%)	GEN II-B ($)	Relative change (%)
Head	25404	25404	0	5661	-78%
Shell	14439	15869	+ 9.9%	9397	-35%
Liner	1565	658	-58%	1052	-33%
Concrete	1320	N/A		N/A	
Wrapping	13200	8000	-39%	14400	+9%
Total	98175	92710	-5.6%	46947	-52%

Accomplishment: Initial Level 1 Cost Optimization

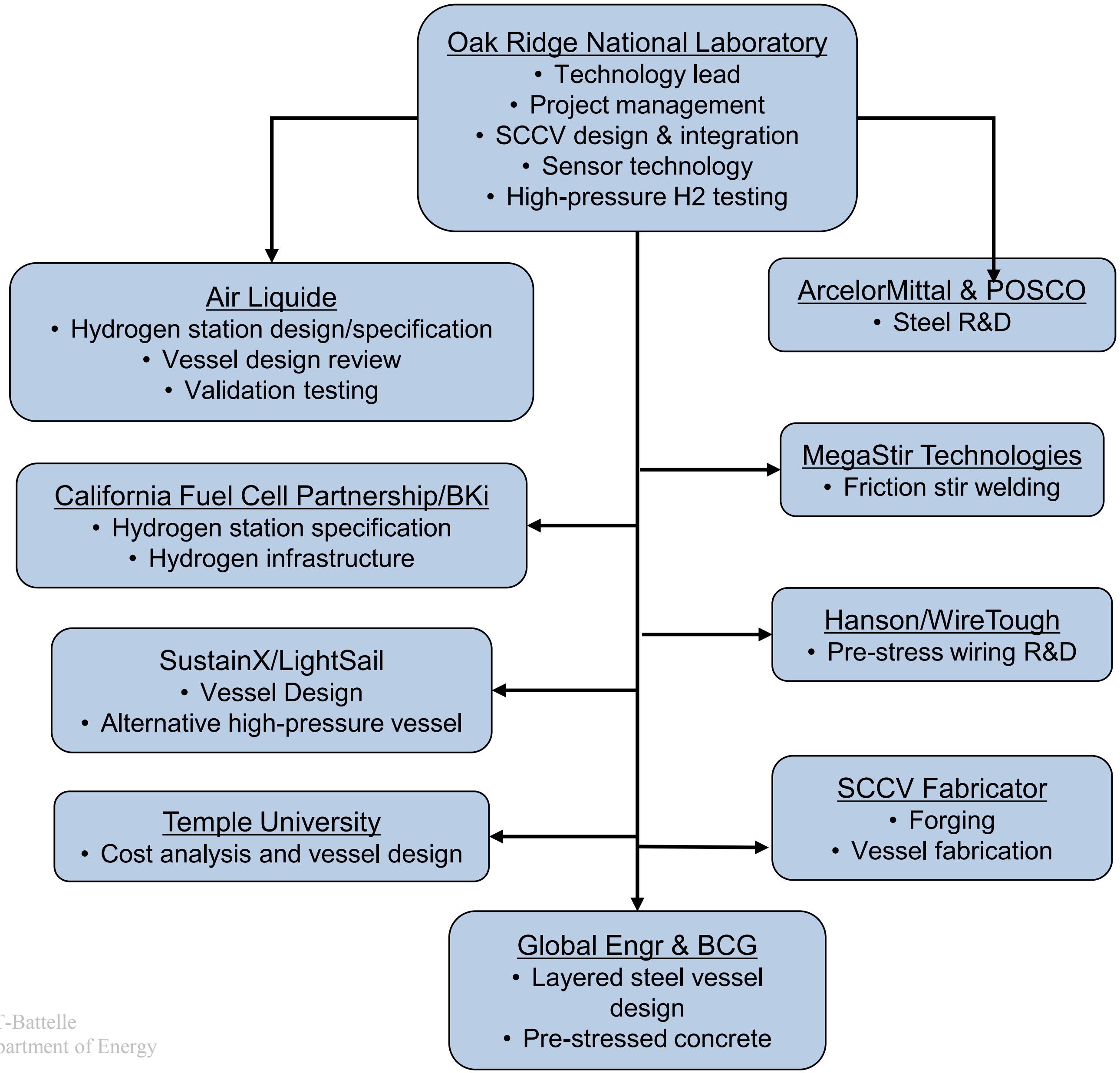
Initial sensitivity analysis suggested that fluctuations in materials and labor costs do not significantly influence the total cost of the vessel.

GENII-B, 100 kg, L/D = 10		Baseline	Materials +5%	Labor +5%	Materials +10%	Labor +10%
Steel tank	Materials	$16,976	$17,825	$16,976	$18,674	$16,976
	Labor	$11,729	$11,729	$12,315	$11,729	$12,902
	Consumables	$2,161	$2,161	$2,161	$2,161	$2,161
Reinforcement	Materials	$5,230	$5,492	$5,230	$5,753	$5,230
	Labor	$15,326	$15,326	$16,092	$15,326	$16,859
	Consumables	$243	$243	$243	$243	$243
Total		$51,665	$52,775	$53,018	$53,886	$54,371
% Change			2.15%	2.62%	4.30%	5.24%

Responses to reviewers' comments

- N/A. New Project

Collaborations and Industry Participations



Remaining Challenges and Barriers

- Potential long-lead time of high-strength steels for inner steel vessel construction
- Cost effective sensor technologies
  - Multiple approaches are being evaluated
- Corrosion prevention in underground storage
  - Will draw upon extensive experiences in concrete industry for underground structures
  - Design of vent hole pathway to ensure no blockage from corrosion

Proposed Future Work

- **FY15**
  - Complete evaluation of weldability of new high-strength steels for inner steel vessels (Q3)
  - Improved reinforcement technologies (Q4)
- **FY16/FY17**
  - Complete Reference Engineering and Fabrication Design (Q1 FY16)
  - Complete cost optimization of the standard reference designs (Q2 FY16)
  - Remote Sensor Technology for Vessel Health Monitoring and Inspection (Q2 FY16)
  - Finalize mockup design and vendor cost bids (Q3,FY16)
  - Complete mockup construction (Q1, FY17)
  - Complete hydro test of mockup (Q2, FY17)
  - Evaluate the vessel performance during and after cyclic test (Q4, FY17)

Technology Transfer Activities

Several mechanisms have been identified to deploy the SCCV technology to the market.

- A strong and vertically-integrated industry team suited for technology development and future commercialization
- Multiple inquires from a number of companies for potential applications of the technology
  - Underground storage
  - Development and application of ultra high-strength steels (beyond these in current ASME code)
- Potential future funding
  - Hydrogen initiatives in California
  - Beyond hydrogen storage
- Patent and licensing
  - N/A

Project Summary

Relevance:	• Address the significant safety and cost challenges of the current industry standard steel pressure vessel technology • Demonstrate the high-pressure storage vessel technology for CGH_2 that will be 20% lower than the DOE cost target
Approach:	Integrated vessel design and fabrication technology: • A systematic approach to refine and optimize all major aspects of SCCV technology (design, engineering, materials and fabrication), focusing on high-cost areas identified in development of GNE I SCCV.
Technical Accomplishments	• High-strength steels for inner steel vessel have been identified and are available from industry partners • Identified cost-effective hydrogen permeation barrier materials • **Initial level 1 cost optimization shows significant cost reduction potentials**.
Collaborations:	An exceptionally strong, strategically selected and vertically-integrated project team is well suited for both technology development and future technology commercialization.
Future Plan:	• Follow the SOPO R&D plan