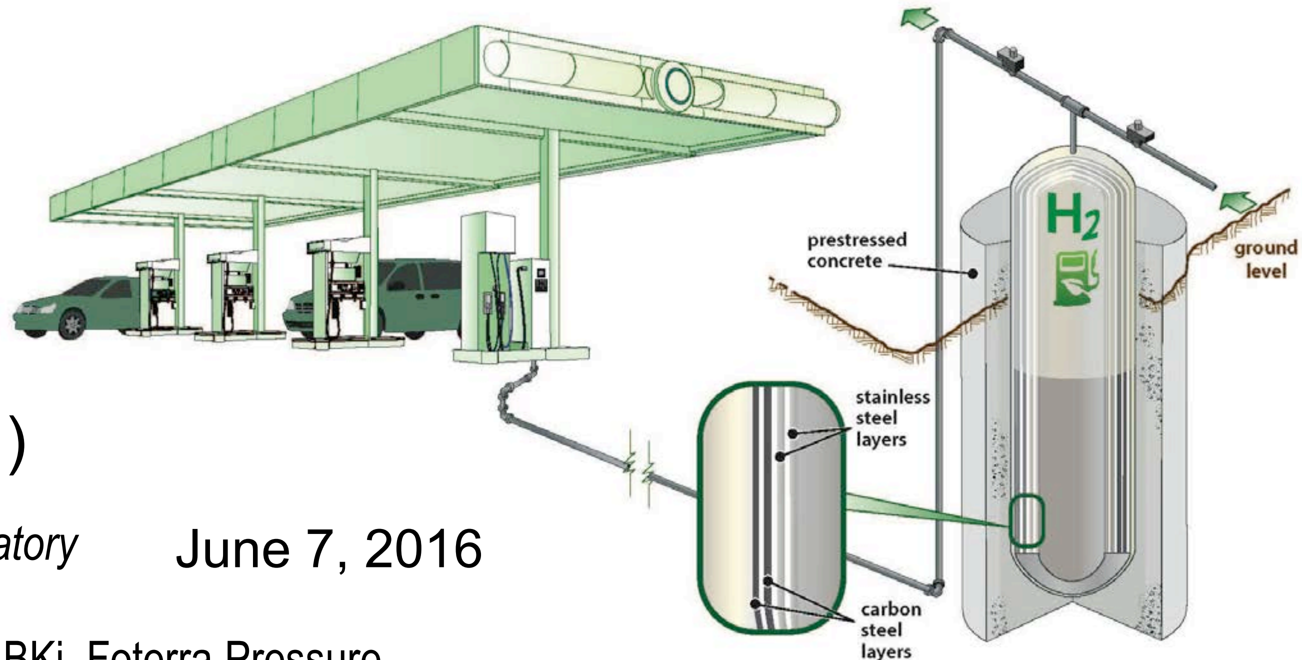
Steel Concrete Composite Vessel for 875 bar Stationary Hydrogen Storage



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Air Liquide, AccerlorMittal, BKi, Foterra Pressure Pipe, Global Engineering & Technology, LightSail, MegaStir Technologies, POSCO, SustainX, Temple University, WireTough Cylinders

This presentation does not contain any proprietary, confidential, or otherwise restricted information

PD109

Overview

Timeline

- Project start date: Oct. 2014
- 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: $533K

  * as of 3/31/2016

Barriers

- Barriers addressed
  - E. Gaseous hydrogen storage cost.

Partners

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

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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 pressure
- Demonstrate 30 year service life under conditions at fueling station.
- Construct and test a prototype system of sufficient size to adequately demonstrate the capability of the technology to be scaled to storage capacities 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/*

Relevance

Revised DOE Cost Target as of 8-2015

The project also considers the recently revised DOE cost target for stationary gaseous hydrogen storage tanks

Pressure	DOE 2015 Status	GEN II SCCV (2017)	DOE 2020 Target
Low Pressure (160 bar) **Purchased Capital Cost (\$/kg of H_2 stored)** **Corresponding Tank size (kg)**	\$850 25		\$500 710
Moderate Pressure (430 bar) **Purchased Capital Cost (\$/kg of H_2 stored)** **Corresponding Tank size (kg)**	\$1100 22		\$600 65
High Pressure (925 bar) **Purchased Capital Cost (\$/kg of H_2 stored)** **Corresponding Tank size (kg)**	\$2000 16		\$600 65
High Pressure (875 bar) (FOA821) **Purchased Capital Cost (\$/kg of H_2 stored)** **Corresponding Tank size (kg)**	N/A	\$600-800 50-500	\$1000

** DOE FCT Multi-Year Plan updated 8-2015 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.

Approach

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

- High cost areas are identified and focused on for considerable *further* cost reduction in Gen II SCCV

R&D Areas	Estimated potential 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%

Approach: Cost Reduction by Vessel Design Optimization

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

- Apply the cost model methodology developed in Gen I design. 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 reinforcement vessel
- Work with manufacturers to understand the limits and constraints of today's manufacturing technologies in SCCV optimization

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 and keeps inner vessel in compression, thereby minimizing impact of hydrogen assisted fatigue.
  - Risk of fatigue crack growth will be further evaluated in FY16.
- High-strength steels can therefore be used in the vessel. Use of high-strength steels reduces the vessel wall thickness, the associated fabrication cost and the weight for transportation.
  - Gen II design targeted 35-60% increase in steel strength. From Gen I's 50-75 ksi (SA765 Gr IV and SA724 Gr B) to 100-120 ksi yield strength
  - Increased design allowable stress to 50ksi vs 33ksi in Gen I design

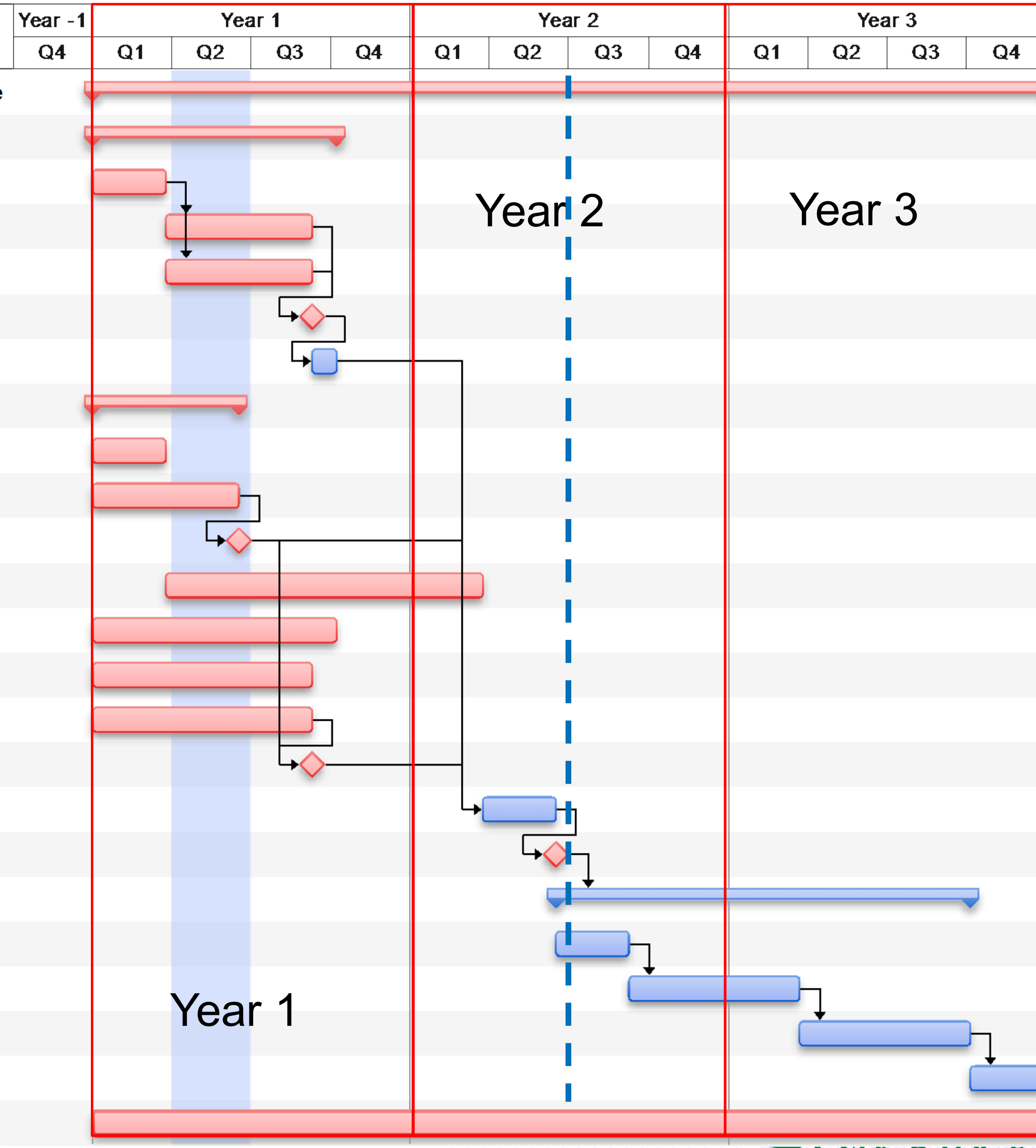
Approach: New fabrication and sensor technologies enable further cost reduction

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

- Replace manway with state-of-the-art non-contact vessel inspection and remote repair welding technology,
- Application of friction stir welding
- New wire winding techniques for pre-stressing, directly on the inner vessel
- New sensor technologies for vessel health monitoring to lower maintenance costs
- Fully or partially covered with concrete or mortar for protection and underground storage

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



FY2016 Milestones and Go/No Go Decisions

- Complete baseline reference design of Gen II for 4 different hydrogen storage capacities: 100, 200, 500 and 1000kg. Perform design and engineering optimization to develop the technical basis towards the cost reduction goal of $800/kg H2 at 875bar. (12/31/2015) Completed
- Go/No Go: Perform holistic design and engineering optimization toward achieving the project cost target of $800 /kg H2 stored at 875 bar. Provide a detailed cost analysis report that validates the $800/Kg H2 cost target, using the bottom-up high-fidelity cost analysis methodology used in Gen I of the project. (3/31/2016) Under FCTO Review
- Complete the design and engineering of a 100 kg H2 at 875 bar storage mockup . The mockup will capture all major features of GEN II SCCV technology optimized for cost reduction. Obtain vender bids for the mockup that are no more than 50% premium of the cost of the same design for moderate volume production (i.e. 50 vessels per order). (6/30/2016) on-schedule
- Remote Sensor Technology for Vessel Health Monitoring and Inspection. Develop the technology capable of detecting failure of individual layers and local internal damage under simulated hydrogen service conditions. (9/30/2016) in progress

Accomplishment (FY15)

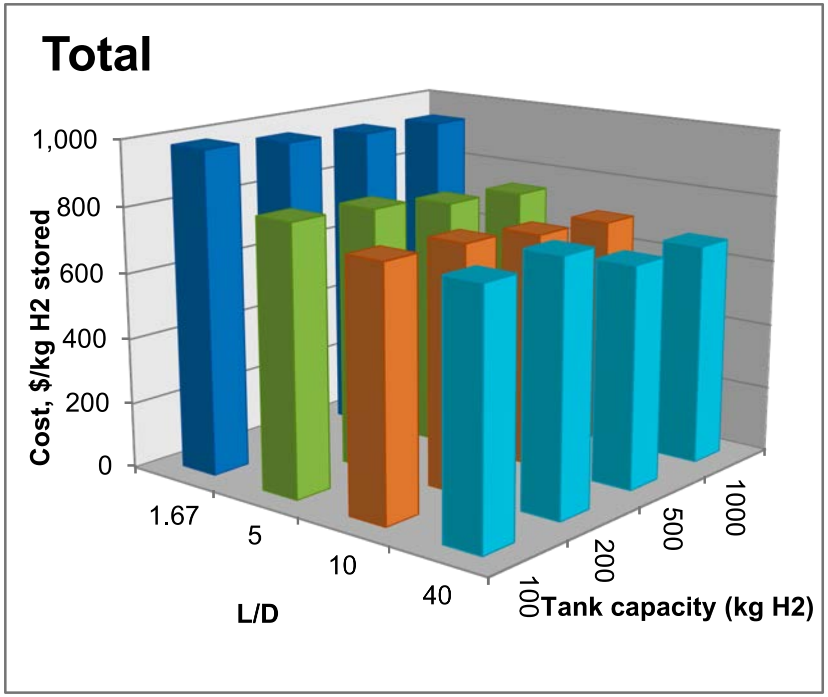
A set of standard reference designs has been selected for GEN II SCCV optimization.

- 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
  - Search for other intermediate capacities that may be cost optimal

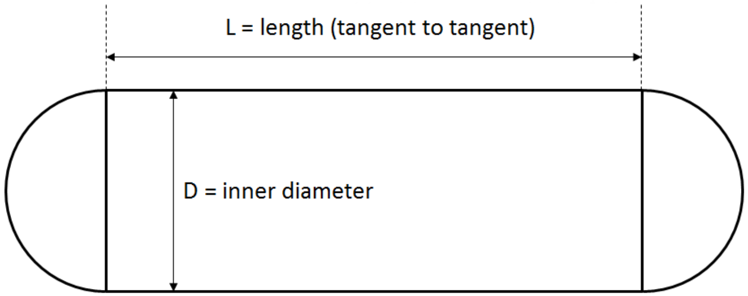
- Basis for GEN II SCCV optimization
  - Capital cost
  - Shipping cost
  - Manufacturing constraints
  - Scalability

Accomplishment (FY15)

Initial cost analysis using Gen I material and design shows that the unit cost (per kg H_2) decreases with increase in capacity and increase in L/D ratio. Pointed to the direction of further design and cost optimization for Gen II



($/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



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Accomplishment: High-Strength Steels

High-strength steels have been selected for Gen II storage vessel, based on design strength requirement, cost, availability and code acceptance

- A number of high-strength steels have been identified and evaluated for use in Gen II storage vessel
  - 5 types of high-strength steels accepted in ASME BPV code
  - 6 different high-strength steels commercially available from project partners (ArcelorMittal and POSCO), but not in ASME code.
    - Generally have higher design allowable strength than ASME code accepted steels.
    - Higher cost due to limited production offsets the strength benefits for near term commercialization. But has potential for further cost reduction in long-term.
- One of the ASME code accepted high-strength steels has been down-selected as the primary steel for Gen II design
  - Cost competiveness
    - $1.11/lb from US vendor. ~15% premium over steels in Gen I for ~50% strength increase.
  - Meet optimized Gen II design requirement
    - Design allowable: 48ksi (slightly lower than 50 ksi target)
  - Near term commercialization potential as code accepted material
  - Meet overall $800/kg H2 cost target of the project

Accomplishment: Case Study for Cost Optimization (Round II)

The new GEN II SCCV was systematically analyzed in several steps to study the effects of different design improvements on the cost

GEN I
- Gen I steel
- Stainless steel hydrogen permeation barrier
- Steel wire/concrete wrapping

GEN I-A
- Gen I steel
- Stainless steel liner
- Gen II direct steel wire wrapping on inner vessel (with and w/o pre-stressing)

GEN I-B
- Gen I steel
- Gen II low cost hydrogen permeation barrier
- Gen II wire wrapping

GEN II-A
- Gen II high-strength cylinder
- Gen I steel head
- Gen II hydrogen barrier
- Gen II wire wrapping

GEN II-B
- **Gen II cylinder**
- **Gen II head**
- Gen II H_2 barrier
- Steel wire wrapping

Increased utilization of high-strength steel is the most important factor for cost reduction

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Accomplishment: Effect of SCCV design

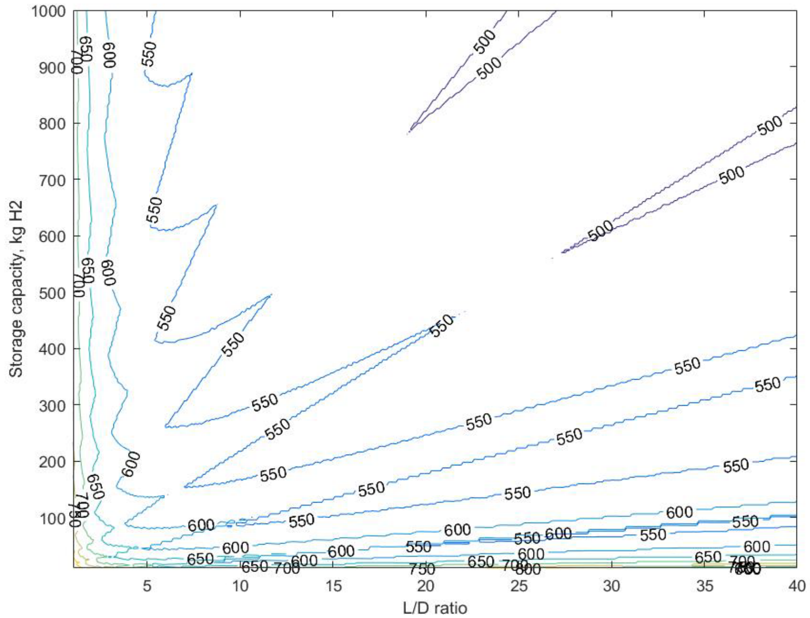
Significant cost reduction is achieved when high-strength steel is used to construct both shell and *head*. Thickness of the head dictates the thickness of the entire SCCV.

GEN I-A	Tank capacity (kg H2)			
L/D ratio	100	200	500	1000
1.67	$982	$957	$940	$930
4	$834	$815	$802	$777
10	$770	$781	$717	$695
40	$879	$784	$742	$677

GEN I-B	Tank capacity (kg H2)			
L/D ratio	100	200	500	1000
1.67	$948	$930	$921	$915
4	$782	$773	$749	$753
10	$693	$693	$672	$660
40	$656	$680	$668	$619

GEN II-A	Tank capacity (kg H2)			
L/D ratio	100	200	500	1000
1.67	$923	$918	$903	$895
4	$775	$745	$737	$732
10	$668	$685	$643	$645
40	$692	$643	$598	$613

GEN II-B	Tank capacity (kg H2)			
L/D ratio	100	200	500	1000
1.67	$667	$651	$637	$630
4	$594	$576	$545	$544
10	$560	$510	$518	$500
40	$507	$526	$509	$500



Only GEN II-B SCCVs have the potential to meet our cost target ($800/kg H_2) in a wide range of the design space

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Accomplishment

Manufacturability and transportation constraints are included in Gen II design optimization

L/D ratio = 1.67

Capacity (kg H2)	ID (in)	L (t-t, ft)	Thickness (in)	Total length (ft)	Weight (vessel + wrapping) (lb)
100	41.84	5.81	2.85	9.78	18,638
200	52.72	7.32	3.6	12.31	36,050
500	71.55	9.94	4.87	16.71	87,492
~~**1000**~~	~~90.14~~	~~12.52~~	~~6.13~~	~~21.05~~	~~172,018~~

L/D ratio = 4.00

Capacity (kg H2)	ID (in)	L (t-t, ft)	Thickness (in)	Total length (ft)	Weight (vessel + wrapping) (lb)
100	33.21	11.07	2.28	14.22	18,785
200	41.84	13.95	2.86	17.91	36,416
500	56.79	18.93	3.88	24.31	86,199
~~**1000**~~	~~71.55~~	~~23.85~~	~~4.87~~	~~30.62~~	~~171,047~~

L/D ratio = 10.00

Capacity (kg H2)	ID (in)	L (t-t, ft)	Thickness (in)	Total length (ft)	Weight (vessel + wrapping) (lb)
100	25.21	21.01	1.74	23.4	19,279
200	31.76	26.47	2.18	29.48	35,568
500	43.11	35.92	2.95	40.01	88,958
1000	54.31	45.26	3.71	50.41	172,100

L/D ratio = 40.00

Capacity (kg H2)	ID (in)	L (t-t, ft)	Thickness (in)	Total length (ft)	Weight (vessel + wrapping) (lb)
100	16.14	53.79	1.13	55.33	18,983
200	20.33	67.77	1.41	69.70	38,351
500	27.60	91.98	1.9	94.6	92,329
1000	34.77	115.89	2.39	119.19	180,710

Accomplishment: Final GEN II Reference Design

Reference geometries are determined for an ASME accepted high-strength steel, and based on material availability from US manufacturers

- ASME Steel 1 selected
  - Properties
  - Code acceptance
  - US availability
- Reference geometries determined
  - 30” ID
  - 2.125” thickness
  - Variable length for different storage capacities
- Cost data determined based on vendor quotes

Steel	Allowable stress (ksi)	Cost ($/lb)	Technology readiness	Source
ASME steel 1	49 (<2.5”)	1.11	ASME accepted	US vendor
ASME steel 1	43 (>3”)	1.29	ASME accepted	US vendor
ASME steel 2	49	1.19	ASME accepted	US vendor
ASME steel 3	49	1.29	ASME accepted	US vendor
High strength steel 1	~ 50	1.28	Commercial	US vendor
High strength steel 2	47 (< 3.1”)	0.64	Commercial	International vendor
High strength steel 3	47	0.605	Commercial	International vendor
SA724 (GEN I ref)	39.6	1.01	ASME accepted	US vendor

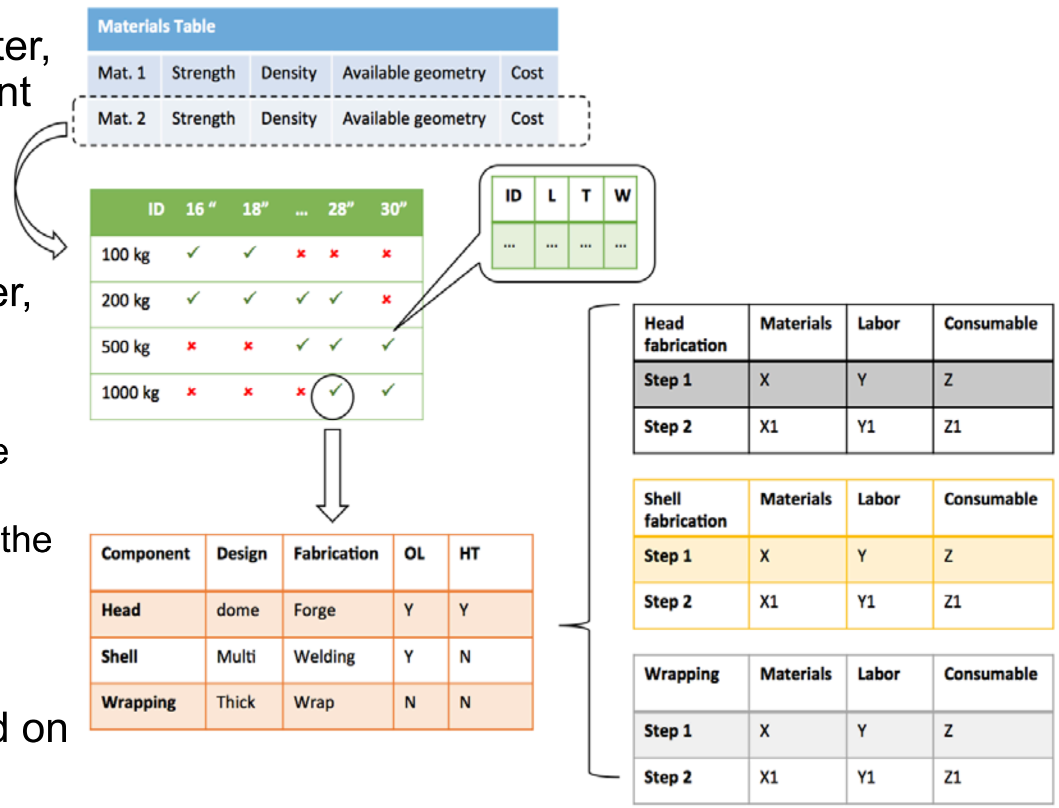
Capacity (kg H2)	100	167	200	270	320	500
Head/Shell thickness (in)	2.125					
Inner diameter (in)	30					
Layer of wrap	5					
Outer diameter* (in)	34.25					
Total length (ft)	17	28	32.9	44	52.5	78.7
Total weight* (lb)	20180	33178	39592	53193	63027	97741

SCCV components	Material	Unit cost ($/lb)
Head	ASME steel 1	1.11
Shell	ASME steel 1	1.11
Head liner	Gen II low cost	1.00
Shell liner	Gen II low cost	1.00
Wrapping wire	ASTM648	0.56
Protective layer	Mortar	0.10

Approach: Detailed bottom-up cost analysis in final design

Cost analysis model based on detailed study of manufacturing technologies suitable for high-strength steels

- Identify high-strength steels, obtain information on strength, available geometry, and unit cost;
- Design the SCCV based on the material strength and availability, determine key design parameters including inner diameter, thickness, length, number of reinforcement wrapping, weight;
- Identify appropriate manufacturing technologies for each vessel component including head, head liner, shell, shell liner, and wrapping
- Calculate the cost of the SCCV
  - Calculate the cost of materials based on the amount and unit cost;
  - Calculate the manufacturing cost based on the time required for each fabrication step;
  - Estimate the cost of welding consumables based on the base materials used;
- Estimate the shipping/delivery cost based on the total weight of the completed SCCV



Accomplishment

Gen II design optimization also included consideration of material utilization and transportation

- For both formed and extruded shell sections, when the length of a shell section is fully utilized (e.g. 200 kg formed shell, 167 kg and 320 kg extruded shell), less middle welds are required, and shell-related unit storage cost can be minimized.

	100 kg	167 kg	200 kg	270 kg	320 kg	500 kg
Formed and seam welded shell						
Number of formed shell rings	2	3	3	4	5	8
Number of middle welds	1	2	2	3	4	7
Unit cost due to shell (\$/kg H_2)	454	390	359	363	364	354
Extruded shell						
Number of extruded shell sections	1	1	2	2	2	3
Number of middle welds	0	0	1	1	1	2
Unit cost due to shell (\$/kg H_2)	493	420	433	408	394	381

- Maximum weight of a truck traveling on federal highway is limited to 80,000 lb. The storage capacity should be limited to 320 kg H_2 in order to avoid significant transportation penalty.

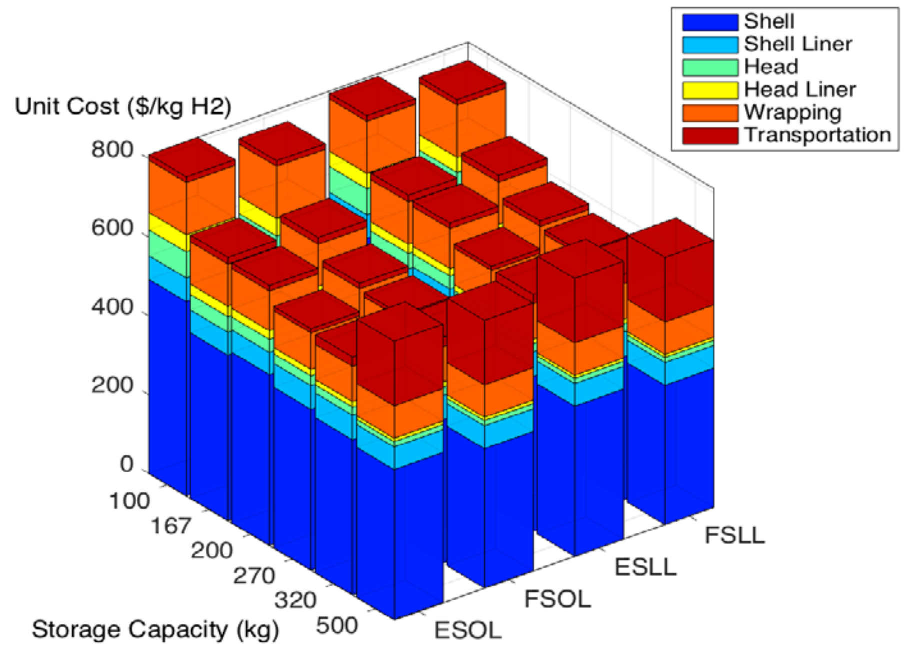
	100 kg	167 kg	200 kg	270 kg	320 kg	500 kg
Weight (lb)	20,180	33,178	39,592	53,193	63,027	97,741
Highway transportation cost (\$)	1425	2850	2850	2850	7750	82000
Unit cost due to highway transportation (\$/kg H2)	14.25	17.07	14.25	10.56	24.22	164

Accomplishment: Gen II Final Design Summary

Final Gen II design can be constructed with today's manufacturing technologies, with projected costs below \$800/kg H2 for a number of design, manufacturing and capacity options.

- The \$800/kg H_2 project cost target has been met. Several designs also meet DOE revised cost target of \$600/kg H_2.
- Key factors contributing to cost reduction
  - High strength steel ~ 50 psi design allowable
  - Vessel length vs diameter ratio for given capacity
  - Fully utilize the material and manufacturing capacity
  - Larger vessels are generally more cost effective. However, high cost and other constraint of highway transportation will practically limit the size of the vessel.
- Our current cost analysis is based on projected 50-100 vessels per year production rate. Cost reduction from production scale up should be substantial but not full analyzed

	100 kg	167 kg	200 kg	270 kg	320 kg	500 kg
FSOL	771	639	585	568	574	680
FSLL	765	635	583	566	572	679
ESOL	810	669	660	613	604	707
ESLL	805	665	658	611	603	706



Responses to Previous Year Reviewers' Comments

"Nice detailed cost reduction analysis. The reviewer is concerned about the overall plan to manufacture part of this at a factory then move to the site for the balance of the manufacturing."

It is true that there is no US manufacturer at this time that can produce the entire vessel (inner vessel, and steel wire wrapping and concrete encasing). However, our Gen II vessel is designed to alleviate this concern based on feedback from potential manufactures, for the following reasons. (1) Our optimal vessel design imposes minimal transportation cost penalty (\$10-24/kg H_2). (2) Steel wire wrapping is a relatively low capital investment. It can be integrated with inner vessel fabrication. (3) Gen II design makes it possible for concrete encasing at the fueling station site.

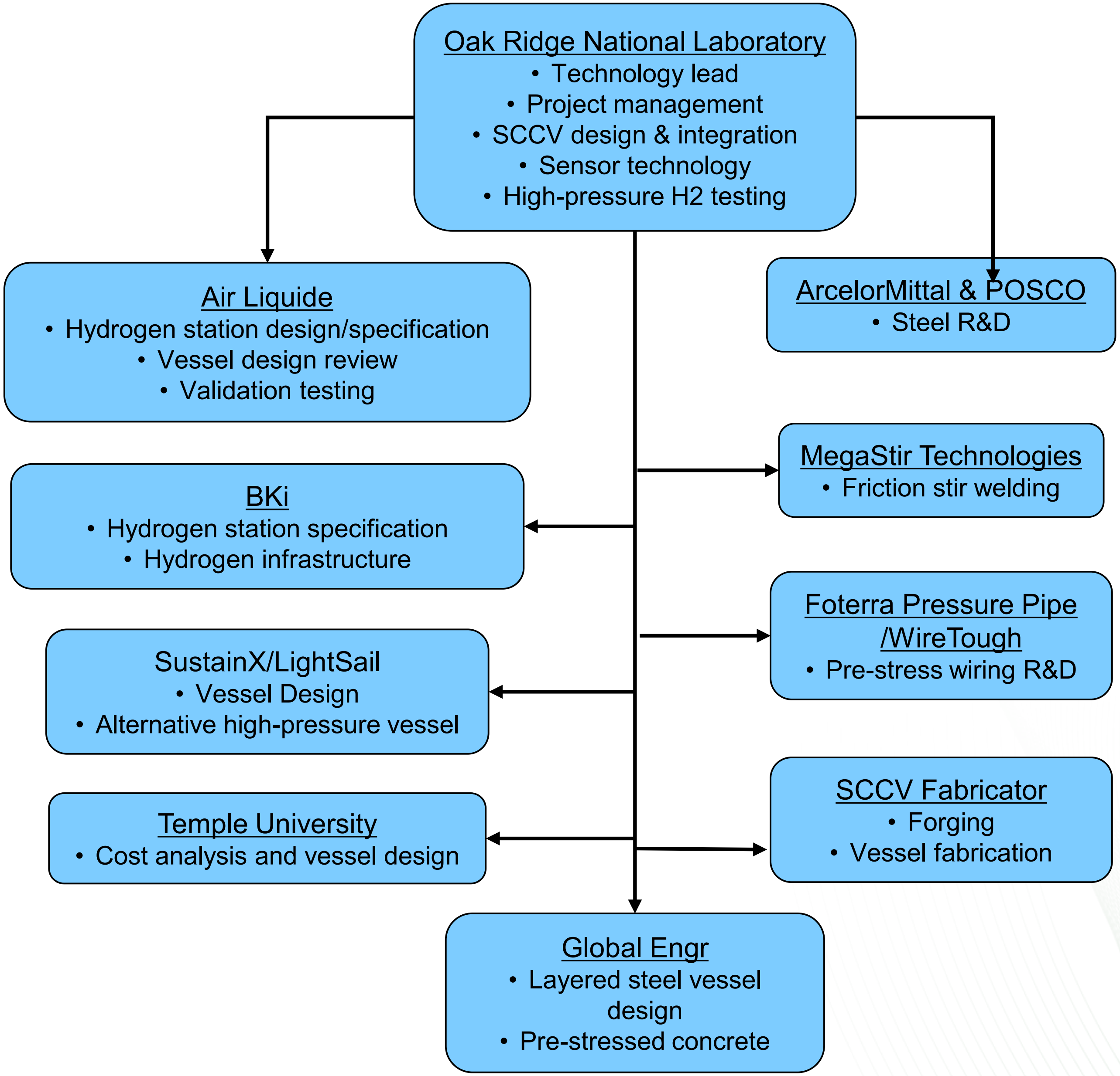
The reviewer did not see any attention given to maintenance .

Gen II is designed per ASME code for 30 years of service. Gen II design is serviceable per ASME code requirement. Novel sensor technology for vessel inspection and monitoring, as well as remote repair welding, are part of the technology development of project. We have made considerable progress and will report them in next review

"It is recommend that the PI justify to the reviewers and the DOE that indeed a pre-stressed concrete structure has enough merit over and above a tank which does not include concrete".

Over the course of this project, we requested quotes from a number of hydrogen storage providers. Their quoted prices are on par with DOE 2015 status and cannot meet DOE 2020 cost target. The use of pre-stressed concrete made it possible to meet and exceed the DOE cost target for Gen I. Pre-stressed concrete only added about 1-3% cost penalty in Gen I design. Gen I used pre-stressed concrete since it was the mature manufacturing technology at the time. There are no other readily available wire wrapping alternatives that are scalable for large storage vessels (>200 kg H_2). In Gen II, two new wire wrapping technology have been developed and tested. This makes it possible to simplify the manufacturing process, and potentially avoid the use of pre-stressed concrete. Finally, our vessel has unique features to avoid hydrogen embrittlement *by design*, which are not in others.

Collaborations and Industry Participations



Remaining Challenges and Barriers

- 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

- **FY16/FY17**
  - 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 FOA cost target, and also meet the revised cost target
Approach:	A systematic approach that integrates vessel design and fabrication technology, 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	• Completed detailed vessel design and cost optimization. • Final Gen II reference design can be constructed with today's manufacturing technologies, with projected costs below $800/kg H2 for a number of design, manufacturing and capacity options. Several designs also meet DOE revised cost target of $600/kg H2. • Gen II design is readily scalable to 1000kg with similar cost projection, limited by transportation and space availability
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