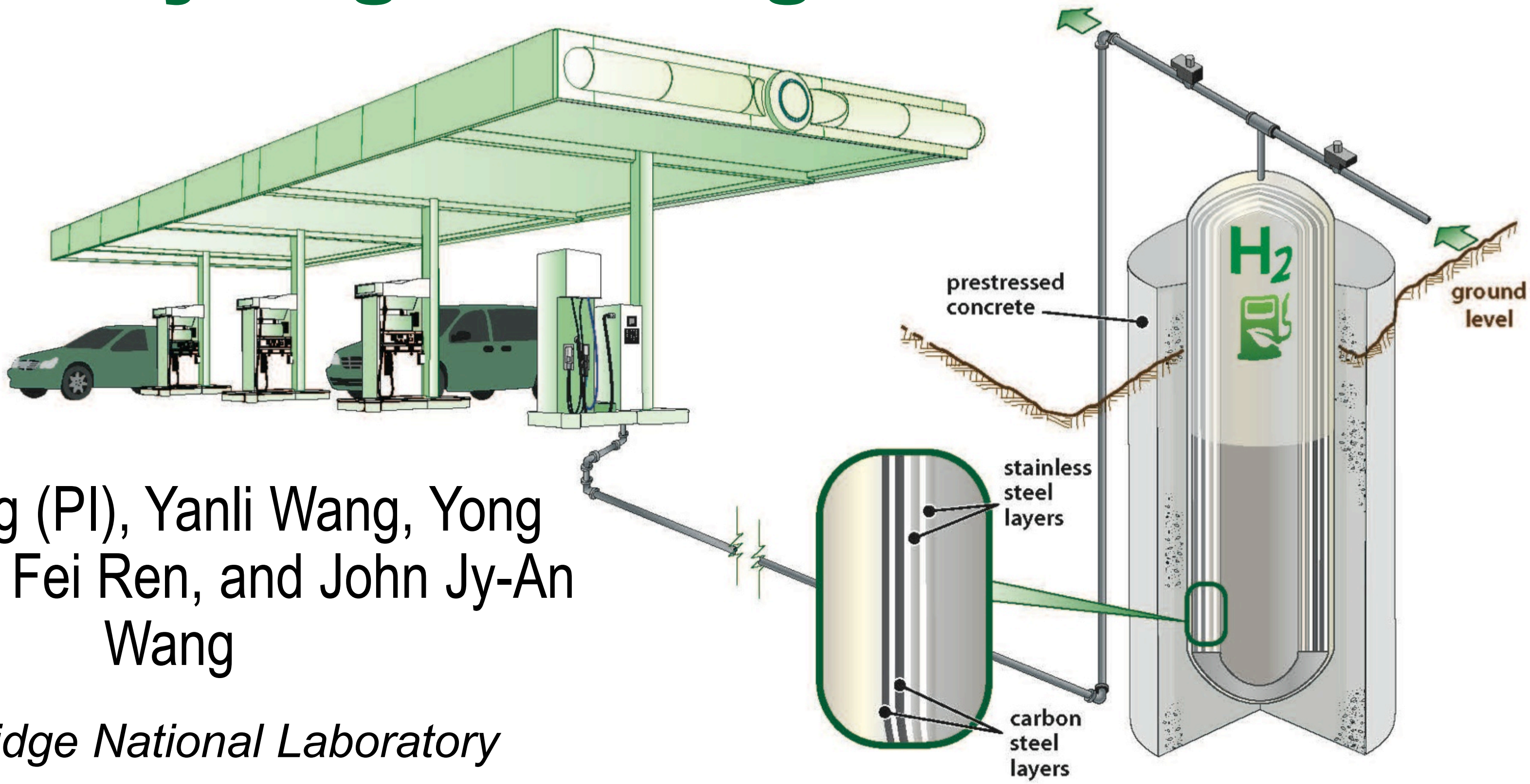
Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage



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Oak Ridge National Laboratory

PD088

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U.S. DEPARTMENT OF ENERGY

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

Overview

Timeline

- Project start date: Oct. 2010
- Project end date: Sep. 2015

Budget

- Total Funding Spent: $2,050K*
- Total Project Value: $3,600K
- FY14 DOE Funding: $80K
- Cost Share %: 20%

*as of 3/31/2012

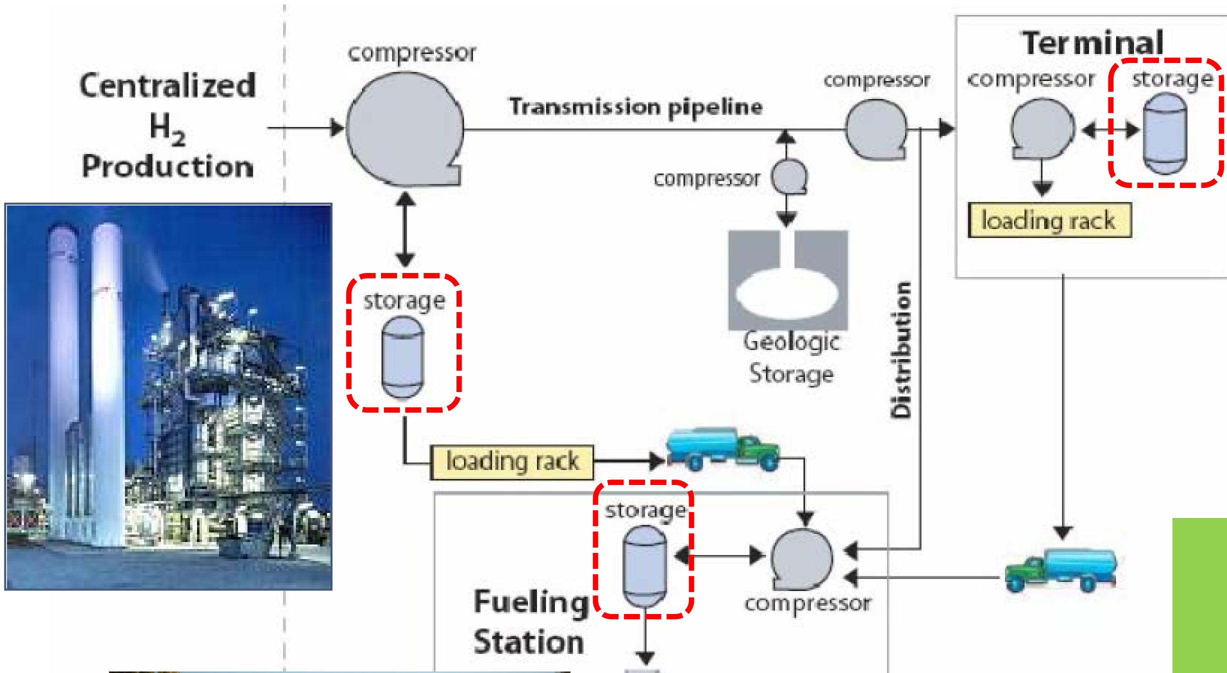
Barriers

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

Partners

- Interactions / collaborations
  - Global Engineering and Technology
  - Ben C. Gerwick, Inc.
  - University of Michigan
  - MegaStir Technologies
  - ArcelorMittal
  - ASME
  - U.S. Department of Transportation
- Project lead
  - Oak Ridge National Laboratory (ORNL)

Relevance – Technology Gap Analysis for Bulk Storage in Hydrogen Infrastructure



Gaseous Hydrogen Delivery Pathway *

Bulk storage in hydrogen delivery infrastructure *

- *Needed at central production plants, geologic storage sites, terminals, and refueling sites*
- *Important to provide surge capacity for hourly, daily, and seasonal demand variations*

Technical challenges for bulk storage

- Current industry status: pressure vessel made of low alloy steels
- Safety concern: hydrogen embrittlement to steels due to long-term H_2 exposure
- High capital cost especially for high-pressure storage

* *Adapted from DOE's Hydrogen Delivery, in Multi-Year Research, Development and Demonstration Plan, 2007*

Project Objectives

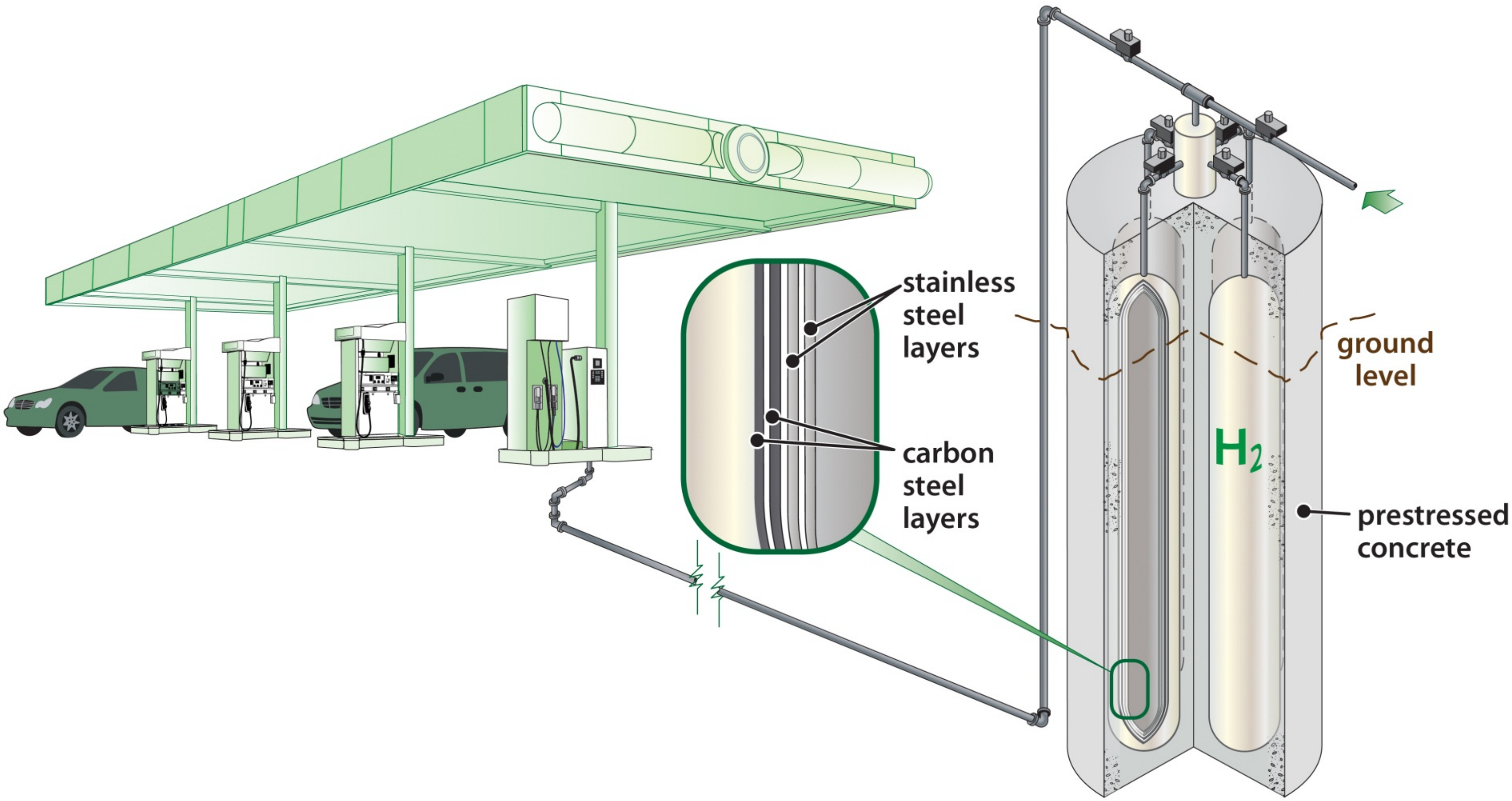
- Address the significant **safety** and **cost** challenges of the current industry standard steel pressure vessel technology
- Develop and demonstrate the steel/concrete composite vessel (SCCV) design and fabrication technology for stationary storage system of high-pressure hydrogen that meet DOE technical and cost targets

Table 3.2.4 Technical Targets for Hydrogen Delivery Components *				
Category	**2005 Status**	**FY 2010 Status**	**FY 2015 Target**	**FY 2020 Target**
Stationary Gaseous Hydrogen Storage Tanks (for fueling sites, terminals, or other non-transport storage needs)				
Low Pressure (160 bar) Purchased Capital Cost (\$/kg of H_2 stored)	\$1000	\$1000	\$850	\$700
Moderate Pressure (430 bar) Purchased Capital Cost (\$/kg of H_2 stored)	\$1100	\$1100	\$900	\$750
High Pressure (860 bar) Purchased Capital Cost (\$/kg of H_2 stored)	N/A	\$1,450	\$1,200	\$1000

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

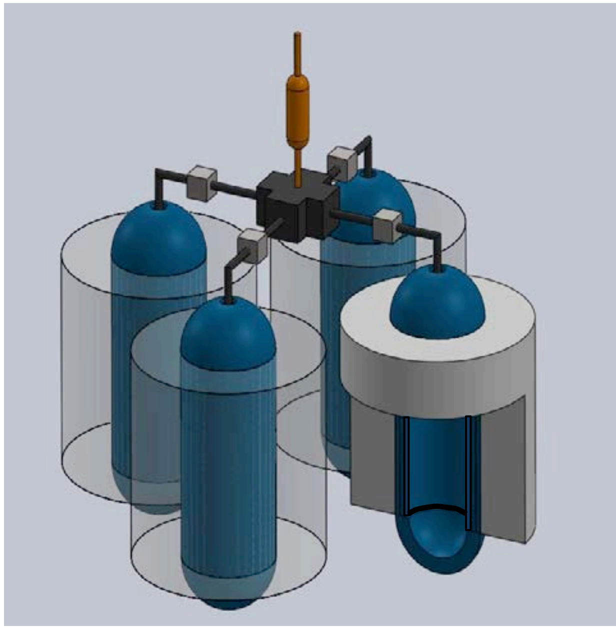
- By 2015: about 17% reduction
- By 2020: about 31% reduction

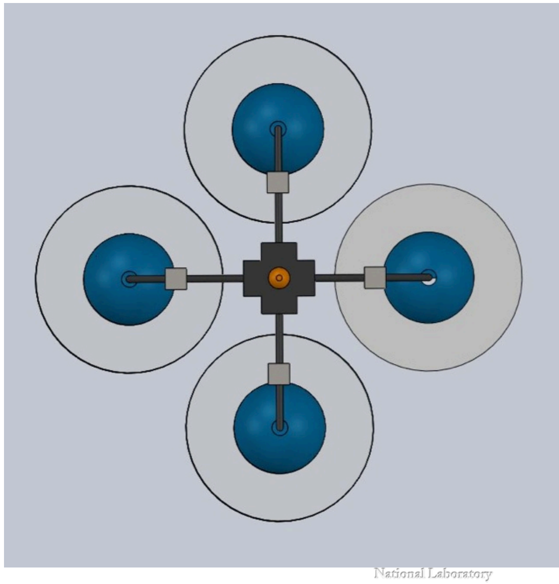
Approach: Steel/Concrete Composite Vessel (SCCV) for High-Pressure H_2 Storage



SCCV Integrates Four Major Innovations

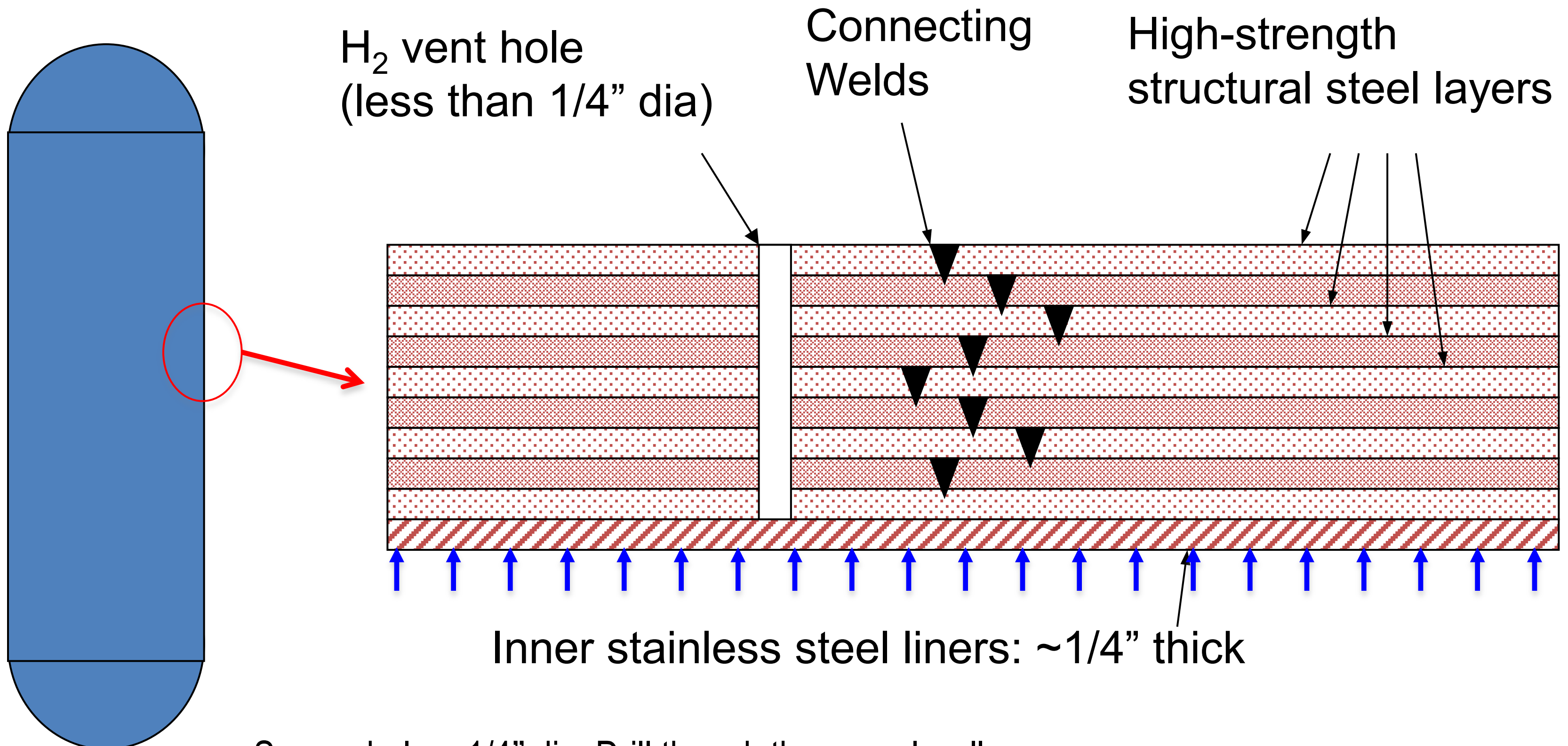
- Modular design of hydrogen storage system
  - Flexibility for scalability
  - Flexibility for cost optimization
  - System reliability and safety
  - Individual vessels are self contained and monitored. Can be shut-down individually to reduce the overall impact
- Composite steel/concrete storage vessel for cost reduction
  - An inner multi-layered steel vessel encased in a pre-stressed outer concrete reinforcement
  - Use of cost-effective commodity materials (concrete and steel)
- Novel inner steel vessel design to eliminate hydrogen embrittlement problem <u>*by design*</u>
- Advanced fabrication and sensor technologies for cost reduction and improved operation safety





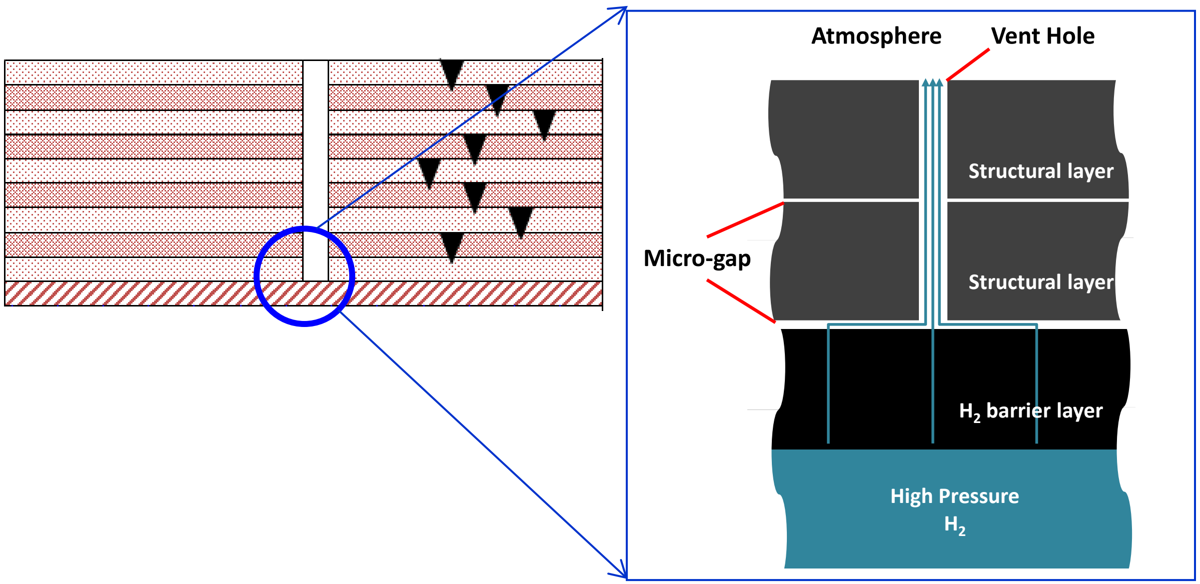
Multi-layered Inner Steel Vessel – Eliminating HE *by Design*

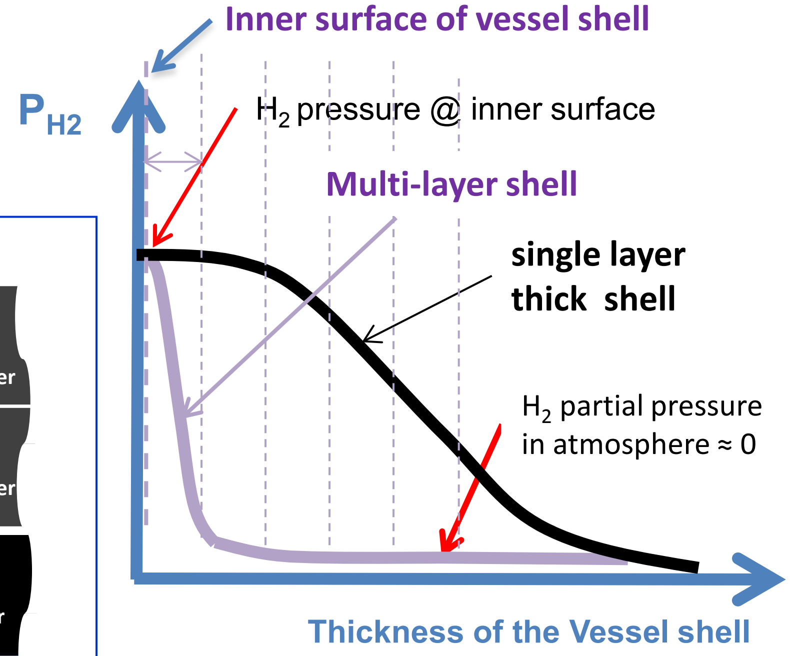
- A multi-layer design with strategically placed vent holes to prevent the intake and accumulation of hydrogen in the steel layers except the innermost layer



- Sensor hole: ~1/4” dia. Drill though the vessel wall
- Except the SS liner. Also used for embedded sensor connection
- Sensor can be attached to the surface of each layer (except the inner surface of the first layer).

Hydrogen Mitigation Concept for Multi-Layered Inner Steel Vessel





- Small vent ports are created on the 2nd and all the outer layers of the vessel without sacrificing the structure’s mechanical integrity.
- Hydrogen migrated through the innermost layer will pass through the vent ports, resulting in little or no pressure buildup in the other layers. Thus, hydrogen embrittlement is mitigated _by design_ in the layered low alloy steel vessel.

SCCV

- 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.)

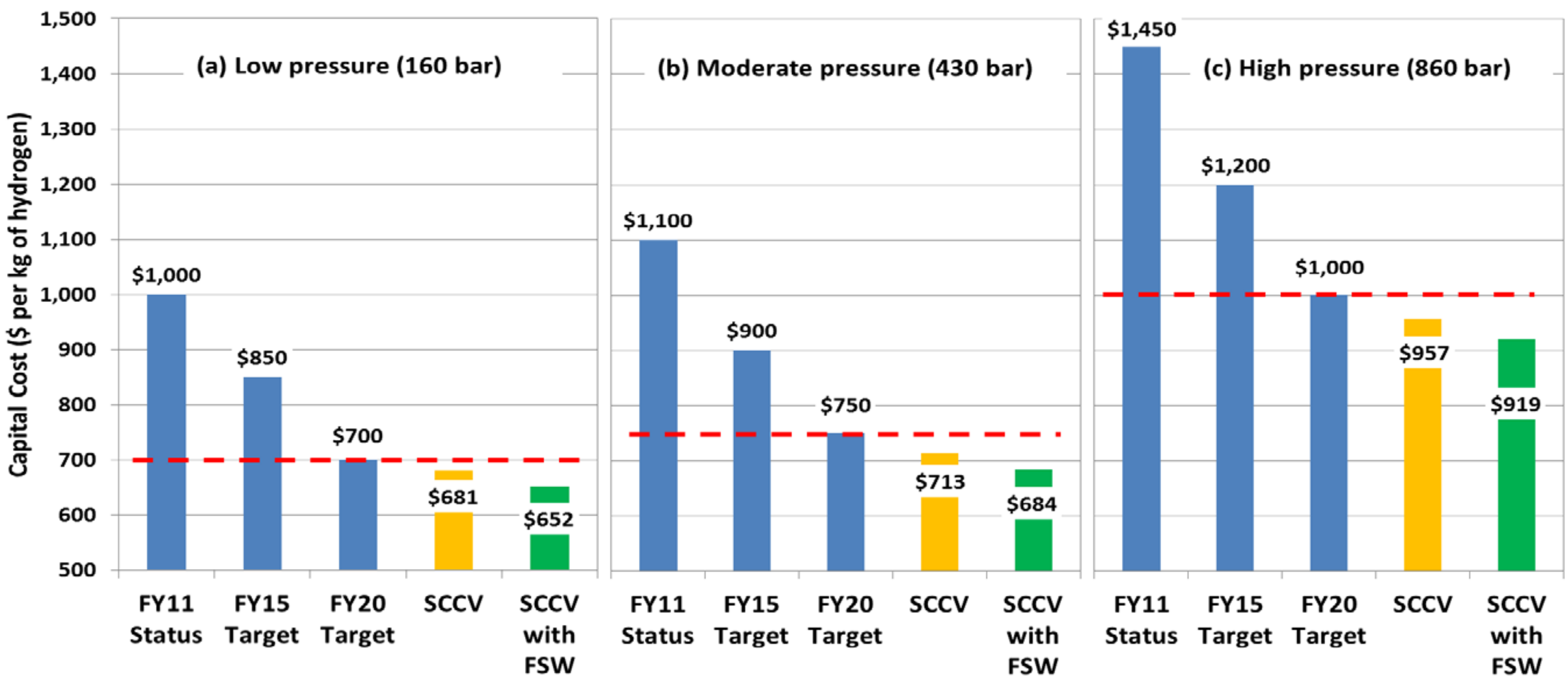
96 ft long layered steel vessel

FY2014 Milestones/Deliverables

- Validate that SCCV can reduce the cost of stationary hydrogen storage by more than 15% and meet the DOE MYRDD 2015 cost target of $1200/kg-stored at 860 bar through detailed vessel design and supplier quotes (Q1)
- Develop the testing plan to validate the SCCV technology for high-pressure hydrogen services, to pass (1) ASME pressure vessel requirement and (2) a 500 cyclic loading test representative of 430 bar high-pressure hydrogen charging and discharging operation conditions. Identify the testing sites. (Q3)
- Complete construction of the inner steel vessel of a mock-up SCCV rated at DOE MYRDD moderate pressure level (430bar) and 90 kg of H_2, to demonstrate the design, engineering and manufacturing technology for SCCV (a long-lead item). (Q4)

Accomplishment: SCCV Cost Analysis

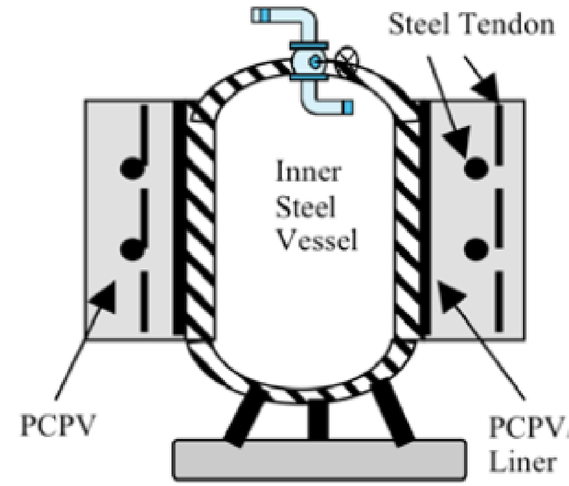
- With the support of industry partners, we successfully completed a high-fidelity manufacturing cost analysis and demonstrated that the SCCV technology can exceed the relevant cost targets set forth by DOE
- Reference SCCV design: 50/50 load carrying ratio, 1500kg H_2 in moderate volume production (24 identical vessels per order)
- Details of cost analysis in ORNL Technical Report ORNL/TM-2013/113



Lessons Learned from The Detailed Cost Analysis/Optimization

- 50/50 concrete/steel design is the most cost effective in the current design

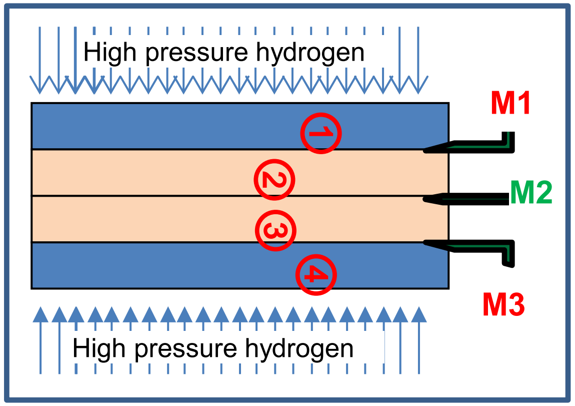
- Many options have been identified for considerable *further* cost reduction
  - Hydrogen permeation barrier
  - Steel vessel design
  - Concrete reinforcement design
  - Novel sensor technologies



Case 2: 50% Steel + 50% Concrete

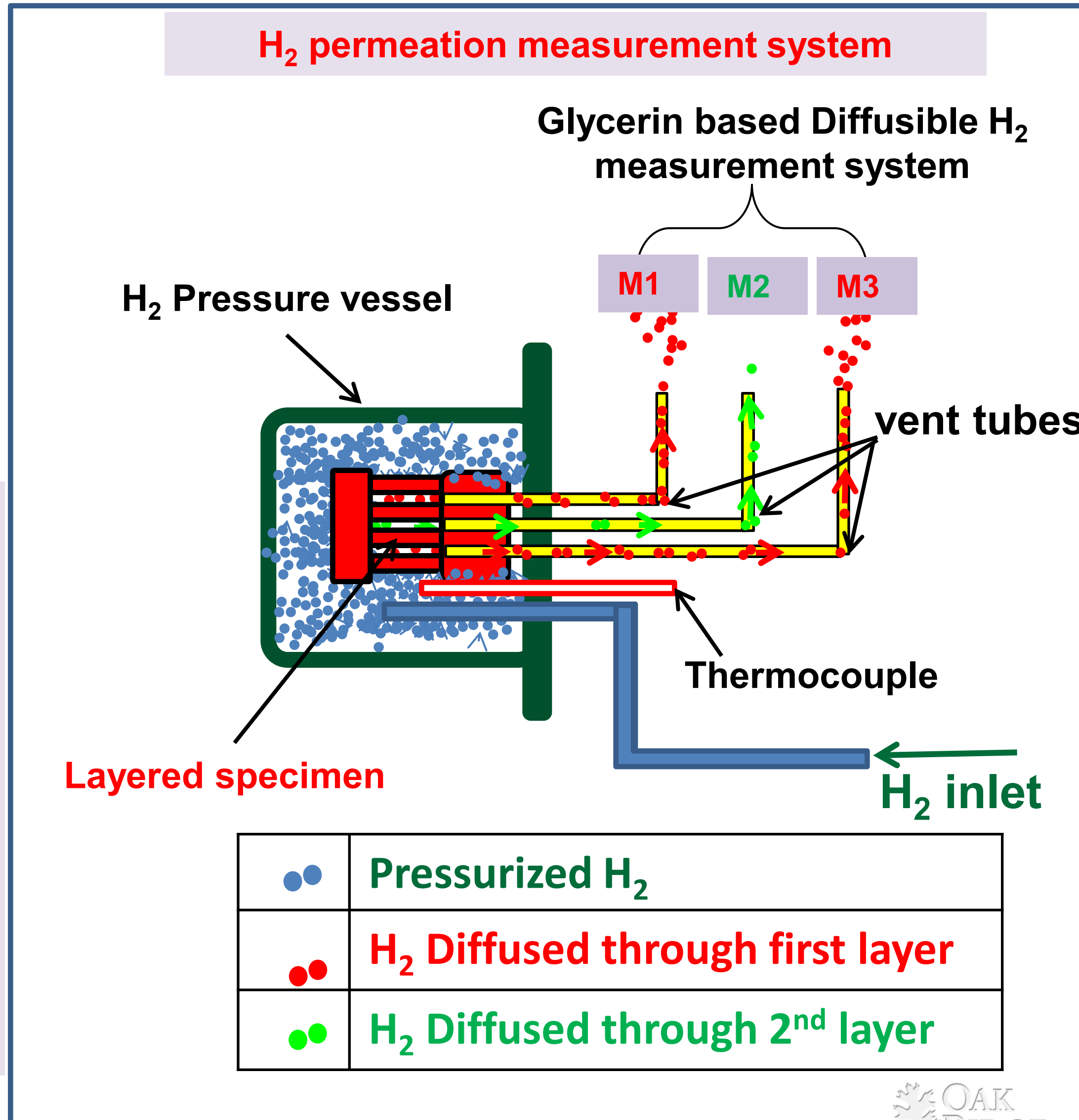
Pre-stressed concrete sleeve carrying 50% of hoop stress

Accomplishment: H_2 Permeation Experiment Validating Hydrogen Mitigation Technology

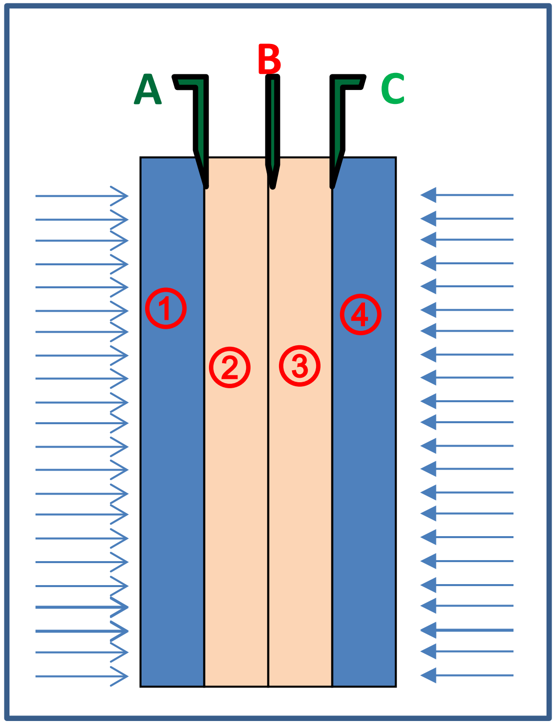


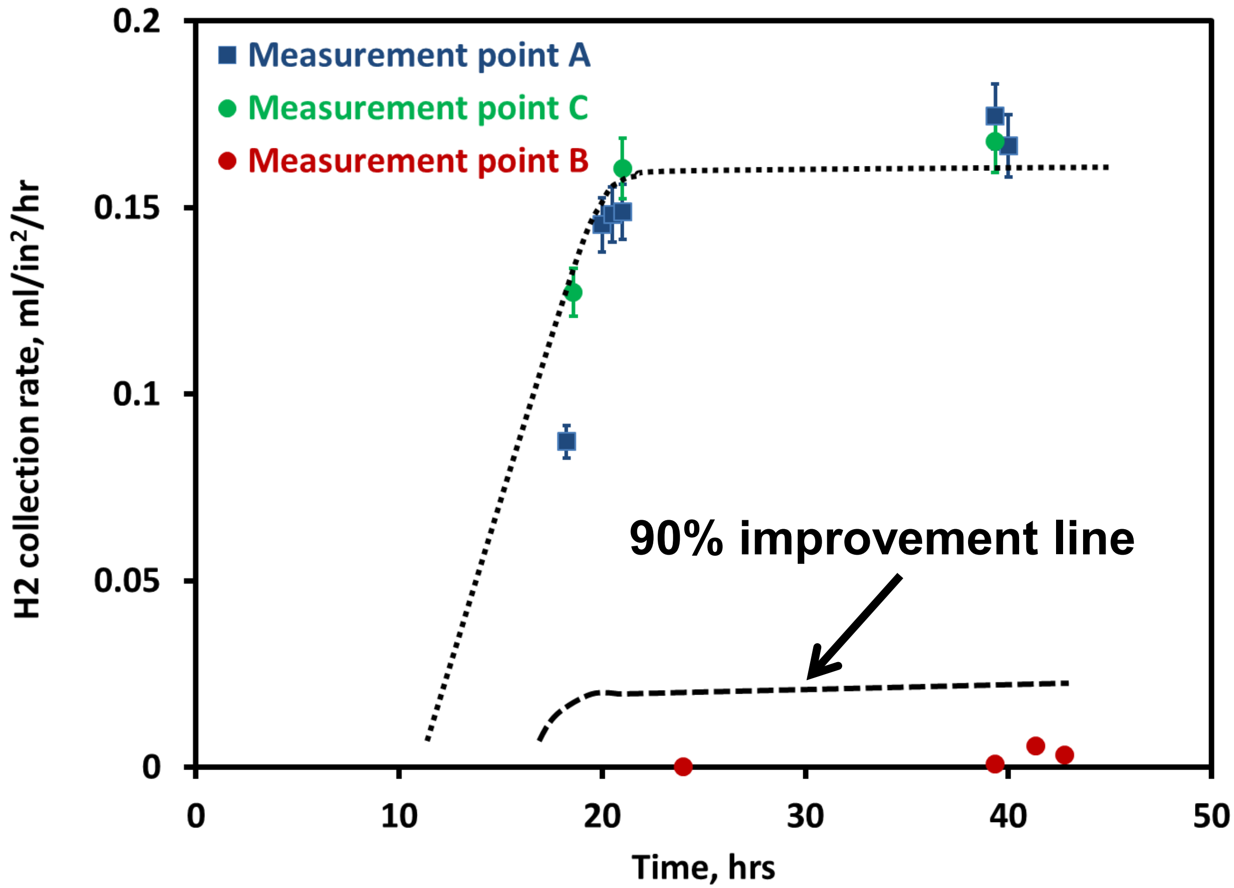
Layered specimen design

- A hydrogen permeation apparatus designed to confirm the effectiveness of novel hydrogen mitigation technology
- The specimen has a layered structure and designed to fit into a H_2 pressure cell
- Diffusible H_2 collected through each layer provides quantitative measure of the effectiveness of the novel design concept



Testing Results at 150C, 2000Psi H_2





- Minimum measurement resolution is 0.01ml ; each data point collected a minimum of 0.1ml H_2.
- H_2 permeation rate through the 2nd layer was reduced more than 95%

Theoretical Analysis of Permeation Rate

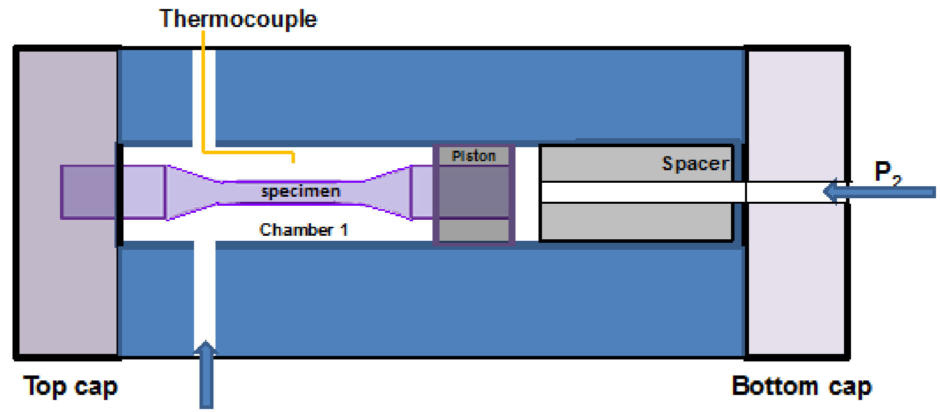
- According to Sievert's law, the permeation rate is proportional to the square root of pressure
- Intake pressure in the first layer: ~2000psi
- Intake pressure in the second layer: ~1atm (14psi) max. In reality, it would be much lower

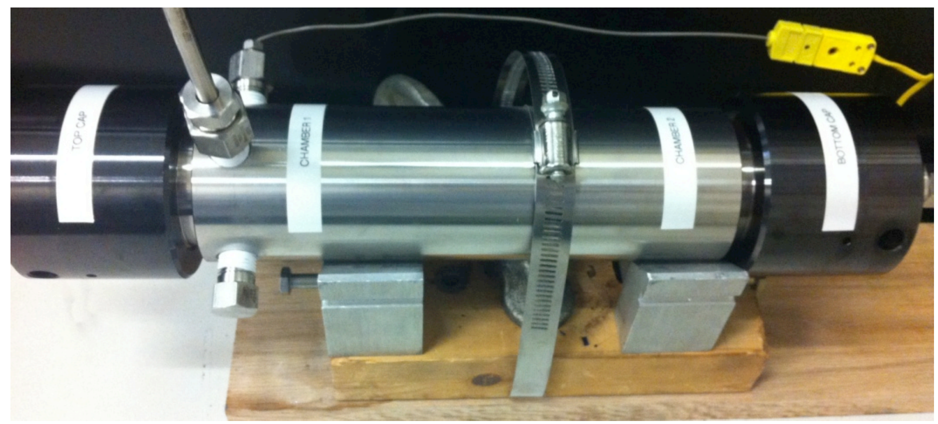
$$\frac{\sqrt{14}}{\sqrt{2000}} = \frac{3.74}{44.72} = 8.3\%$$

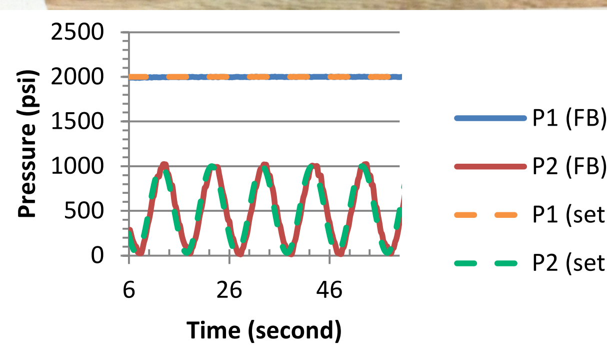
- **Only ~8% of hydrogen will diffuse into the second layer, and ~0.5% into the third layer**
- **The reduction is even higher for higher inner pressure (~4% at 8000psi)**
- **This means the steel inner vessel is designed to eliminate hydrogen embrittlement**

Accomplishment: Development of a Low Cost, High H_2 Pressure Low Frequency Fatigue Test

- Utilizing pressure differential in two hydrogen chambers to apply the cyclic loading
- Mimic hydrogen vessel/pipeline operating conditions
  - Very low frequency @ several cycles per day,
  - Effect of hydrogen pressure variations
- Low cost and compact system
  - Simultaneous testing with multiple systems (tens even hundreds) to generate the fatigue data
- US Patent No. 8,453,515B2
- Co-sponsored by US Department of Transportation







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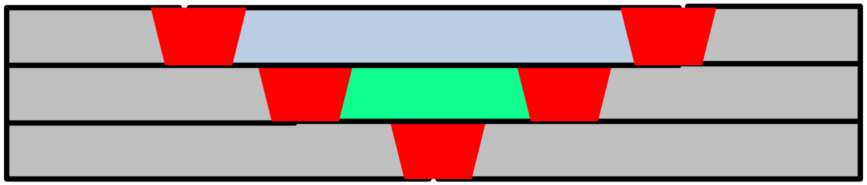
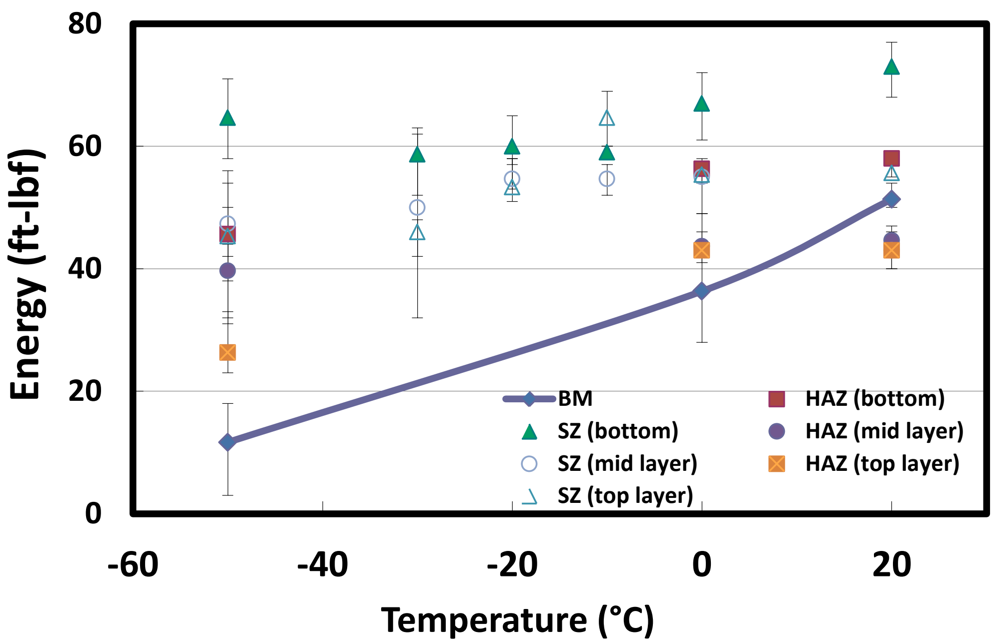
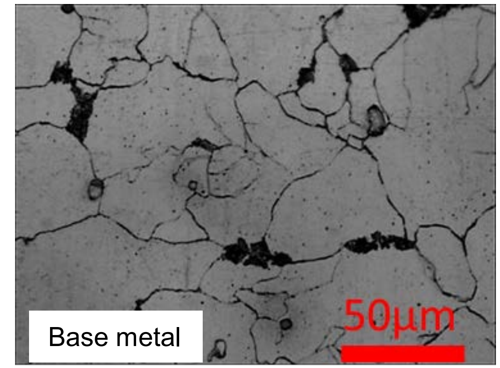
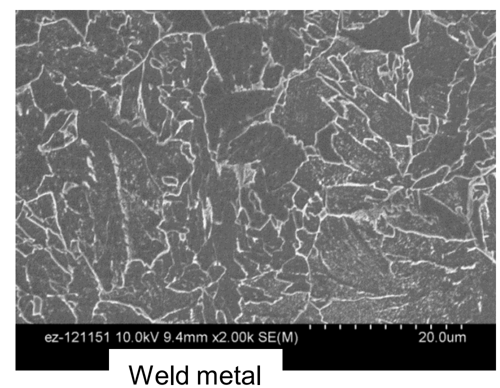
Accomplishments - Fabrication Technology for Layered Steel Vessel: Multi-Layer, Multi-Pass Friction Stir Welding





Superior Charpy impact properties, much higher than the base metal



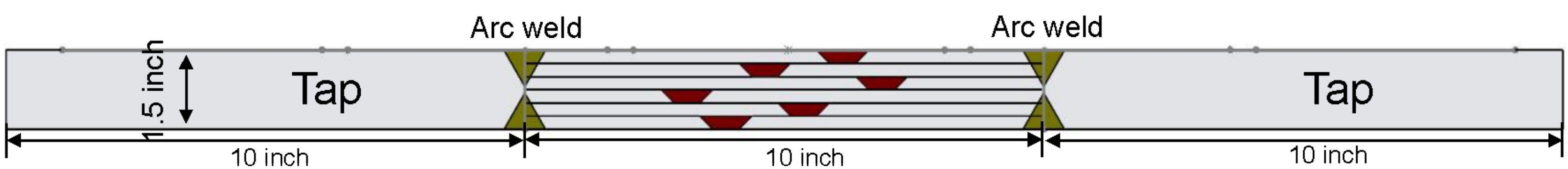


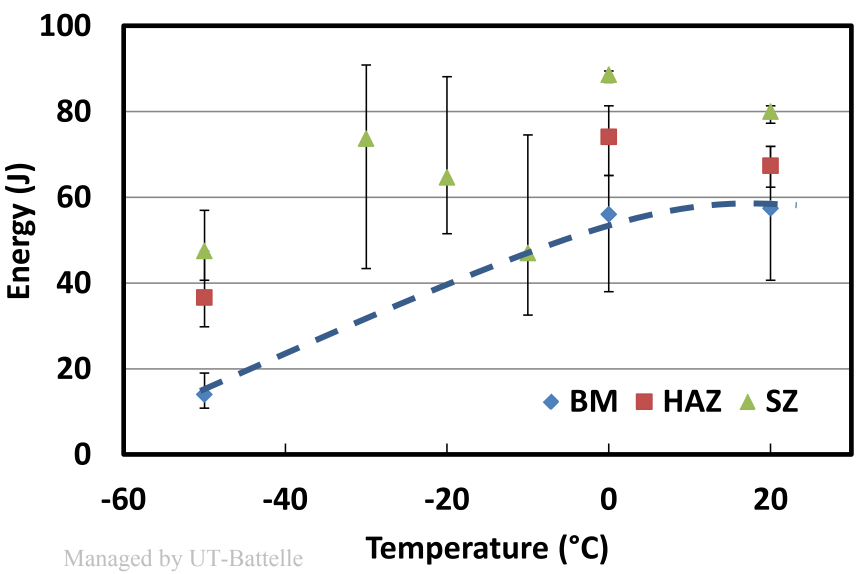
Grain refinement results in improvement in mechanical properties

A572 Grade 50 steel

Multi-Layer, Multi-Pass Friction Stir Welding Scale-Up

- 6-layer, 1.50-in thick welds have been successfully produced
- Full scale mechanical property testing confirmed the effectiveness of layered structure to avoid catastrophic failure
- SA-516 Grade 70





 Managed by UT-Battelle for the U.S. Department of Energy

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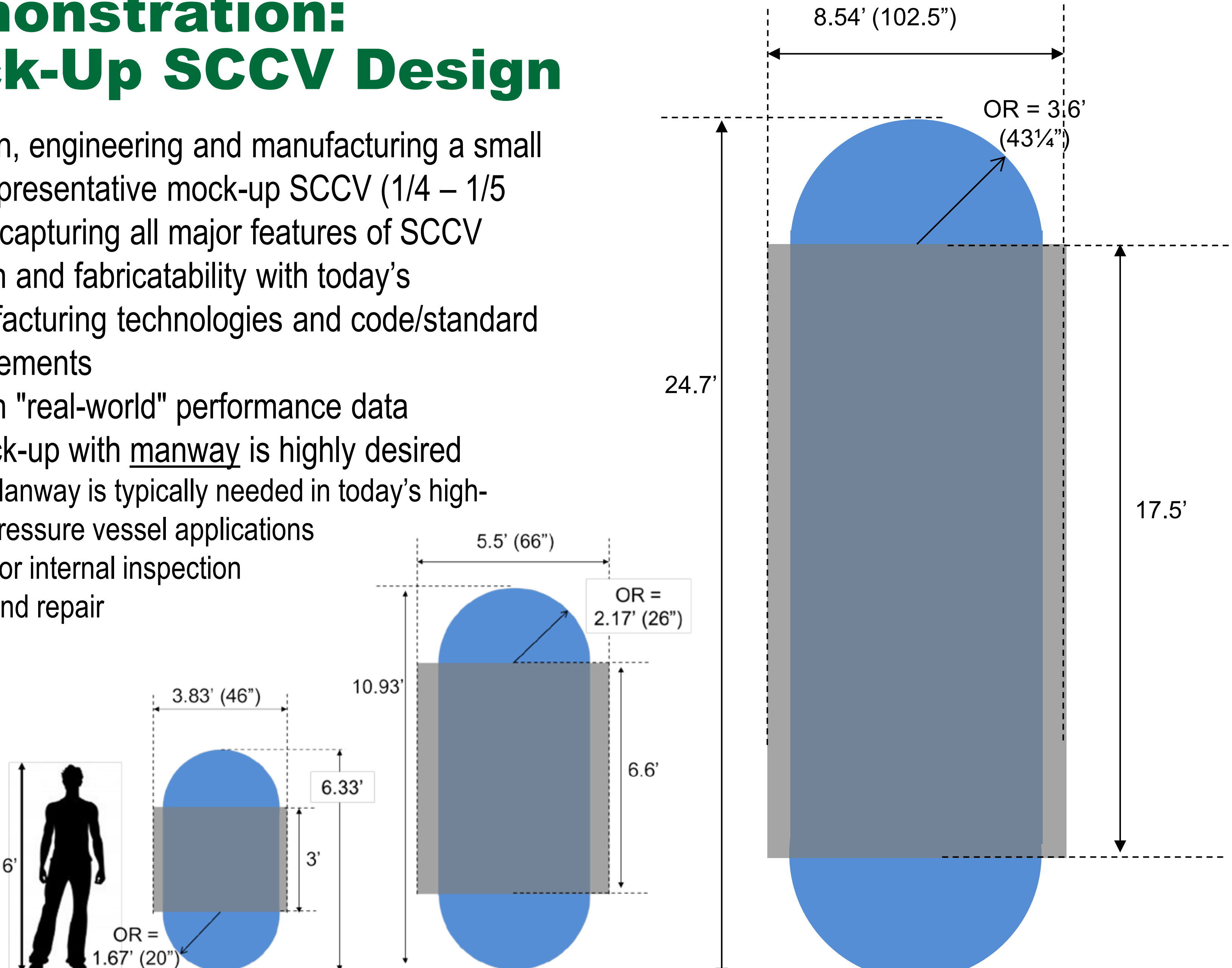
Demonstration: Mock-Up SCCV Design

- Design, engineering and manufacturing a small but representative mock-up SCCV (1/4 – 1/5 size), capturing all major features of SCCV design and fabricatability with today's manufacturing technologies and code/standard requirements
- Obtain "real-world" performance data
- A mock-up with manway is highly desired
  - Manway is typically needed in today's high-pressure vessel applications
  - For internal inspection
  - And repair



Mock-up: Small (~ 30 kg of H_2)

Mock-up: Large (~ 90 kg of H_2)

Full-size: (564 kg of H_2)

Mockup SCCV Demonstration

- Design pressure: 6250 psi (430 bar)
- Code of construction for inner steel vessel: ASME Section VIII Division 2, 2013 edition
  - Steel: SA-765 Gr IV for head, SA-724 Gr B for layered shell
  - 3-mm thick 308/304 stainless steel liner
- ACI design allowables for pre-stressed concrete
- Hydro-static testing at 1.4 times of design pressure as part of code acceptance (8940psi, 615 bar)
- Cyclic hydrogen pressure loading to simulate service conditions

- Status
  - Inner steel vessel under construction
  - Fabrication specification of pre-stressed concrete completed
  - Concrete fabrication vendor identified

Responses to reviewers' comments

- The opportunity to further reduce cost is important, cost impact of manway, steel head, etc
  - *We have leaned a lot through this work. We have identified many options that could potentially lead to considerable further cost reduction. There options will be considered in the next generation SCCV design optimization.*
- The only limitation preventing a rating of four here is the lack of concrete plans for the prototype testing phase
  - *Test planning is a major task in FY14. The testing plan includes (1) code required hydro-static testing and (2) high-pressure cyclic H_2 loading. We have identified four potential testing sites that will be finalized by June, 2014 based on the cost, safety and schedule considerations.*
- Installation cost
  - *Installation cost varies greatly and is highly dependent on a number of factors - location, location and location. We are working with California Fuel Cell Partnership on this subject.*

Collaborations and Industry Participations

Partners / Interactions	Expertise and Extent of collaboration
• Global Engineering and Technology	Design, engineering and consulting firm specialized in high-pressure steel vessels
• Ben C. Gerwick, Inc.	Design, engineering and consulting firm specialized in pre-stressed concrete vessels
• University of Michigan	High-performance concretes
• MegaStir Technologies	Friction stir welding of thick steel sections
• ArcelorMittal	High-strength steels
• ASME (B31.12)	Relevant code committee on high-pressure hydrogen services
• DOT	Qualification of stationary storage vessel for high-pressure hydrogen

Interactions with Industry

- Multiple Inquires from a number of company for potential applications of the technology
  - Underground storage
  - Development and application of ultra high-strength steels (beyond these in current ASME code)
- California Fuel Cell Partnership
  - Supporting hydrogen initiatives in California
  - Underground storage
- Beyond hydrogen storage

Remaining Challenges and Barriers

- Long lead construction leading time:
  – 6-9 months for inner steel vessel
  – 3-5 months for pre-stressed concrete reinforcement

Proposed Future Work

- **FY14**
  - Complete the mockup inner steel vessel construction
- **FY15**
  - Complete the outer pre-stressed concrete vessel, and deliver the entire mock-up SCCV vessel (430 bar and 90 kg H_2) for testing (Q1, FY15)
  - Complete testing of the mock-up SCCV under high-pressure hydrogen to demonstrate both the constructability and performance of the SCCV for hydrogen storage. Perform long-term evaluation of the mock-up SCCV performance under cyclic hydrogen loading (Q4, FY15)
- **FY16 and beyond**:
  - As a follow-on project, identify and apply SCCV for underground hydrogen storage for forecourt fueling stations to address a major and immediate cost factor in hydrogen delivery infrastructure

Project Summary

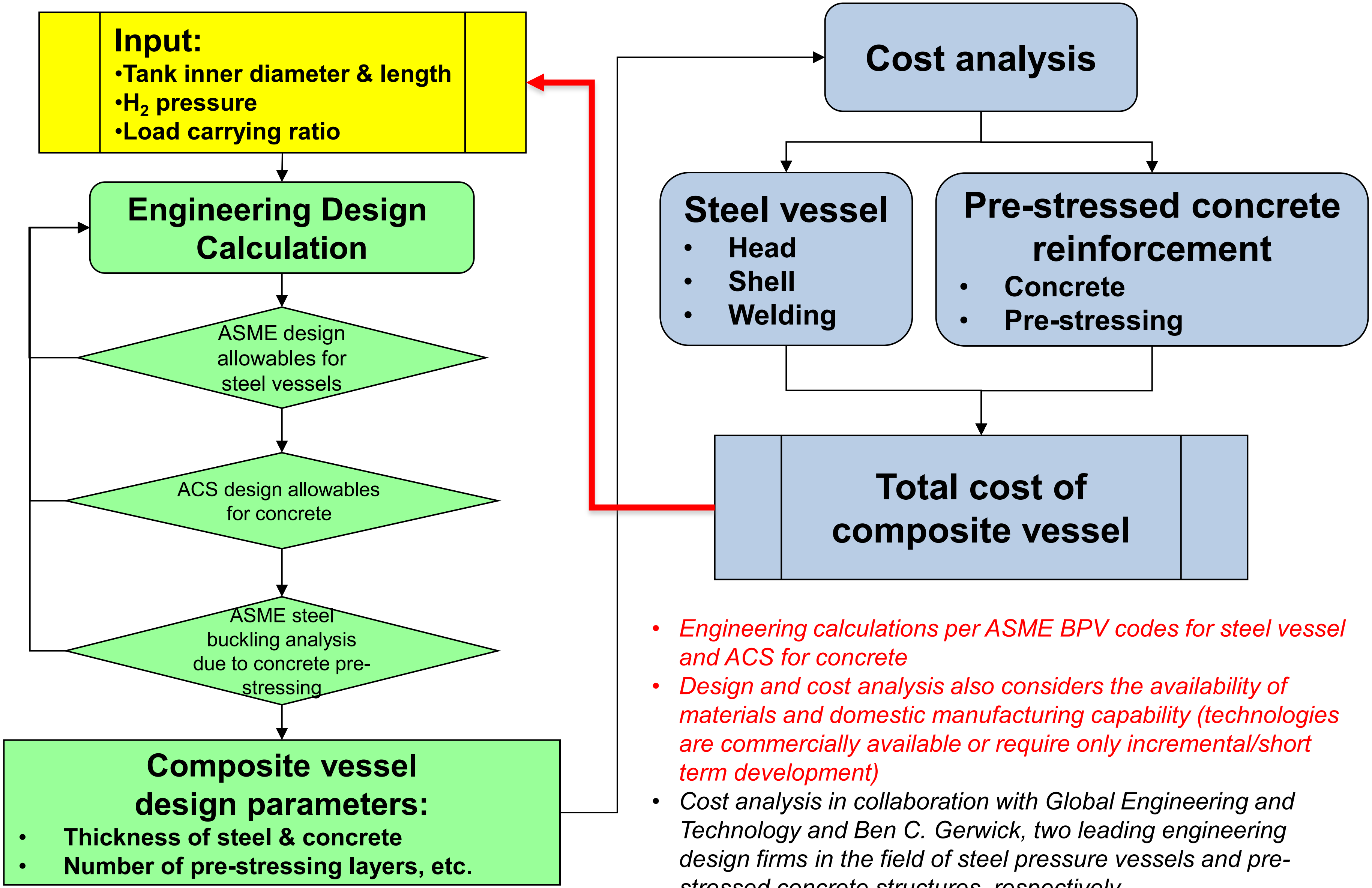
Relevance:	• Address the significant safety and cost challenges of the current industry standard steel pressure vessel technology • Demonstrate the high-pressure storage vessel technology for CGH_2 that can meet or exceed the relevant DOE cost target
Approach:	Integrated vessel design and fabrication technology: • Use of commodity materials (e.g., steels and concretes) in SCCV • Mitigation of hydrogen embrittlement to steels by design • Advanced, automated manufacturing of layered steel tank
Technical Accomplishments	• A high fidelity design and manufacturing cost analysis demonstrated that the SCCV technology can exceed the relevant cost targets set forth by DOE • Successfully validated the effectiveness of the novel hydrogen mitigation technology to prevent hydrogen entering the structural steel layer • Multilayer-multipass friction stir welding technology can potentially further reduce the cost and improve the weld properties • Technology demonstration is underway with a ¼ scale mockup SCCV
Collaborations:	Active partnership with industry, university and other stakeholders
Future Plan:	• Complete the construction of mockup SCCV (Q1, FY15) • Perform technology validation testing of SCCV under cyclic hydrogen service conditions (FY15) • Technology demonstration and transfer (FY15/16)

Technical Backup Slides

Cost Analysis Modeling

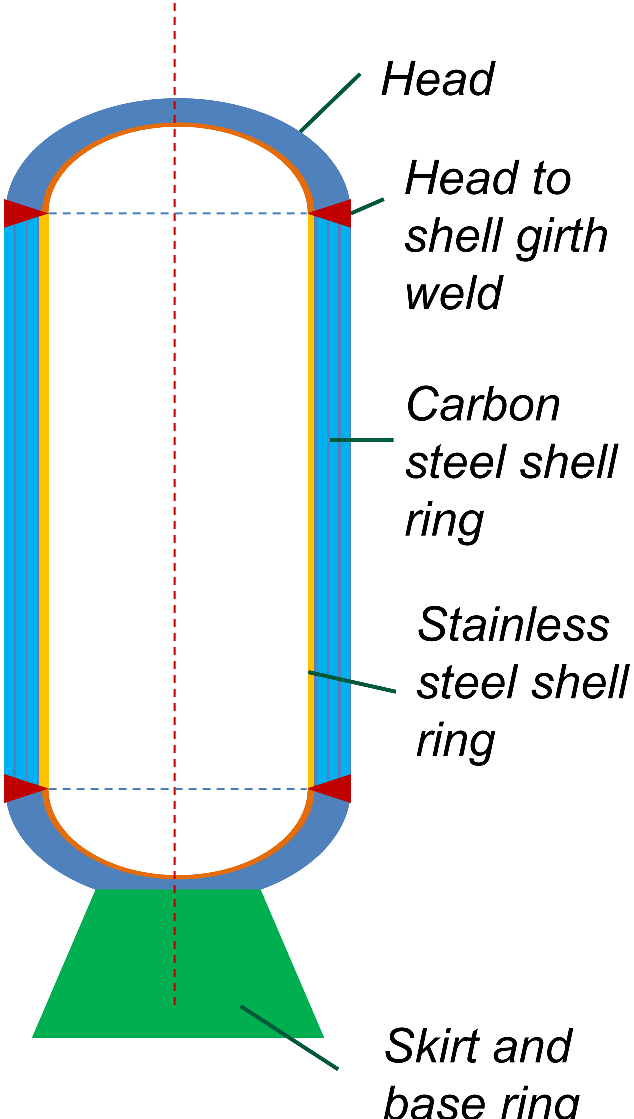
Step #1	•	Engineering calculations based on relevant design codes (e.g., ASME BVP) to determine the vessel dimensions such as steel wall thickness, concrete wall thickness, etc. • Dimensions constrained by typical capacity of industrial manufacturing facilities.
Step #2	•	Detailed, step-by-step manufacturing process flow for composite vessels
Step #3	•	Cost estimation for each manufacturing step by considering: ○ Materials, consumables, and labor • Basis for cost estimation: ○ Vendor quotes ○ Data from relevant fabrication projects by Global Engineering and Technology and Ben C. Gerwick, Inc.

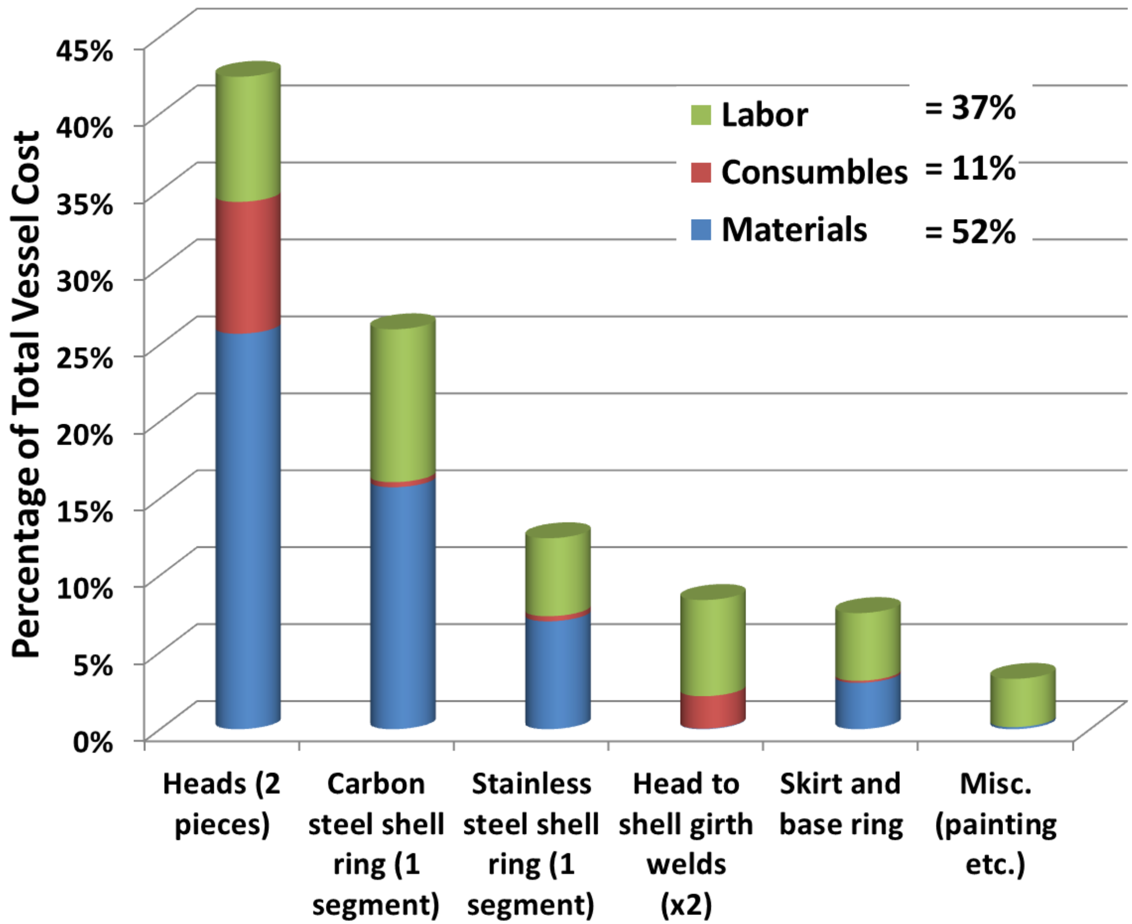
Overview of Cost Analysis Approach



- *Engineering calculations per ASME BPV codes for steel vessel and ACS for concrete*
- *Design and cost analysis also considers the availability of materials and domestic manufacturing capability (technologies are commercially available or require only incremental/short term development)*
- *Cost analysis in collaboration with Global Engineering and Technology and Ben C. Gerwick, two leading engineering design firms in the field of steel pressure vessels and pre-stressed concrete structures, respectively.*

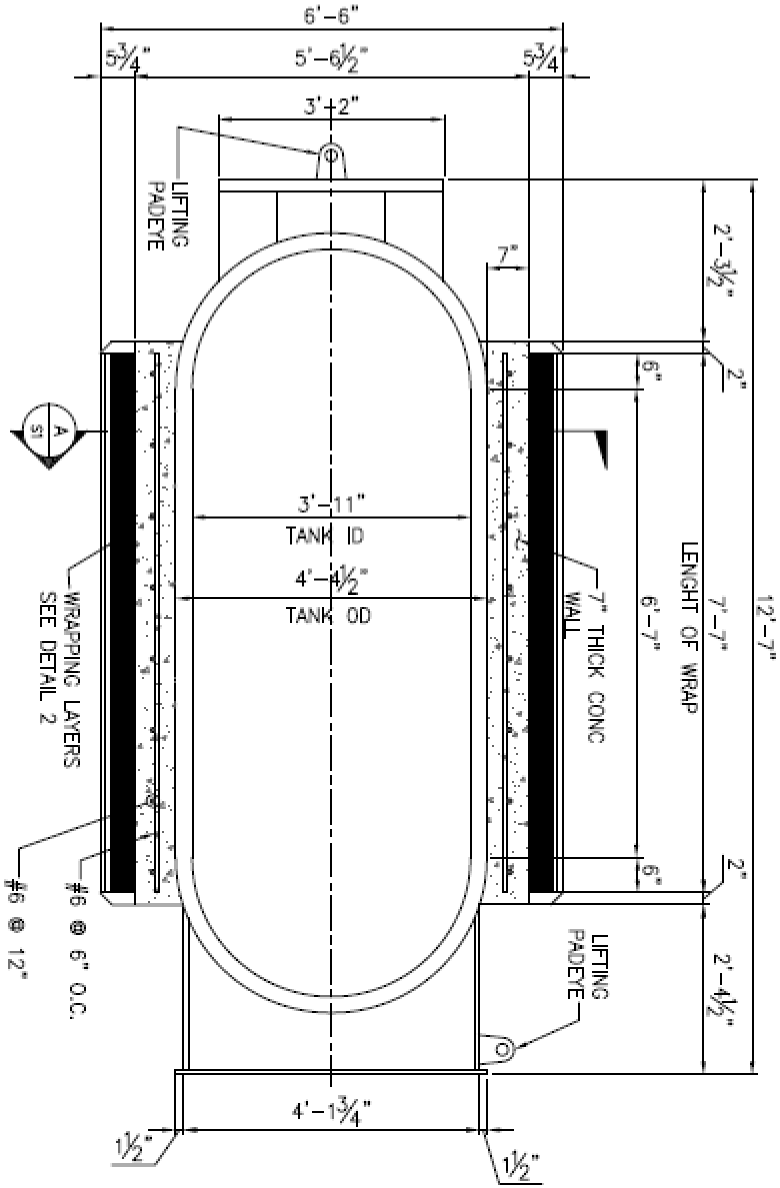
Example: Cost Analysis for Inner Steel Tank



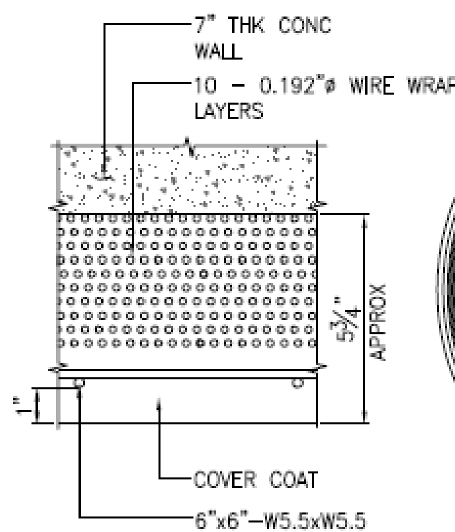


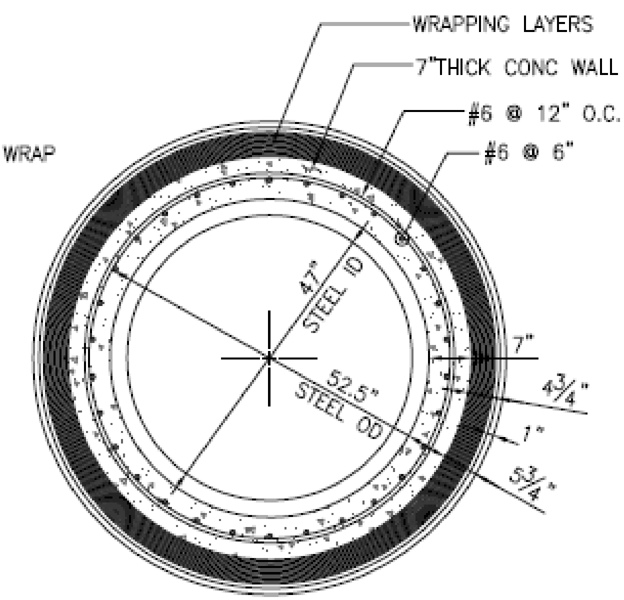
- *Consumables including welding filler wires and shielding gases etc.*
- *Assumed labor rate: $75 per hour*

Details of Mock-Up SCCV Design

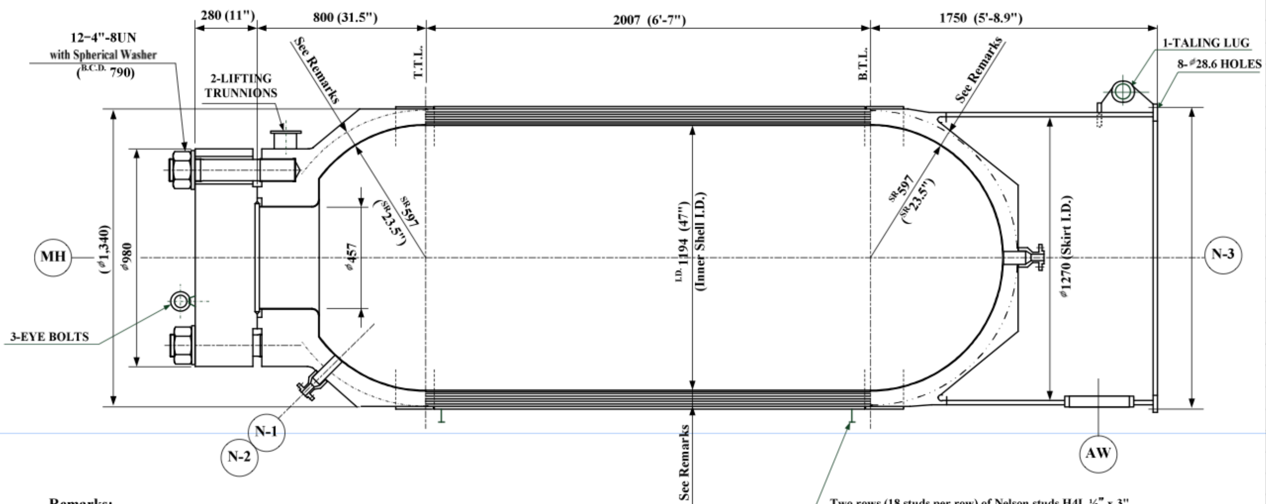


- Design capability: 6250 psi, 89 Kg H_2,
- Height = 9' 7", OD = 4' 1¾"
- Steel inner vessel
  - Manway, Lifting lugs, Support base
- Concrete:
  - 7" thick, additional 6" at each end to mitigate stress concentrate near the joint
- Ten layers of ϕ0.192" pre-stressing wire





Inner Steel Vessel Details



Remarks:
Thickness of pressure retaining parts;
(1) Inner Shell: Nom. t 12 mm (SA-516 Gr.70) with Min. t 3.0 mm (SA-240 Gr.TP304L) clad
(2) Layers: Min. t 13.5 mm x 4 layers (SA-724 Gr.B)
(3) Outer Layer (Shroud): Nom. t 10 mm (SA-516 Gr.70)
Two longitudinal grooves (10 mm wide by 3.0 mm deep) are machined on the inside surface channeling of the hydrogen. These grooves are to be placed directly above the vent holes in the layered shell.

(4) Thickness of top / bottom heads;
Min. t 63.0 mm (SA-765 Gr.IV) + TP308L (Min. t 3.0 mm) OVL

USE OR DISCLOSURE OF INFORMATION CONTAINED ON THIS PAGE IS SUBJECT TO THE RESTRICTION ON THE TITLE PAGE OF THIS PROPOSAL.

PRELIMINARY

DESIGN DATA

CODE		ASME Sec VIII, Div.2
FLUID		PURE HYDROGEN
MAWP for SHELL	Psi (MPa)	3,620 (24.96)
MAWP for HEAD	Psi (MPa)	6250 (43.1)
MDMT (max)	°F (°C)	150 (65.6)
MDMT (min)	°F (°C)	-20 (-28.9)
HYDRO. TEST at Shop	Psi (MPa)	5177 (35.7)
PNEUM. TEST PRESS.	Psi	NONE
POSTWELD HEAT TREAT.		YES FOR HEAD
RADIOGRAPH		PER CODE
JOINT EFF.		PER CODE
CORR. ALLOWANCE	mm	TP304LS/S & TP308L OVL
INSULATION (BY OTHERS)	mm	NONE
PAINT		Rust preventive pant
FIRE PROOF	mm	NONE
VOLUME	m^3	3.1
LIQUID DENSITY	kg/m^3	——
MASS-EMPTY	kg	App. 14,500
(*1) -OPERAT.	kg	
(*1) -FULL WATER	kg	App. 17,600

REMARKS
(*1) EMPTY WEIGHT + UREA SOLUTION
(*1) EMPTY WEIGHT + FULL WATER

REV. NO	REVISIONS	DESIGNED	CHECKED	APPROVED
◇			/	/
◇			/	/
◇			/	/

NAME	NO. REQ'D
LAYERED STEEL VESSEL	1
SCALE	DWG. NO.

MATERIAL LIST

INNER SHELL	SA-516 Gr.70 with SA-240 Gr.TP304L Clad	BOLTS / NUTS	
LAYER	SA-724 Gr.B	-FOR MANHOLE	SA-193 Gr.B7/ SA-194 Gr.2H
OUTER LAYER (SHROUD)	SA-516 Gr.70	DELTA GASKET	SA-182 Gr. F304
TOP HEAD WITH MANHOLE	SA-765 Gr.IV with TP308L OVL		
BOTTOM HEAD	SA-765 Gr.IV with TP308L OVL		
MANHOLE COVER	SA-765 Gr.IV with TP308L OVL		
SKIRT	SA-516 Gr.70		
NOZZLES	SA-182 Gr. F304		

NOZZLE LIST

NOZZLE MARK	NOM. SIZE	NO. REQ'D	FLANGE RATING	SERVICE	REMARKS
AW	I.D. 600	1	-	ACCESS OPENING	
N-3	1"	1	#2500 LWN	DRAIN	WITH COVER
N-2	1"	1	#2500 LWN	OUTLET	
N-1	1"	1	#2500 LWN	INLET	
MH	I.D. 457	1	Special	MANWAY	WITH COVER