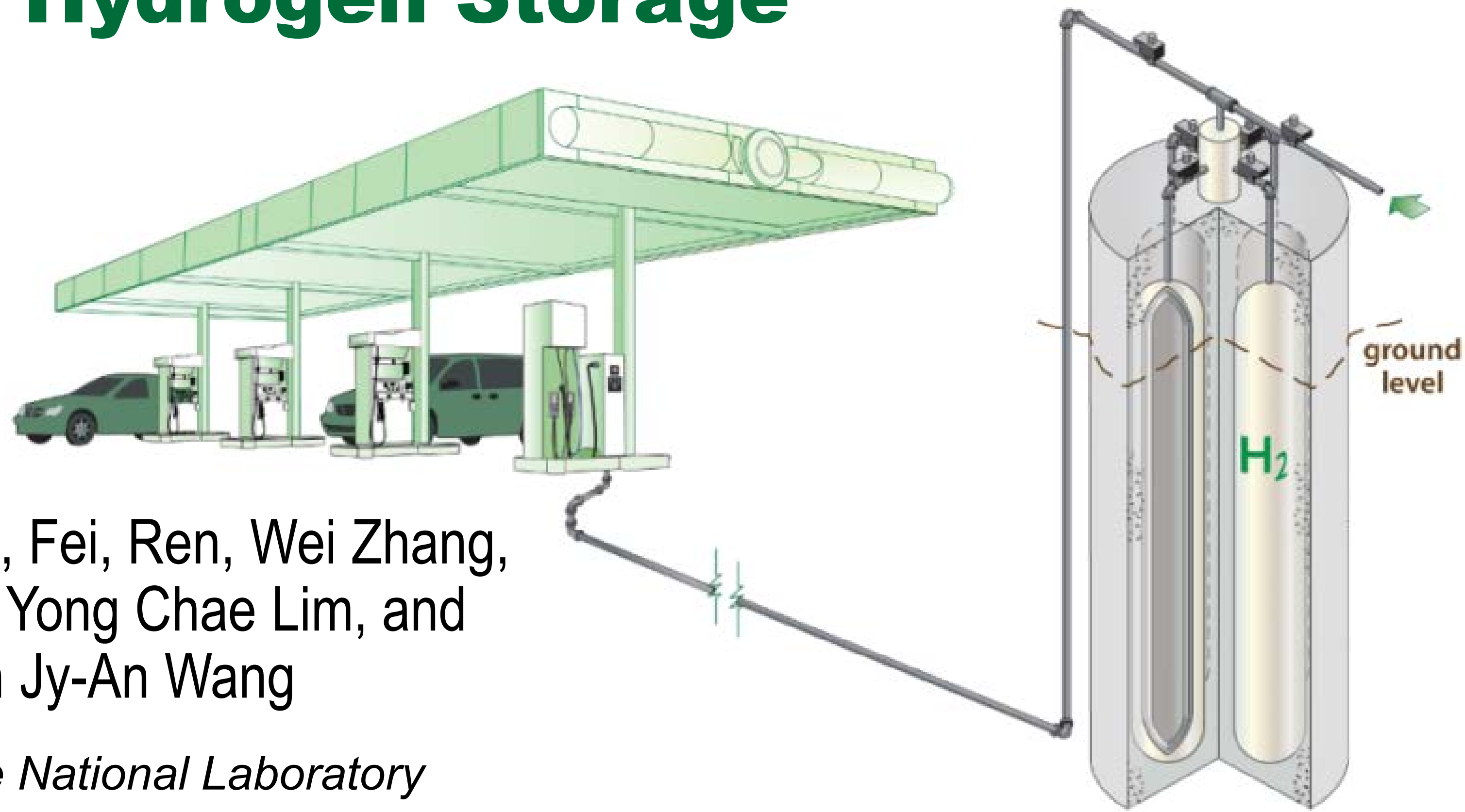
Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage



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PD088

U.S. DEPARTMENT OF ENERGY

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OAK RIDGE NATIONAL LABORATORY
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Overview

Timeline

- Project start date: Oct. 2010
- Project end date: Sep. 2015
- Percent complete: 50%

Budget

- Total project funding
  – DOE share: $3,000K
  – Contractor in-kind share: 20%
- Funding for FY13: $800K (anticipated)

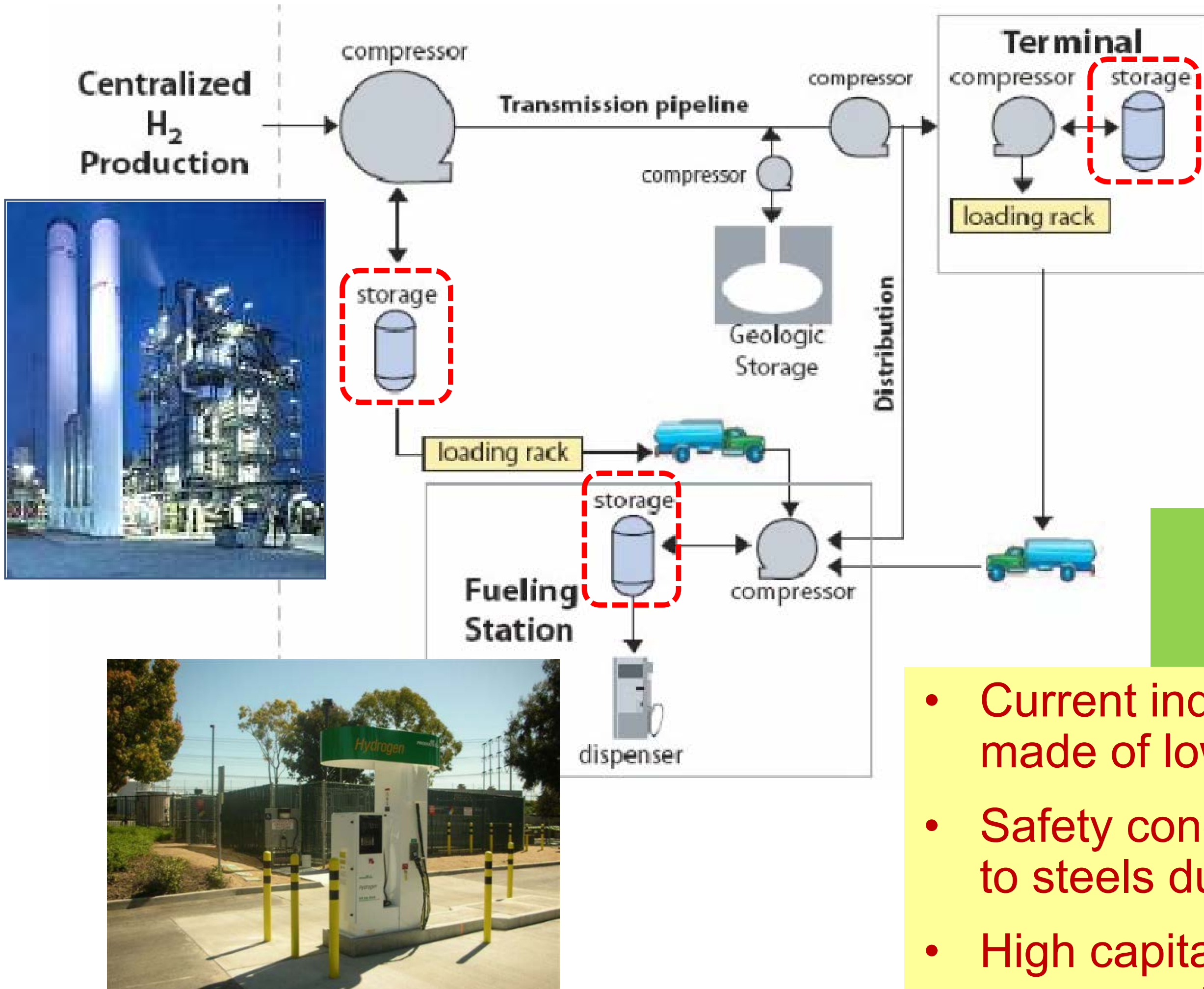
Barriers

- 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

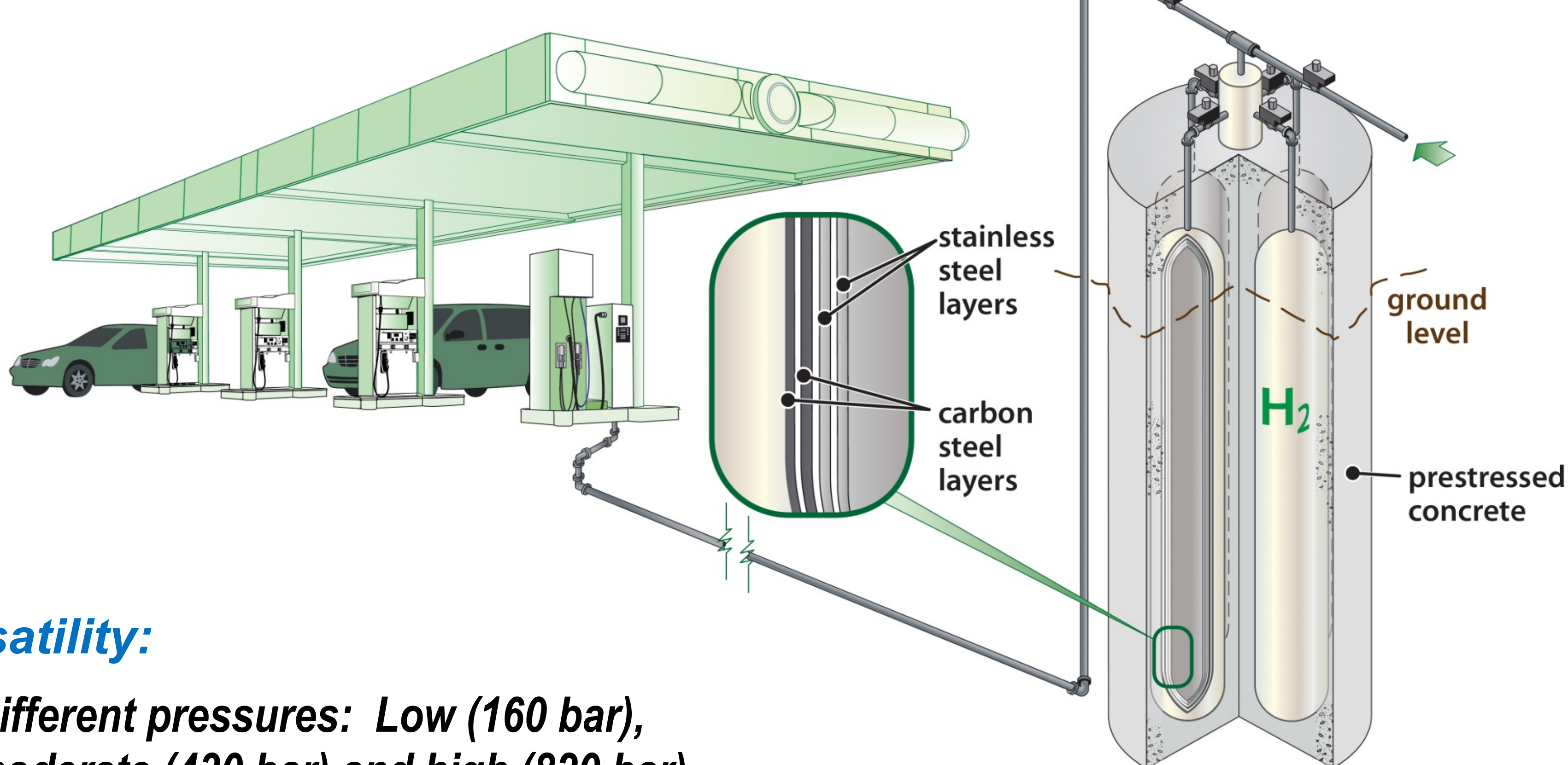
Table 3.2.4 Technical Targets for Hydrogen Delivery Components *

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	$750
High Pressure (820 bar) Purchased Capital Cost ($/kg of H2 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

Technology: Steel/Concrete Composite Vessel for Compressed H_2



Versatility:

- ***Different pressures: Low (160 bar), moderate (430 bar) and high (820 bar)***
- ***Different storage volumes***
- ***Above ground or under ground***

Baseline specifications: 1,500 kg of H_2 in a stationary vessel:

- **Refill 260 passenger cars (*based on 5.6 kg H_2 tank per car*)**
- **Interior volume = 2,300 ft^3 (65.1 m^3) @ 5,000 psi (345 bar) & room temperature**

Technical Approach

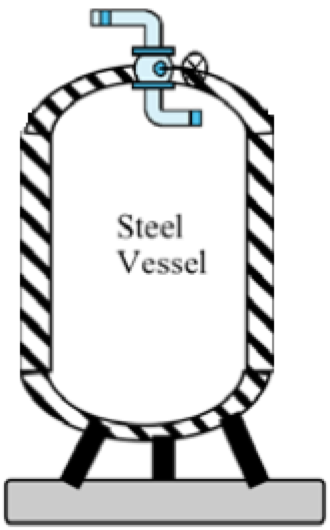
- Vessel design technology:
  - Use of commodity materials (e.g., structural steels and concretes) for achieving cost, performance and safety requirements
  - Mitigation of hydrogen embrittlement to steels especially high-strength low alloy grades
- Vessel fabrication technology:
  - Advanced, automated manufacturing process for layered steel tank
  - Embedded sensors to ensure the safe and reliable operation
- Safety and performance:
  - Industry codes and standards such as ASME Boiler and Pressure Vessel (BPV) Code for safe design of pressure vessel
  - 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., routine inspection, maintenance, repair etc.) for pressure vessels

Overall Project Scope and Plan

- Phase I: Conceptual design (completed FY11)
- Phase II: Cost analysis (completed FY12)
  – SCCV engineering and cost analysis met DOE cost target
- Phase III: Technology development and demonstration:
  – Design, engineering and fabrication of representative mockup vessels (FY13/14)
  – Testing and technology validation (FY14/15)

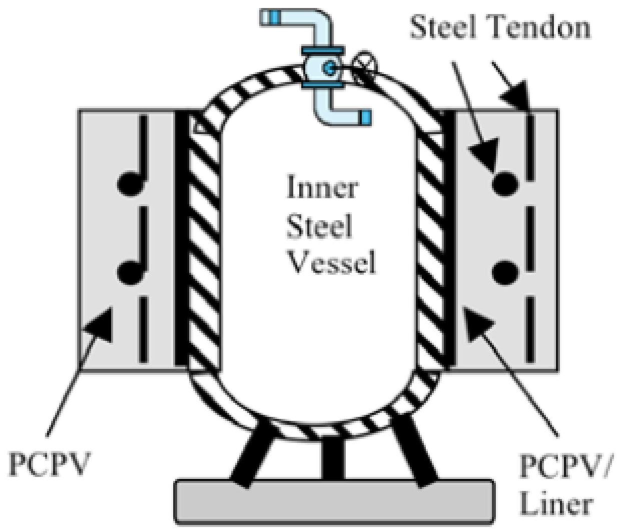
Baseline Designs with Varying Usage of Steels and Concretes

Various combination of steel and concrete for cost and fabricatability considerations



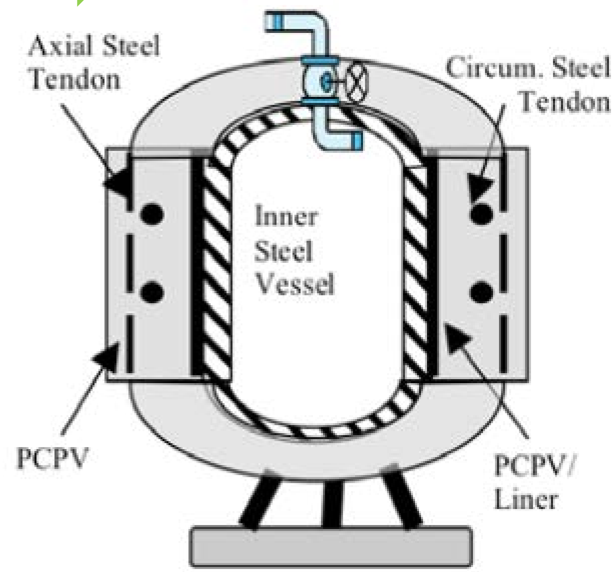
Case 1: Steel only

Current industry status



Case 2: 50% Steel + 50% Concrete

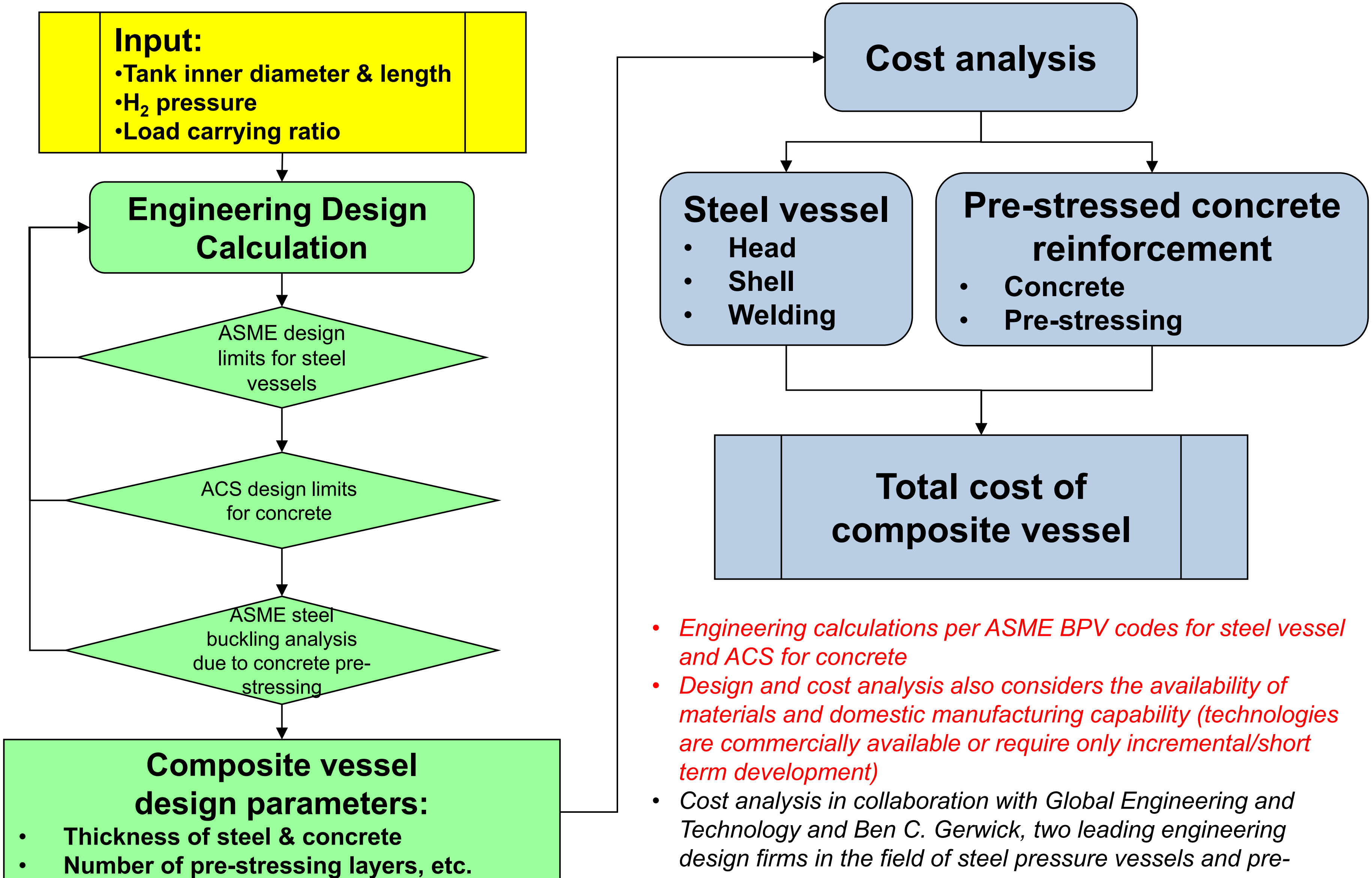
Pre-stressed concrete sleeve carrying 50% of hoop stress



Case 3: Concrete and Steel "Liner"

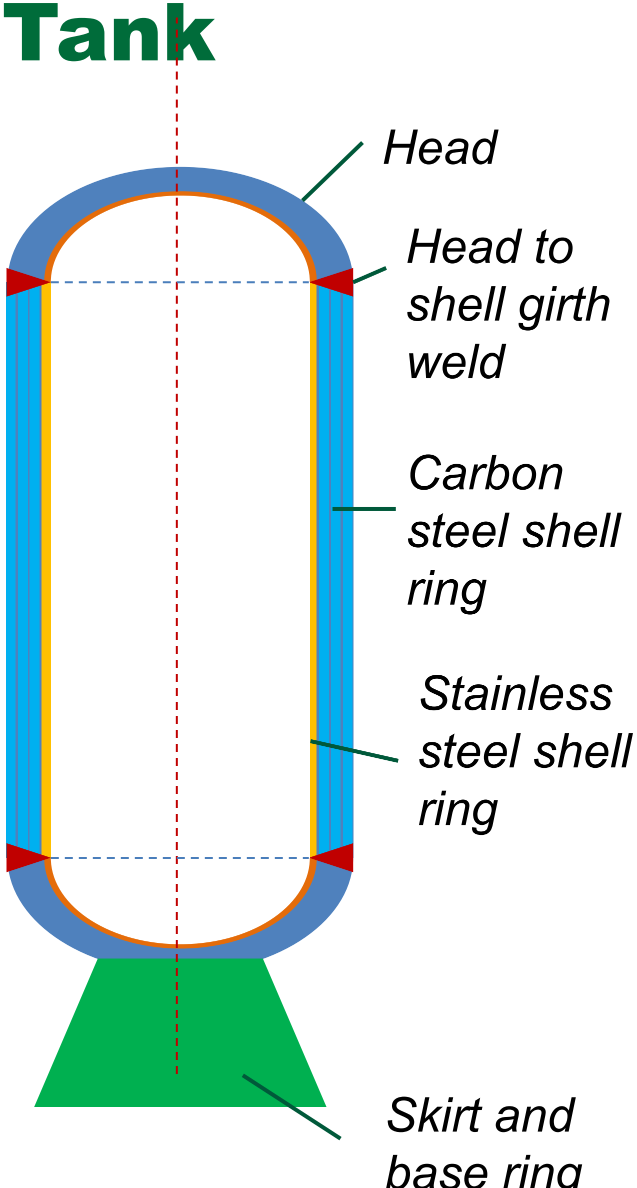
Pre-stressed concrete enclosure carrying 70% of hoop and axial stresses while steel liner carries 30% of the loads

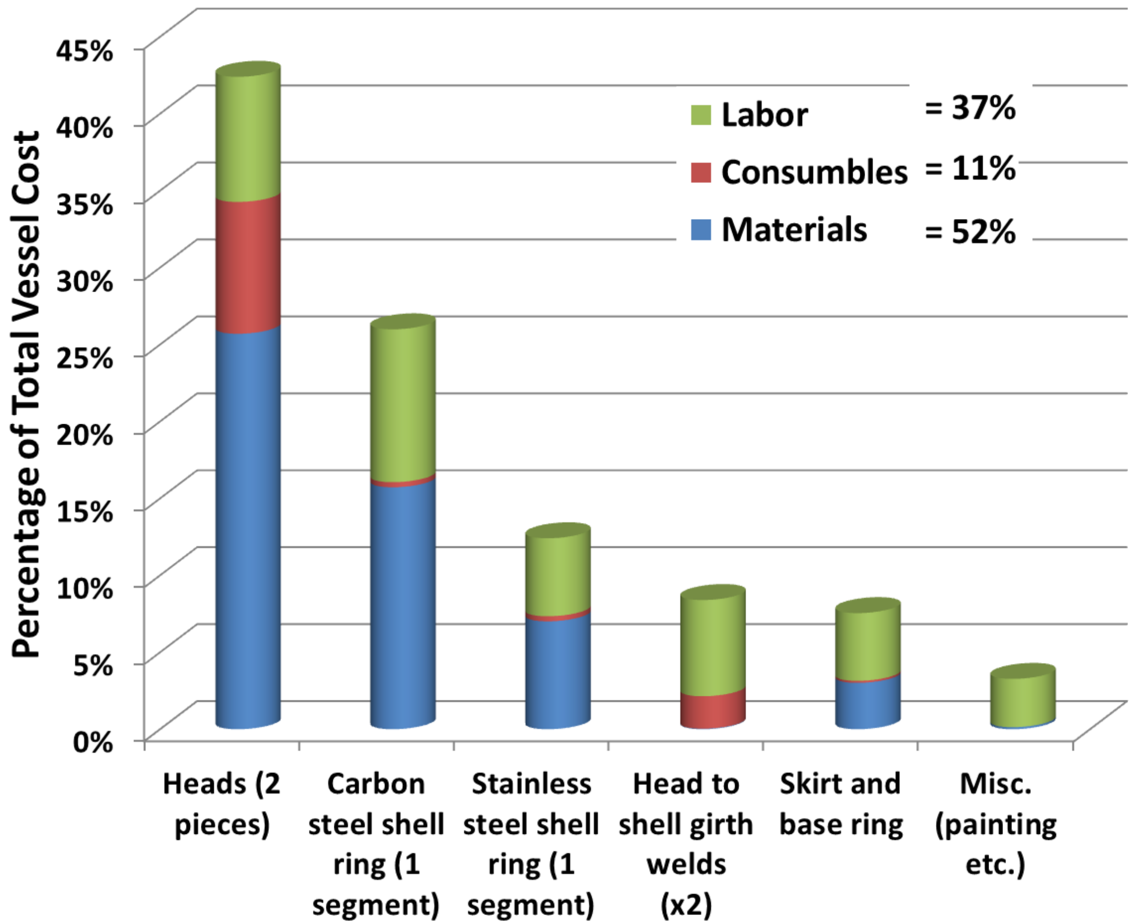
Overview of Cost Analysis Approach



- *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

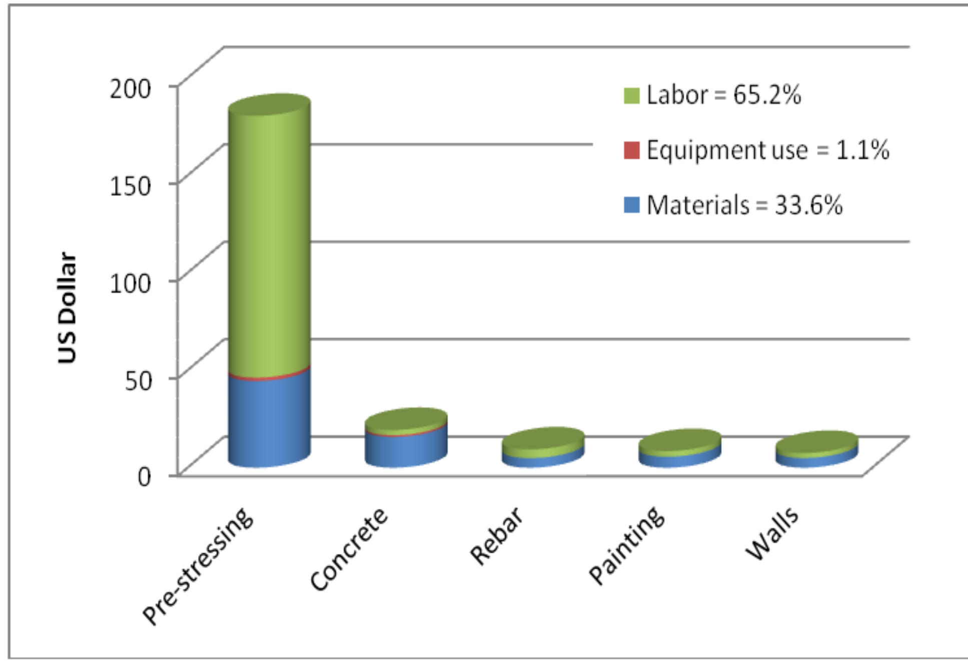




- *Consumables including welding filler wires and shielding gases etc.*
- *Assumed labor rate: $75 per hour*

Example: Cost Analysis for Concrete

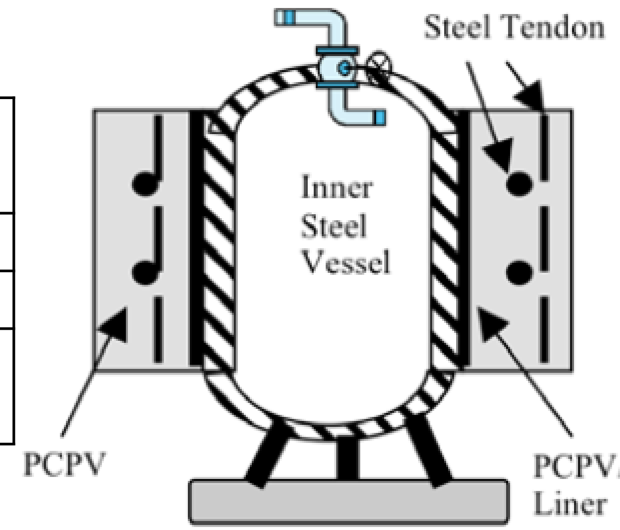
- Structural design
  - Input: 5000 psi, 50/50, ID = 54”, H = 40 ft, 390 kg H2
  - Output: ts = 2.5”, tc = 8”, prestressing = 4 layers (192 ft)
- Direct cost
  - Concrete = 16 yd^3 → $3,919
  - Prestressing = 22,500 lb → $36,527
  - Rebar = 2500 lb → $1,897
  - Wall → $1,528
  - Painting → $1,724
  - Subtotal = $45,595
  - Contract cost = $69,385
    Indirect cost = $37,154



- Total = $106,539
- H_2 storage cost = $106,539/390 kg = $273 /kg H2

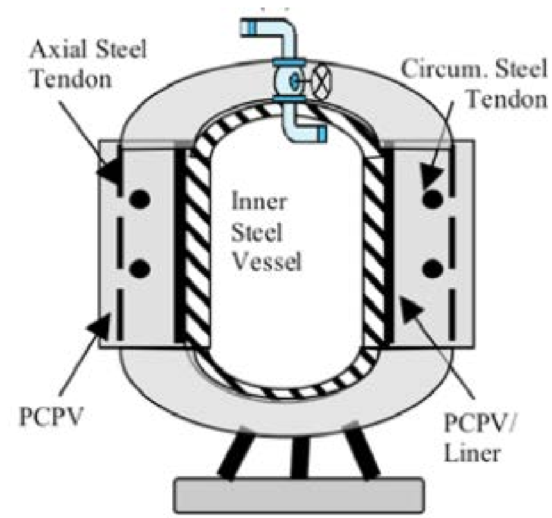
Example: Effect of Load Carrying Ratio (Concrete only)

H_2 pressure	Tank ID	Tank height	***50/50***	40/60	30/70	DOE FY20
160 bar	72”	27.5’	***$214***	$838	$908	$700
430 bar	72”	27.5’	***$173***	$558	$730	$750
860 bar	72”	27.5’	***$245***	$740	$1071	$1,000



50/50

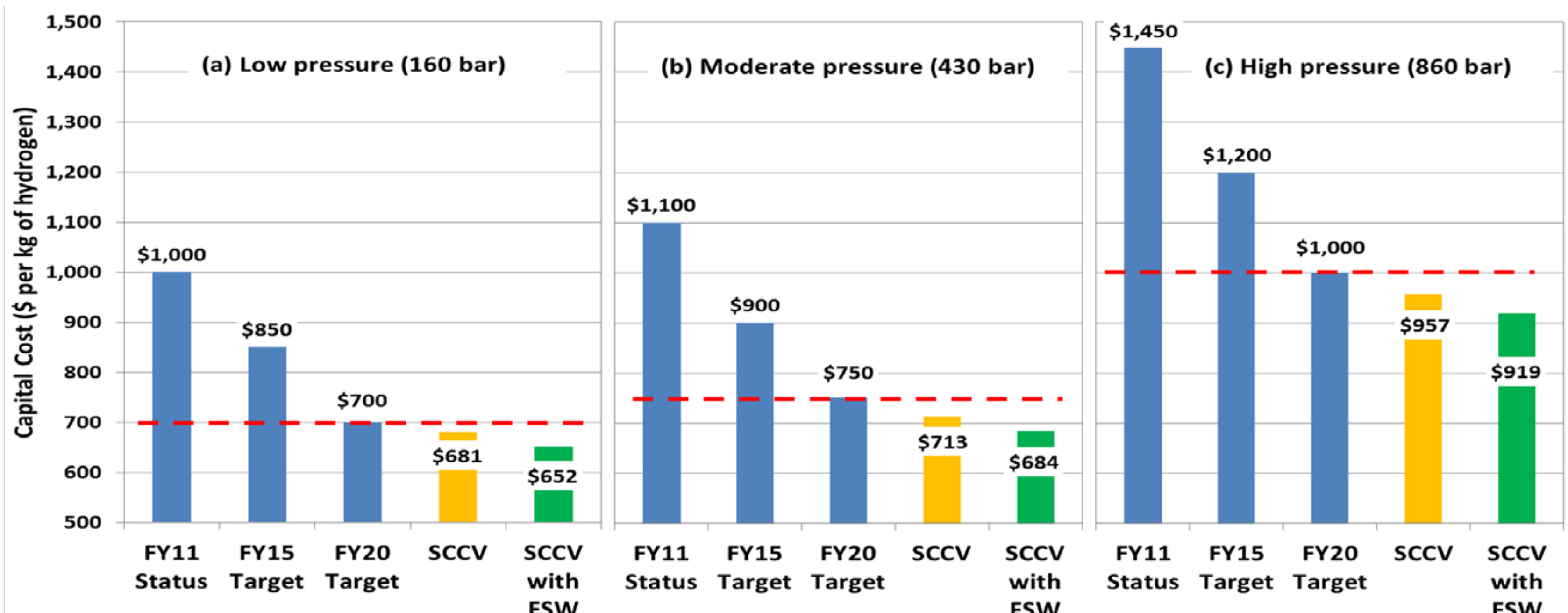
- For 40/60 and 30/70 designs, the concrete cost itself already represents a large percentage of DOE cost target
- The total cost including steel tank and concrete for 40/60 and 30/70 designs is expected to largely exceed DOE cost target.
- Moreover, there is a minimal thickness needed in order to avoid buckling during pre-stressing step in the fabrication. In other words, the bulk concrete vessel with thin liner does not work due to liner buckling.
- Therefore, the 50/50 design is selected and examined in details.



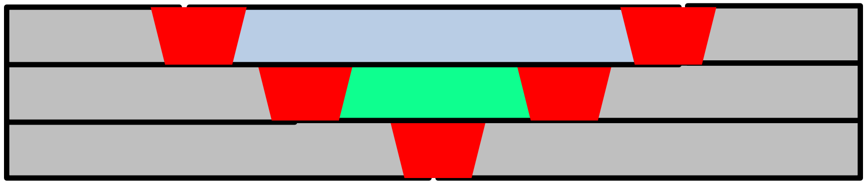
40/60 and 30/70

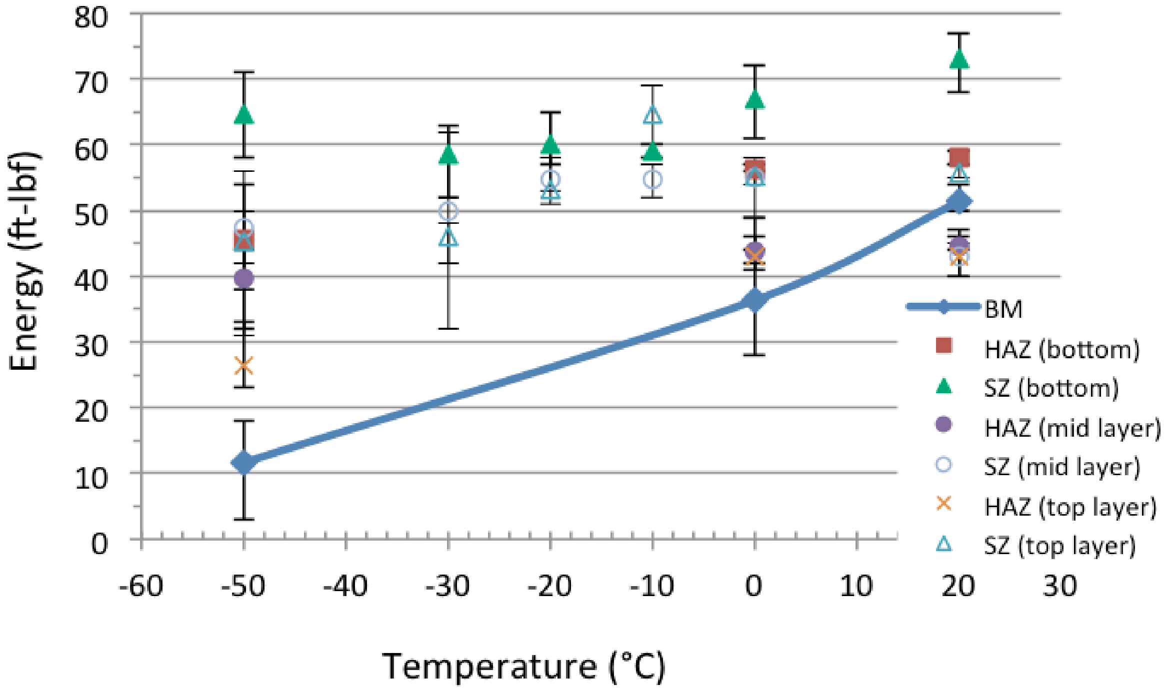
Accomplishment: Manufacturing cost analysis

- 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
- Baseline SCCV design: 50/50 load carrying ratio, 6 ft diameter, 27.5 ft height
- Details of cost analysis in ORNL Technical Report

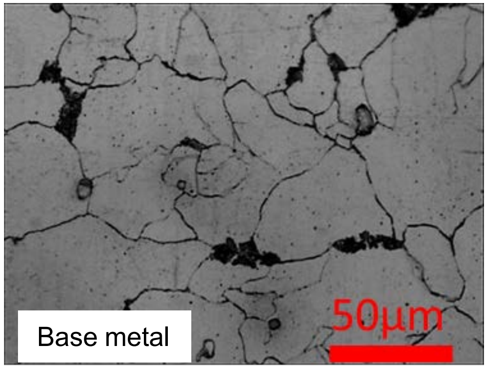


Accomplishments - Fabrication Technology for Layered Steel Tank: Multi-Layer, Multi-Pass Friction Stir Welding of Thick Steel Section

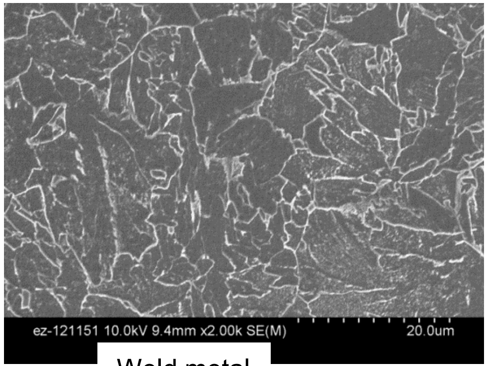




Superior Charpy impact properties, much higher than the base metal



Base metal

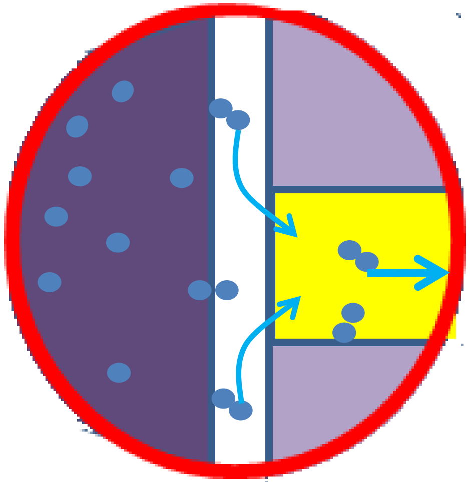


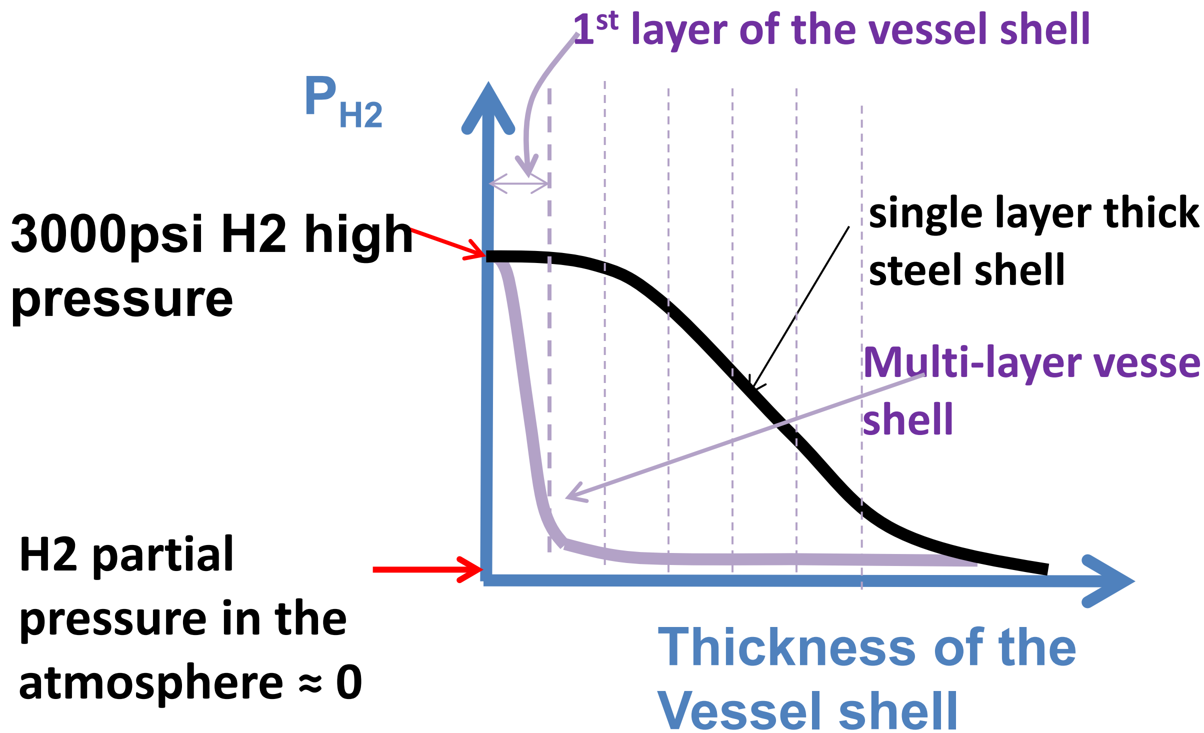
Weld metal

Grain refinement results in improvement in mechanical properties

A572 Grade 50 steel

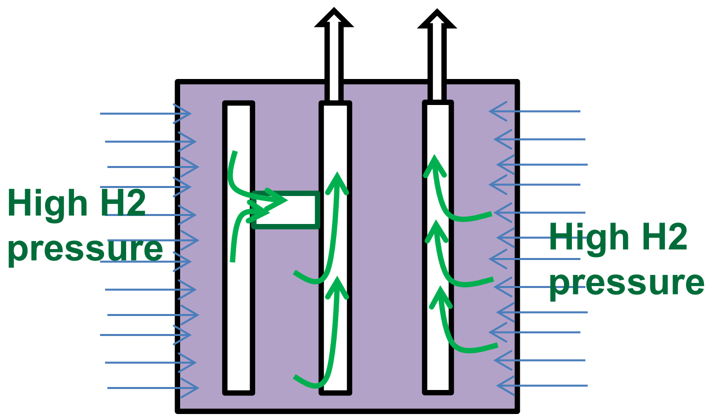
Approach: Hydrogen Mitigation Concept in Multi-Layered Vessel





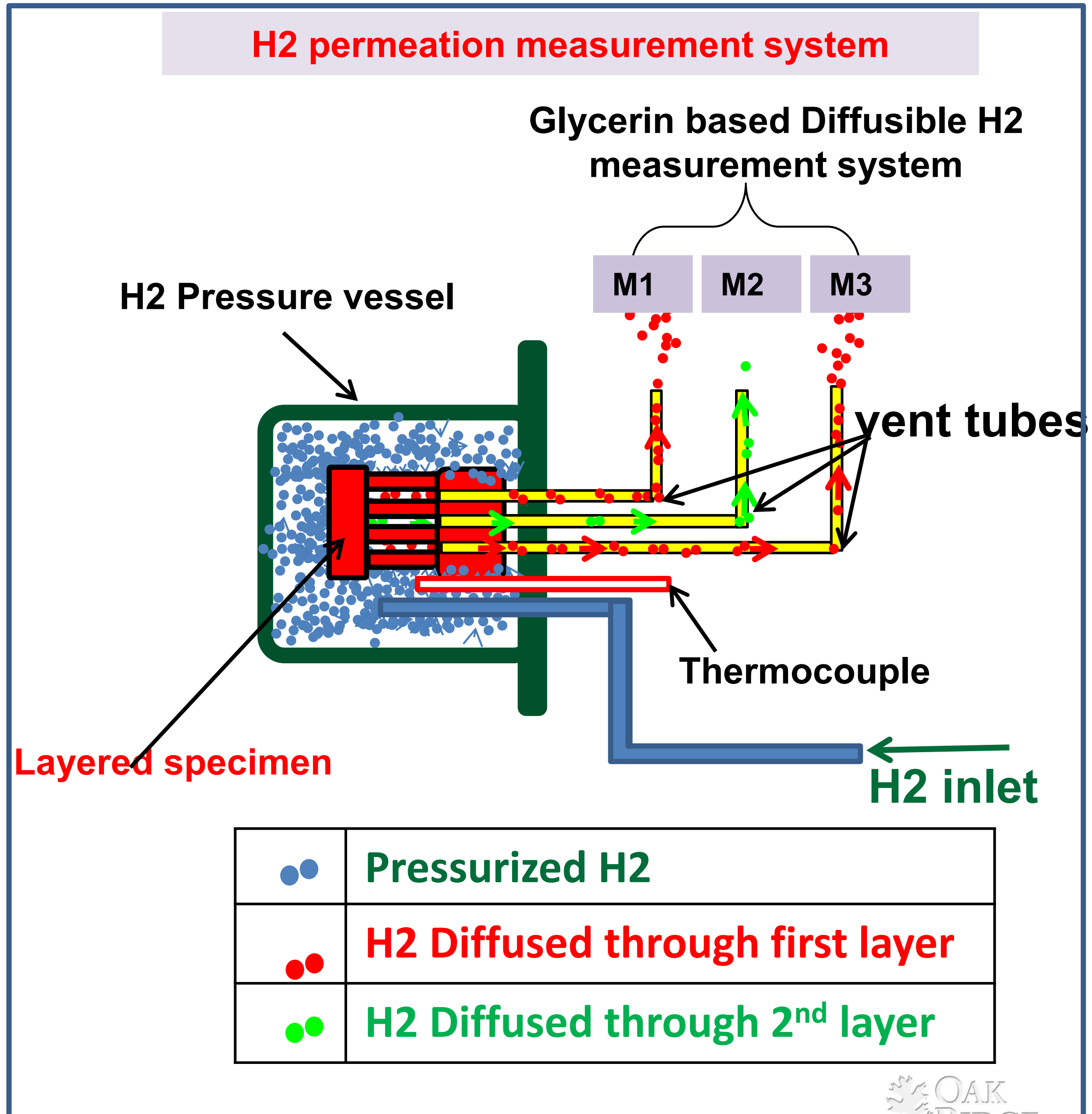
- With little or no hydrogen pressure present for the 2nd and all the outer layers, the damage effect from hydrogen is significantly decreased, and therefore, the service life of the steel vessel is extended.

Approach: Lab Scale H_2 Permeation Experiment

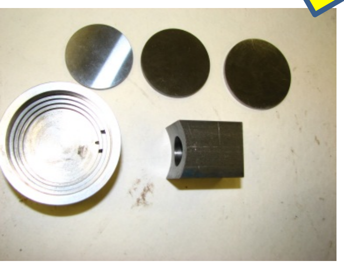


Layered specimen design

- Hydrogen permeation apparatus are designed to demonstrate the effectiveness of the novel hydrogen mitigation technology.
- The specimen has a layered structure and designed to fit into our existing H2 pressure cell.
- The diffusible H2 collected through each layer will provide quantitative measure of the effectiveness of the novel design concept.



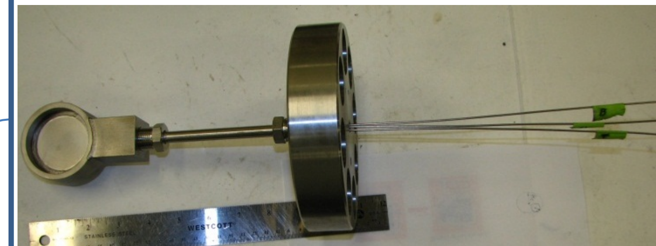
Approach: H_2 Permeation Apparatus

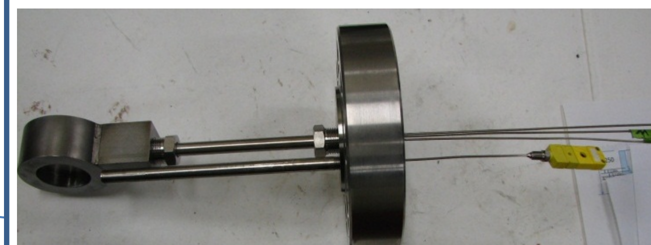


Layered specimen

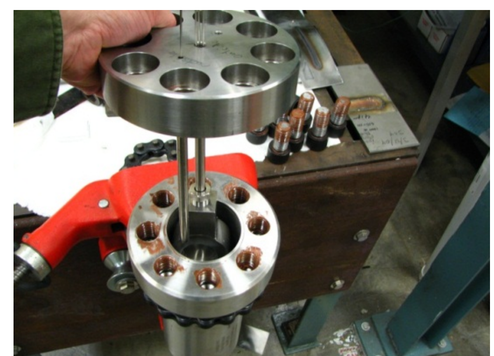
Layered specimen fabrication

specimen assembly





Complete specimen assemble



Specimen installation in to the H2 pressure cell

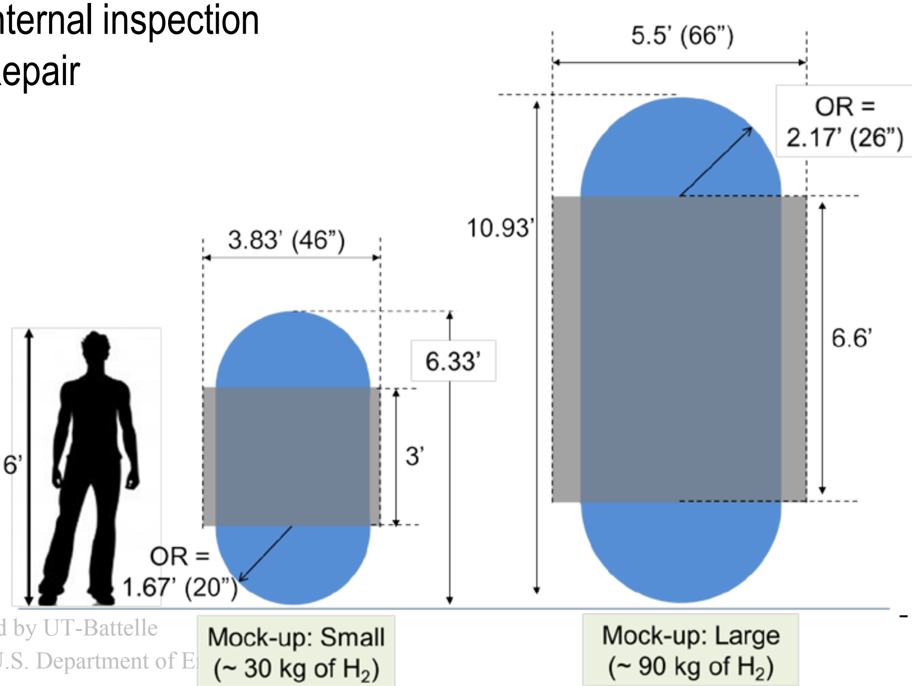
H2 permeation measurement system

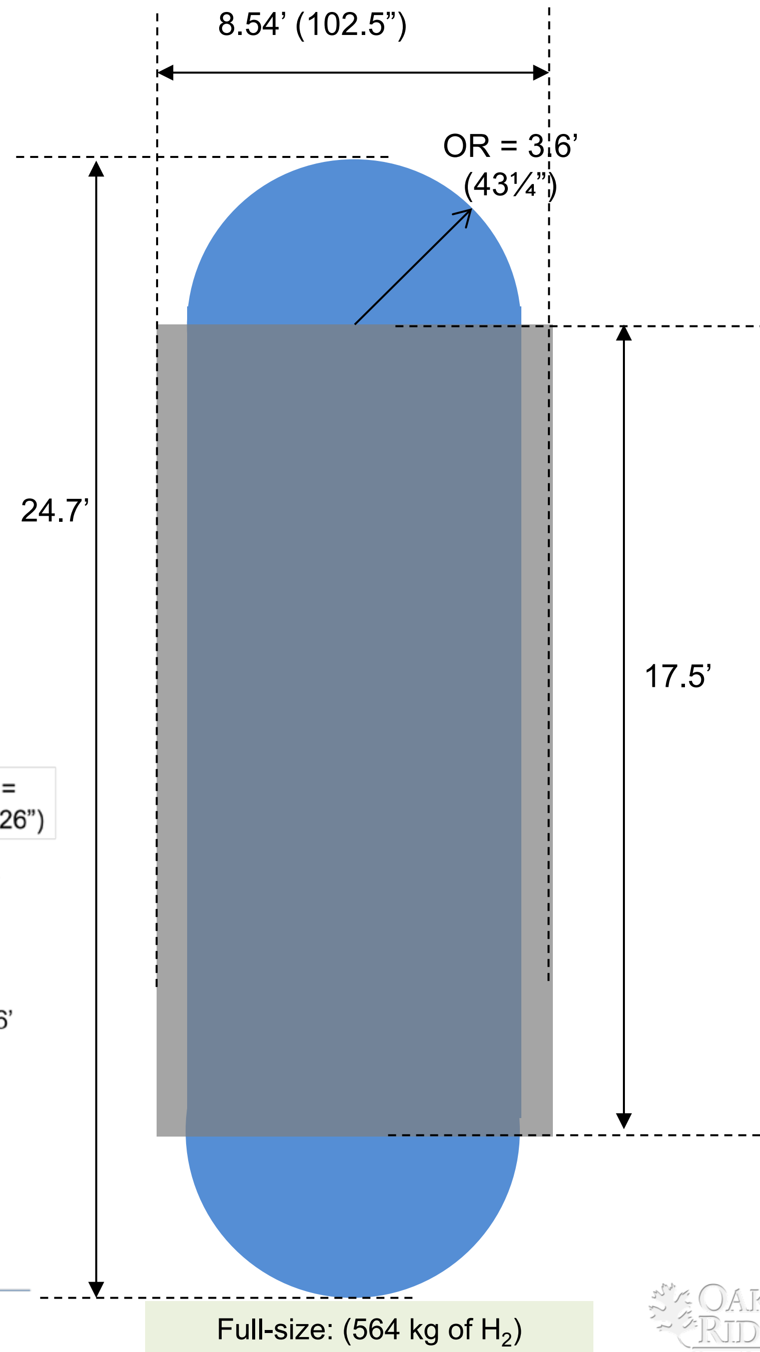
Accomplishment: Hydrogen Mitigation Technology

- We have developed the initial experimental concept to demonstrate the effectiveness of the novel hydrogen mitigation technology to prevent hydrogen entering the structural steel layer
- A layered specimen has been designed and fabricated, and the specimen has passed the initial scoping test.
- Diffusible H2 measurement technique has been selected and will provide quantitative measurement for the proposed technology

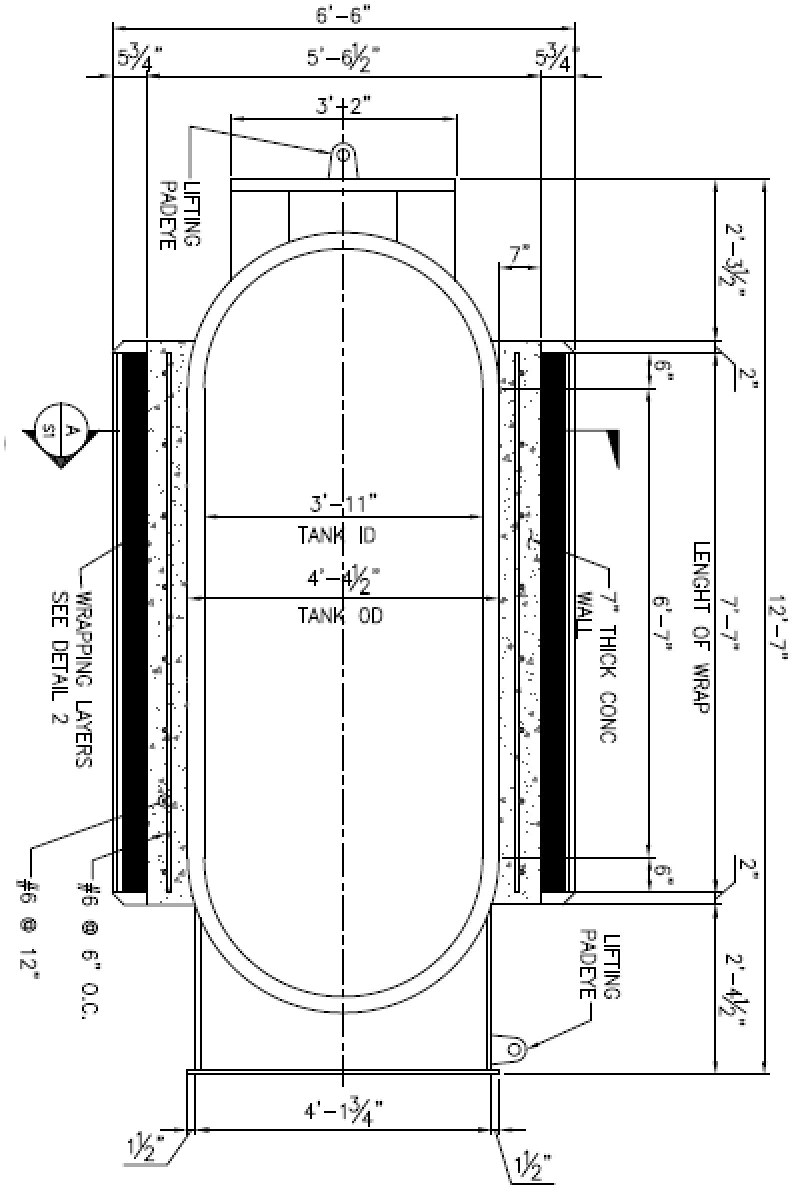
Demonstration: Mock-Up SCCV Design

- 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 real applications
  - Internal inspection
  - Repair

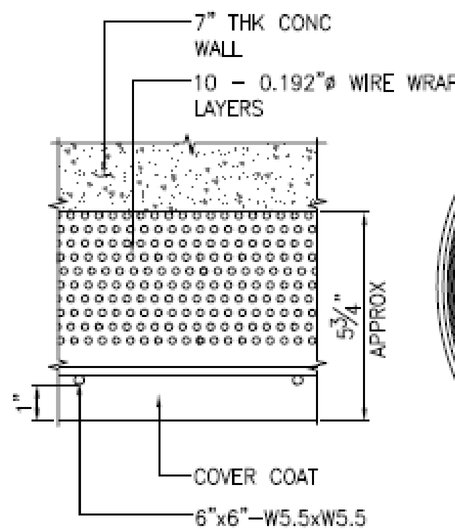


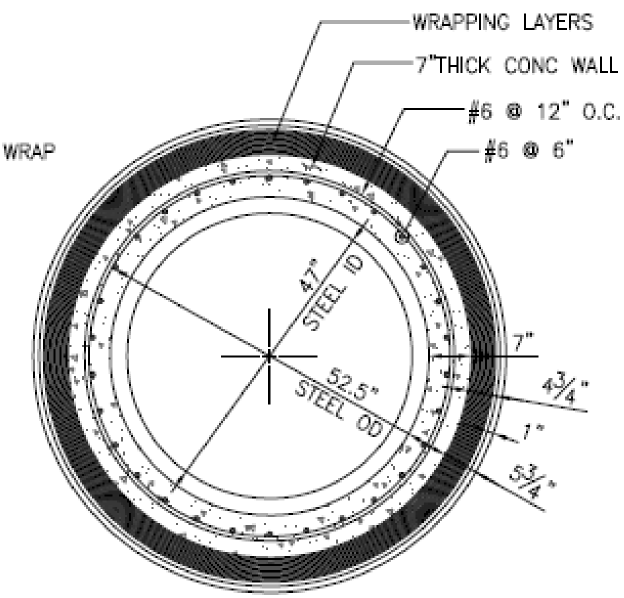


Mock-Up SCCV Demonstration: Design of Composite Vessel



- 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





Mock-Up SCCV Demonstration: Status (March, 2013)

- Vessels with manway are preferred
- Quotes from multiple vendors have been obtained.
- Refinement of mock-up vessel design will be performed to examine the geometry on the manufacturing cost (several iterations may be needed)
- Possible measures to further reduce the mock-up vessel cost will be explored
  - Tank geometry
  - Design pressure
  - Communication with vendors (e.g. shell cladding instead of weld overlay, price negotiation)

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

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) • Mitigation of hydrogen embrittlement to steels • 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 • Friction stir welding technology can potentially further reduce the cost and improve the weld properties • Lab scale experiment test is underway to prove the effectiveness of layer steel structures to manage hydrogen embrittlement in SCCV • Technology demonstration is underway with a ¼ scale mockup SCCV
Collaborations:	Active partnership with industry, university and other stakeholders
Future Plan:	• Complete the final engineering design of mockup SCCV (FY14) • Perform extensive technology validation testing of SCCV under various hydrogen service conditions (FY14/15) • Technology demonstration and transfer (FY15)

Acknowledgements

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- Sara Dillich and Erika Sutherland (DOE)
- David Wood (ORNL)
- James Merritt (U.S. Department of Transportation)
- Louis Hayden (ASME B31.12)
- Hong Wang and Larry Anovitz (ORNL)

Backup slides

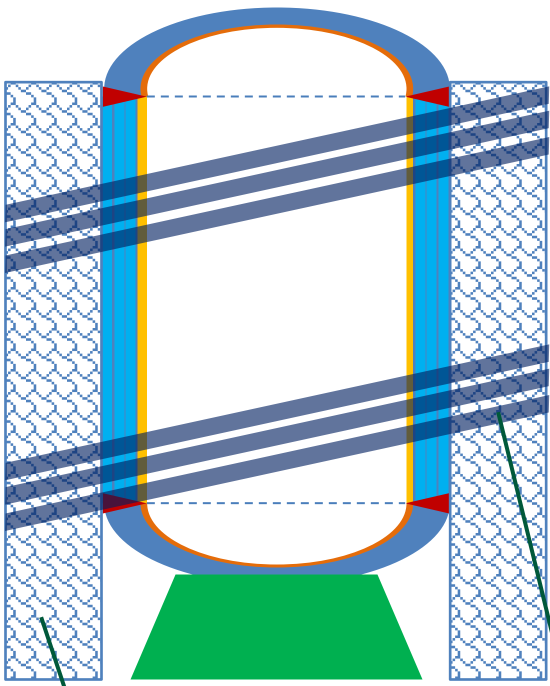
FY2013 Milestones

- 2.1.1 Complete the detailed engineering drawings of a small-scale mock-up composite vessel that is capable of storing hydrogen at 430 bar pressure and obtain vendors' quotes for construction (7/2013)
- 2.1.2 Design and perform a special high-pressure hydrogen permeation experiment, to demonstrate the effectiveness of the multilayer inner tank approach to prevent hydrogen permeating into the structural steel layers to cause hydrogen embrittlement. Achieve 90% reduction of hydrogen permeation through the carbon steel multilayers as compared to conventional thick single layer case, as measured by the amount of hydrogen permeated through the material during the experiment (6/2013).
- 2.1.3 Demonstrate that the tensile strength and ductility of multi-layered friction stir welds for 1.5 inch thick structural steel layers are comparable to those of the base metal, or exceeding those of conventional arc welds (6/2013)
- 2.1.4 Complete the detailed technical report summarizing the mock-up vessel specifications, finite element analysis results, component integrity testing results (9/2013)

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: ○ Data from relevant fabrication projects by Global Engineering and Technology and Ben C. Gerwick, Inc. ○ Vendor quotes

Cost Modeling for Outer Concrete Sleeve



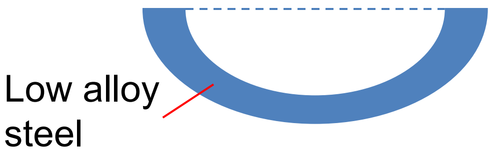
Casting of a concrete core around the steel cylinder

Winding and tensioning of steel tendons

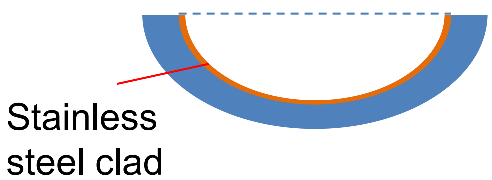
Commercial Production Only (2011 Costs)						
ROM	**Unit**	**Quantity**	**Unit Cost**	**Cost**		**Total**
Concrete (Inc. Labor & Materials)	cy	9	$800	$ 7,200		$ 7,200
Conc. Reinf. (Inc. Labor & Materials)	lb	1,200	$1.80	$ 2,160		$ 2,160
Tank Plate (Inc. Labor & Materials)	lb	127,000	$0.00	$ -		$ -
Prestressing (Inc. Labor & Materials)	lb	35,000	$4.00	$140,000		$ 140,000
Total				$149,360		
Total Purcahse Cost, $						**$ 149,360**

Example of Excel spreadsheet for costing of pre-stressed concrete reinforcement

Cost Modeling of Steel Vessel Head



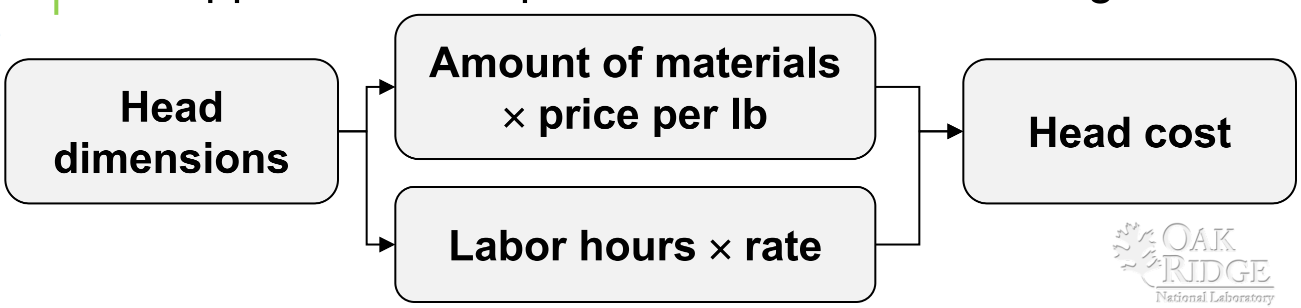
Purchase of two pieces of semispherical heads made of low-alloy steel



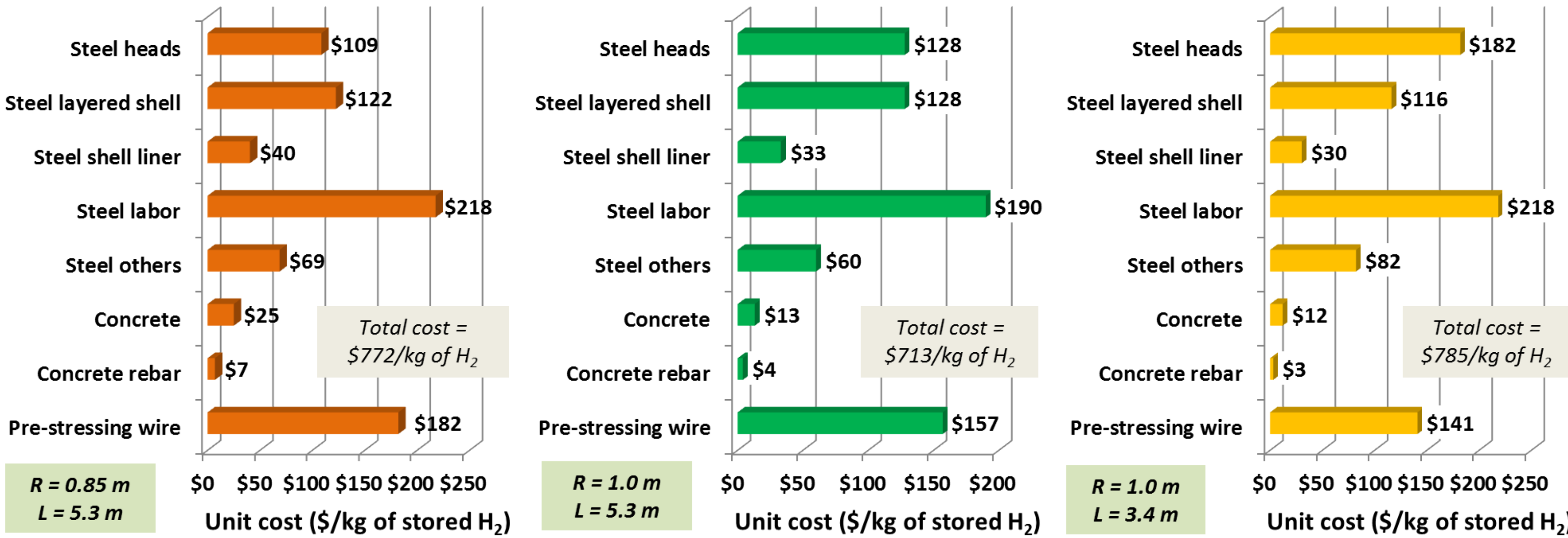
- Weld cladding of austenitic stainless steel layer on the head's inner surface
- Heat-treatment

SA-537 CL2 head				
	Size:	72" ID x 4.25"		
	Weight:	14834		
	Cost:	$29,667	at $2.00 per lb	
Cladding and heat treatment				
Weld overlay strip (3/8") and flux				
	Weight:	424		
	Cost:	$3,469	at $8.18 per lb	
Labor				
	sand blast	4		
	set up	12		
	overlay	9		
	sand blast	4		
		29		
	I,C,T	8		
	H.T.	4		
		37		
	Transport	5		
	Total hrs	42	$100	$4,165
	Freight			$912
TOTAL COST for one head				$ 37,301

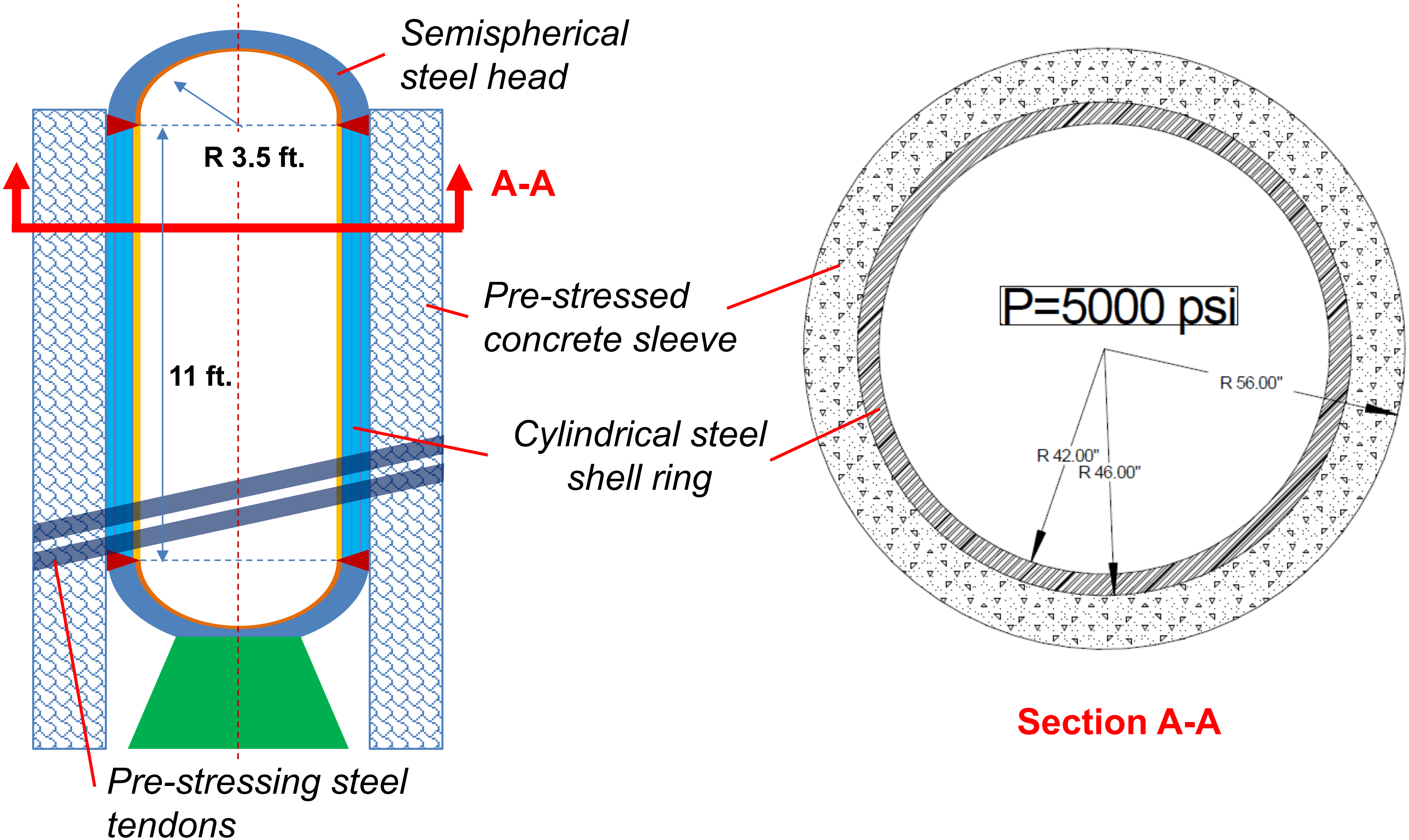
Snippet of Excel spreadsheet for head costing



Effect of Tank Geometry

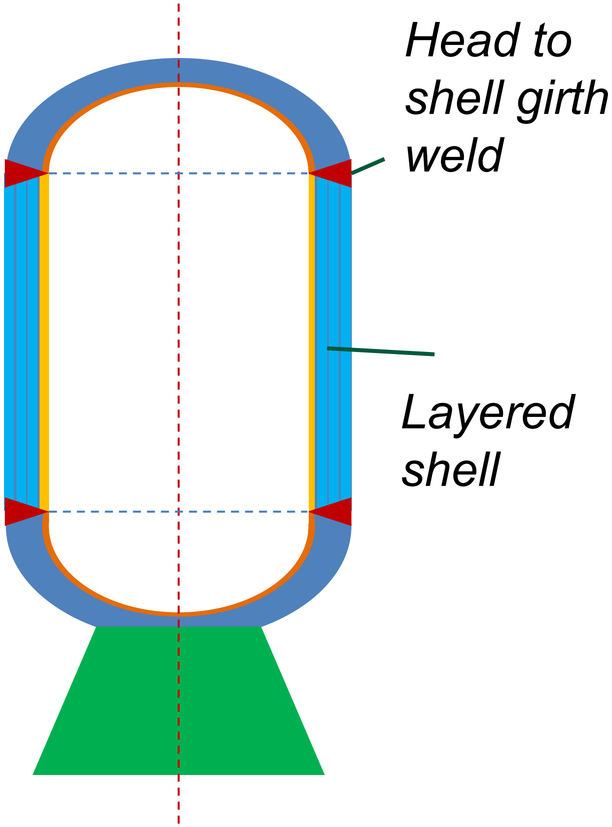


Example: Engineering Calculations for 50% Steel + 50% Concrete Vessel



Baseline vessel design and not optimized for cost

Example: Cost Modeling of Steel Vessel Shell and Other Major Parts



		Bill of Material						
Part	Number	Thickness	Size W	Size L	Material	Weight	Price	Total
Heads	2	4.25+.125	60" ID		SA-537-CL2	30702	$52,730	$105,460
Shell	35	0.3125	96.75	212	SA-724-B	63623	$1.0135	$ 64,481
Tapered PL	1	0.75	36	212	SA-724-B	1623	$0.9535	$1,548
Shell Liner	2	0.5	115	212	304&516-70	7224	$8,810	$18,054
Skirt (2' grd. clr.	1	1.00	60	249	SA-516-70	4237	$1.00	$4,237
Base Ring (pl)	1	1.00	54	69	SA-516-70	1057	$1.00	$1,057
Top Ring (bar)	1	1.00	6	288	SA-516-70	490	$1.40	$686
Gussets	1	0.75	54	54	SA-516-70	620	$1.40	$868
2" noz	2				SA-336-2	576	$4.00	$2,304
Misc. Clips/lugs						600	$1.40	$840
Paint							$250	$150
Fixtures								$500
						110752		$200,186

Machine Heads						21.28
Grind 3:1 Taper 2 heads						7
Plywall Liner stainless clad 1 ring			(46% over standard length)			209
Plywall Shell 1 ring			(46% over standard length)			561
groove final wrap for venting			2' x 2' grid at 10 feet of groove/hou			35
2-2" nozzles (W/O bore)						20
Install 2-2" nozzles						26
Skirt						135
Misc. Clips and Lugs						20
		Subtotal				1034
	Heat Treat heads as sub-assemblies (lugs/nozzles + skir					29
	Sandblast heads on ID after heat treatment					11
	Inspect, Clean, Test			10%		103
	Sandblast and Paint			697	ft2	21
	Load			truck shipment		10
		Subtotal				1208
	Transport			8%		97
				TOTAL HOURS		1305.16

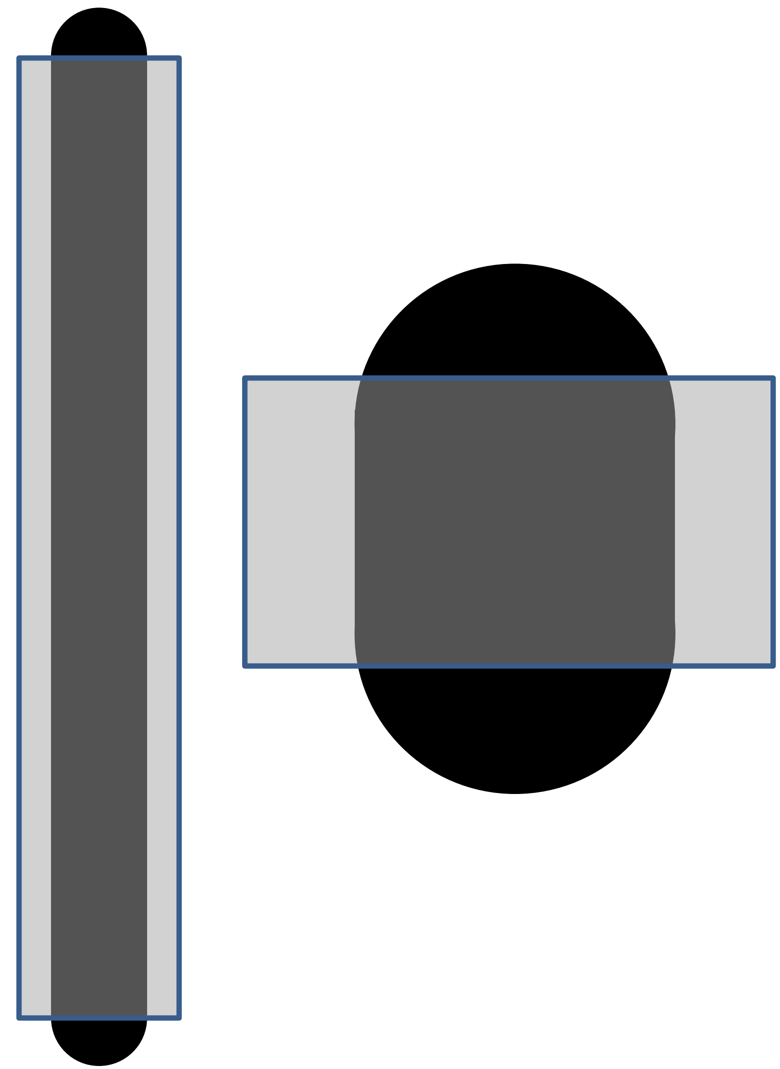
Example of Excel spreadsheet for shell costing

- Fabrication of multi-layered steel ring by repeated wrapping and welding
- Welding of heads to the layered cylinder

Example: Effect of Tank Geometry

- Prestressing cost is proportional to the total length of the wire used, which is proportional to the PCPV outer surface area and the number of layers.

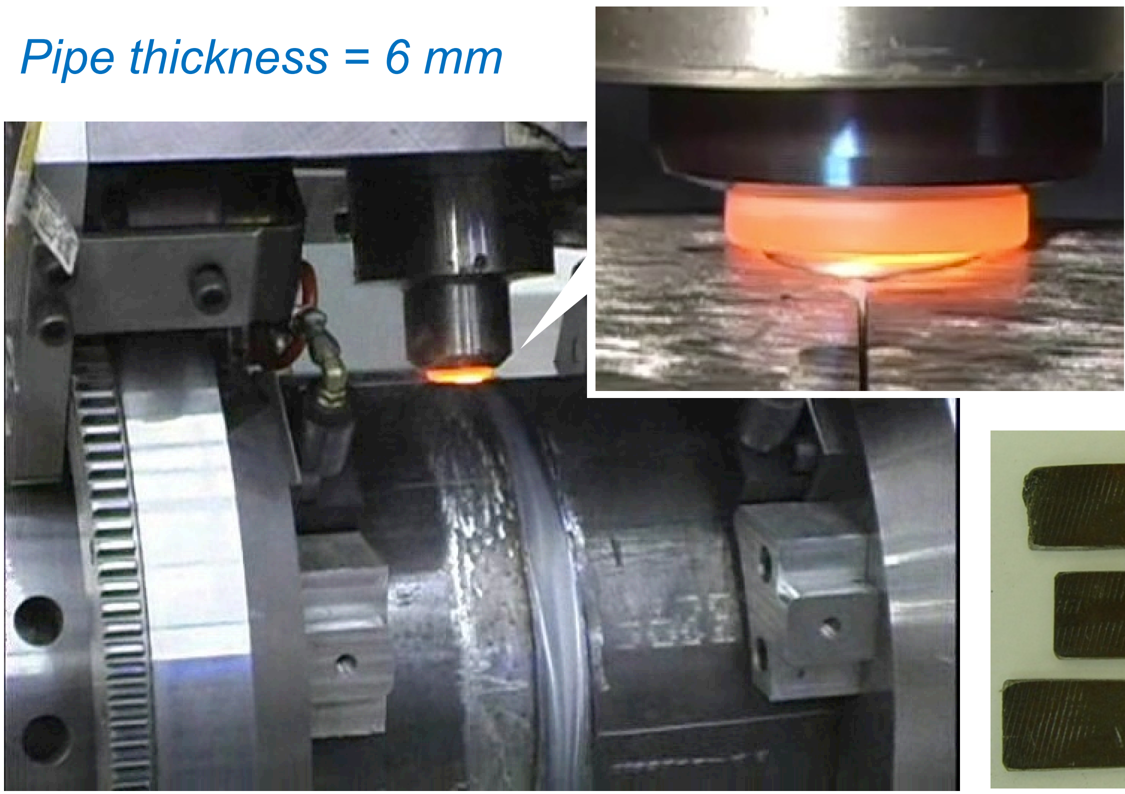
H_2 pressure =160 bar	Tank 1	Tank 2
Height (ft)	55	11
ID (in)	36	84
Steel thickness (in)	3	3
Concrete thickness (in)	8	10
Storage volume (ft^3)	378	314
PCPV cylinder surface area (ft^2)	782	101
Layer of prestressing wire	2	3
Total prestressing wire coverage (ft^2)	1563	303
Prestressing used per unit storage volume (ft^2/ft^3)	**4.1**	**0.96**
Cost of kg H_2 due to prestressing	335	79
Total PCPV cost per kg H_2	456	115

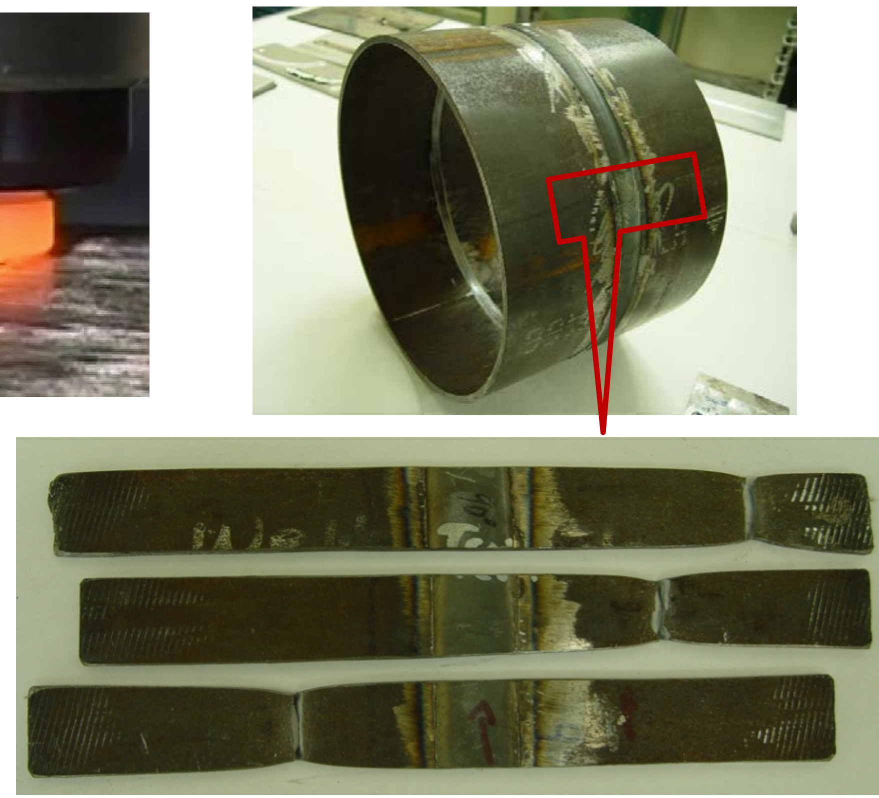


Fabrication Technology for Layered Steel Tank: Friction Stir Welding

- Our previous study* of single-pass friction stir welding (FSW) shows:
  - Highly-automated welding process for reducing labor cost
  - No use of welding consumables (e.g., filler wires)
  - Superior joint strength, low distortion, and low residual stresses

Pipe thickness = 6 mm





** Feng, Z. Steel, R. Packer, S. and David, S.A. "Friction Stir Welding of API Grade 65 Steel Pipes," 2009 ASME PVP Conference, Prague, Czech Republic.*

Mock-Up SCCV Demonstration: Inner Steel Vessel Design