PD088

2012 DOE Hydrogen and Fuel Cells AMR

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

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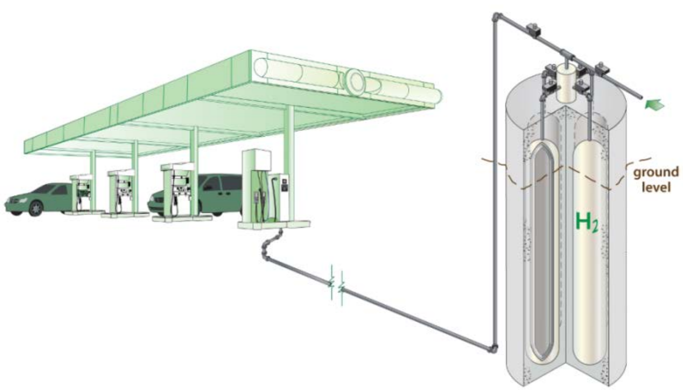

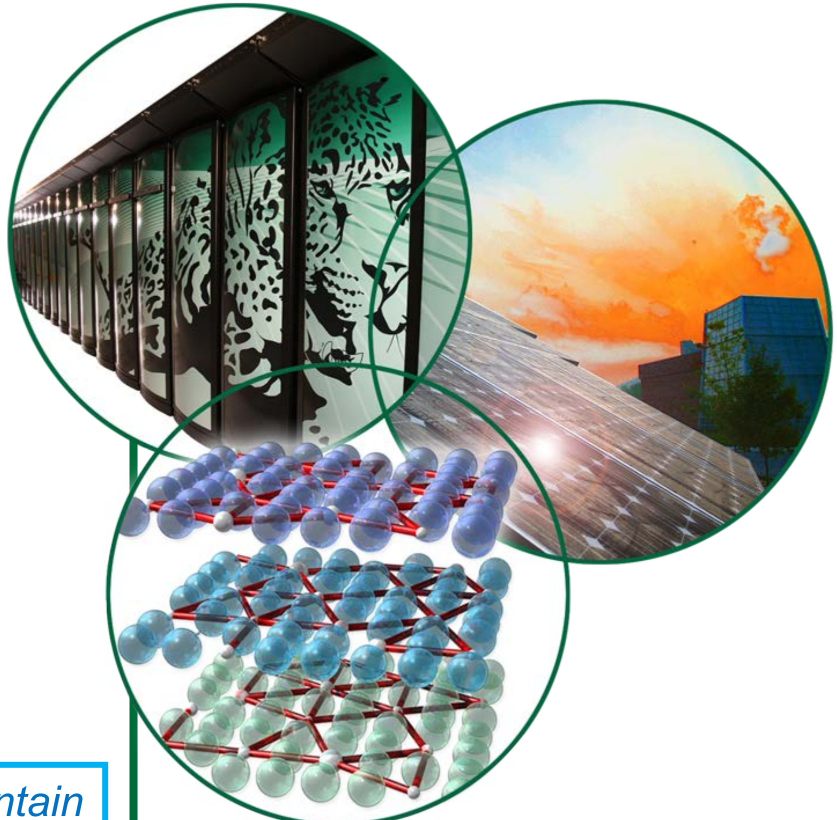

U.S. DEPARTMENT OF ENERGY

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Overview

Timeline

- Project start date: Oct. 2010
- Project end date: Sep. 2014 *
- Percent complete: 30%

** Project continuation and direction determined annually by DOE*

Budget

- Total project funding
  - DOE share: $3,000K
  - Contractor in-kind share: 20%
- Funding received in FY11: $400K
- Funding for FY12: $600K

Barriers

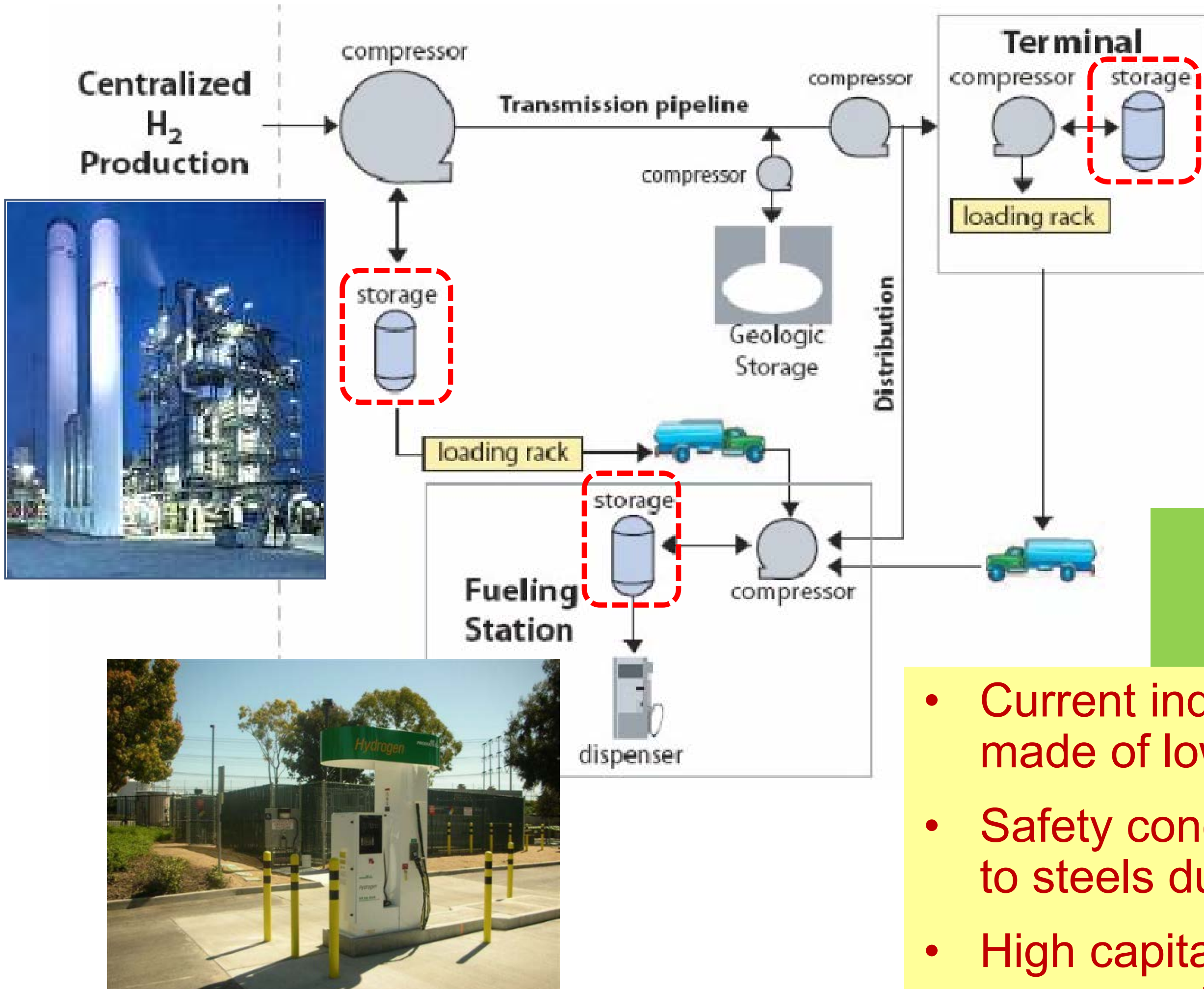
- Barriers addressed
  - **F.** Gaseous hydrogen storage and tube trailer delivery cost
  - **G.** Storage tank materials and costs

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
  - ORNL (Oak Ridge National Laboratory)

*** Additional details on Slide 19*

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*

Relevance - Project Objective

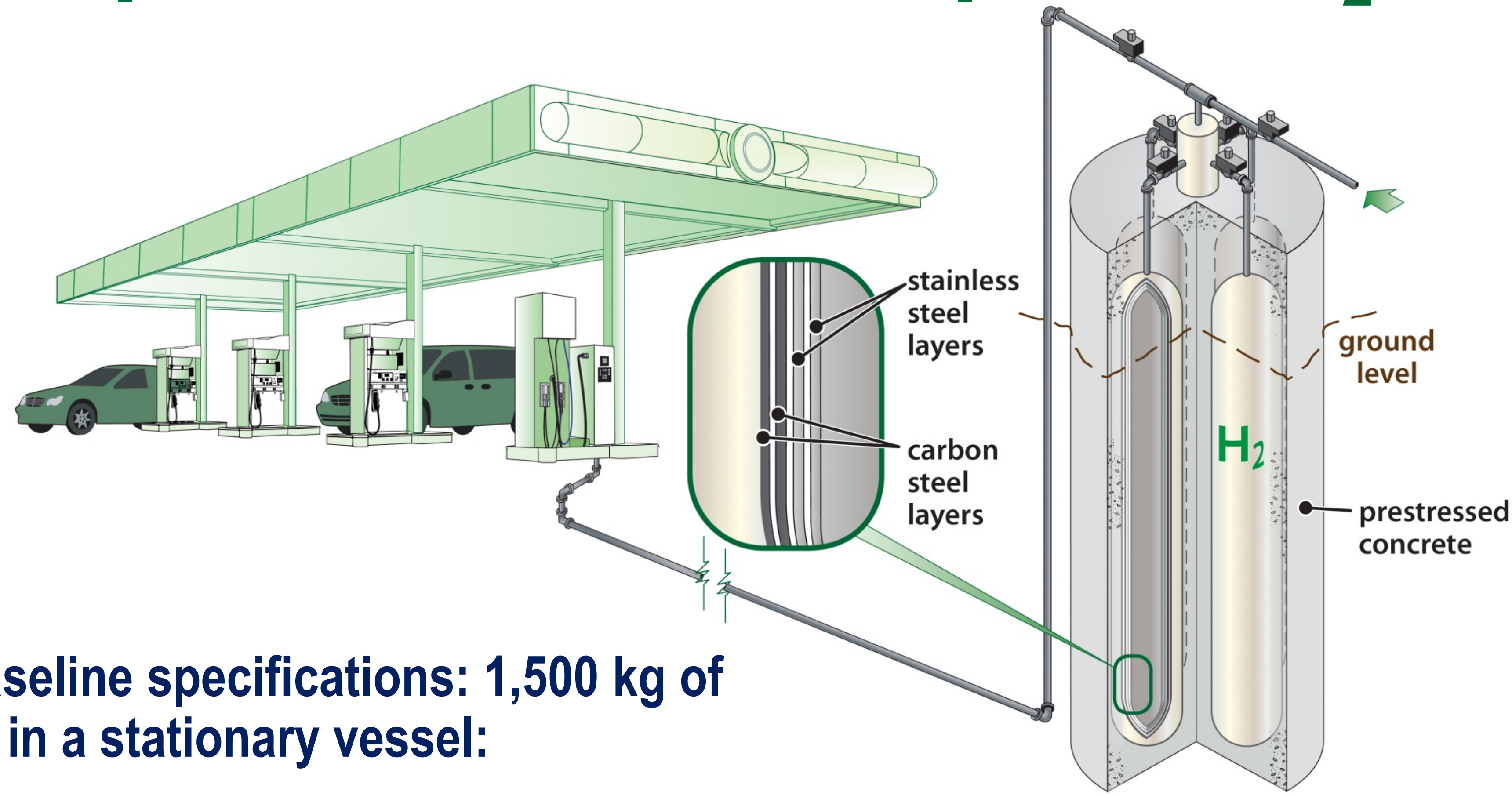
- Address the significant **safety** and **cost** challenges of the current industry standard steel pressure vessel technology
- Develop and demonstrate the composite vessel design and fabrication technology for stationary storage system of high-pressure hydrogen

Table 3.2.3 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

** 2011 DOE technical targets currently being finalized*

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

Composite Vessel for Compressed H_2



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

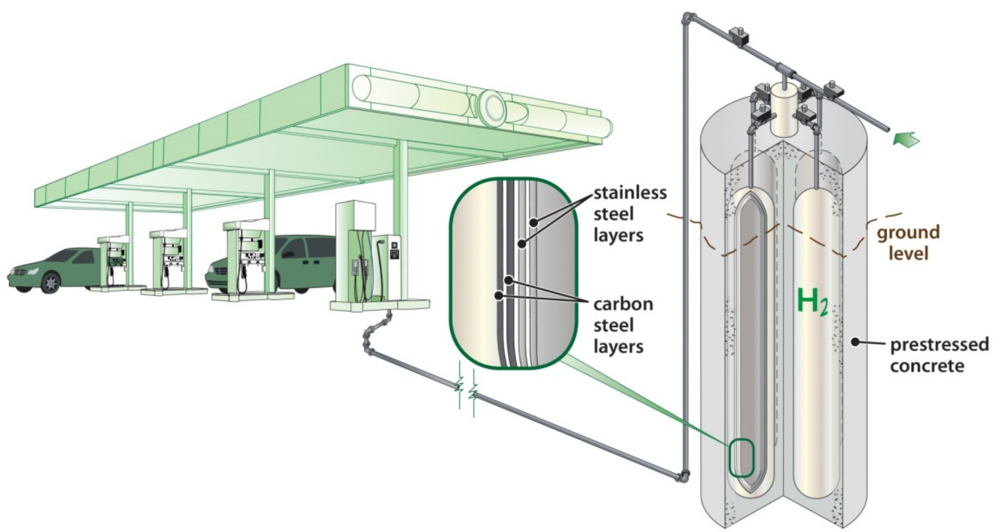
- Refill 260 passenger cars (*based on 5.6 kg H_2 tank per car*)
- Interior volume = 2,300 ft^3 (65.1 m^3) @ 5,000 psi (345 bar) & room temperature

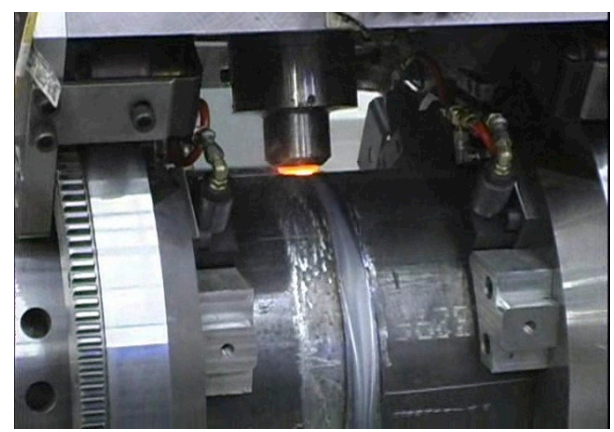
Flexibility in vessel design:

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

Overview of 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





Approach - Selection of Materials driven by Safety, Performance and Cost

Commodity structural materials

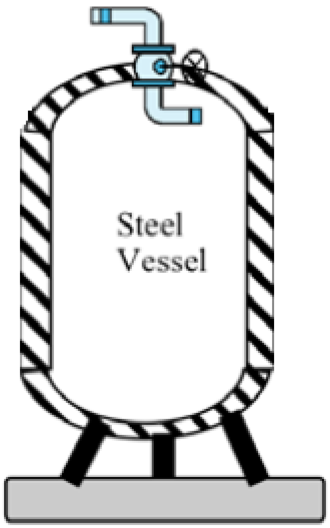
- Cost *:
  - Low-alloy carbon steel: $1.20 per lb.
  - Austenitic stainless steel: $4.00 per lb.
  - Concrete: $0.08 per lb.

** Note: Actual cost depending on the amount of materials used and the manufacturing cost*

- 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

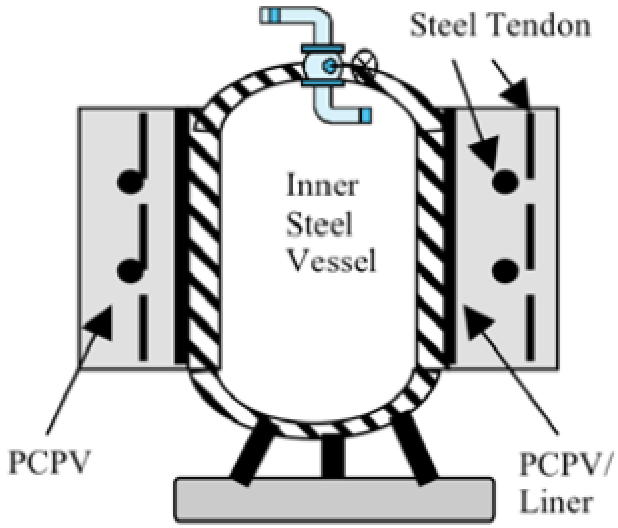
Approach - Baseline Designs with Varying Usage of Steels and Concretes

Increasing usage of concrete (cheaper than steel) for carrying pressure loads



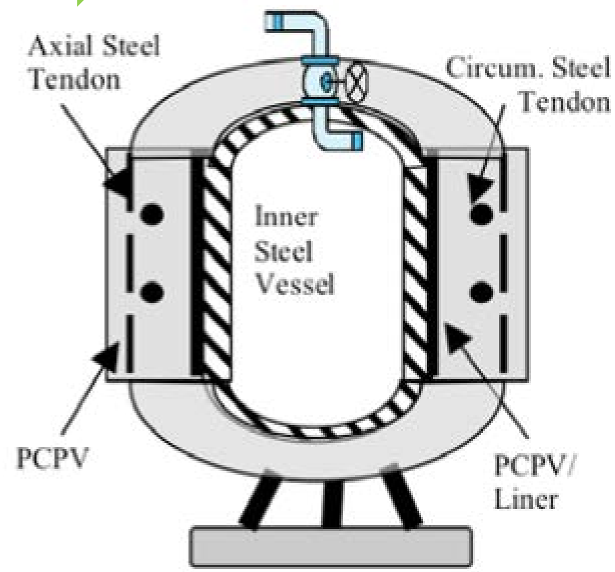
Case 1: Steel only

Current industry status



Case 2: 50% Steel + 50% Concrete

Pre-stressed concrete sleeve carrying 50% of hoop stress



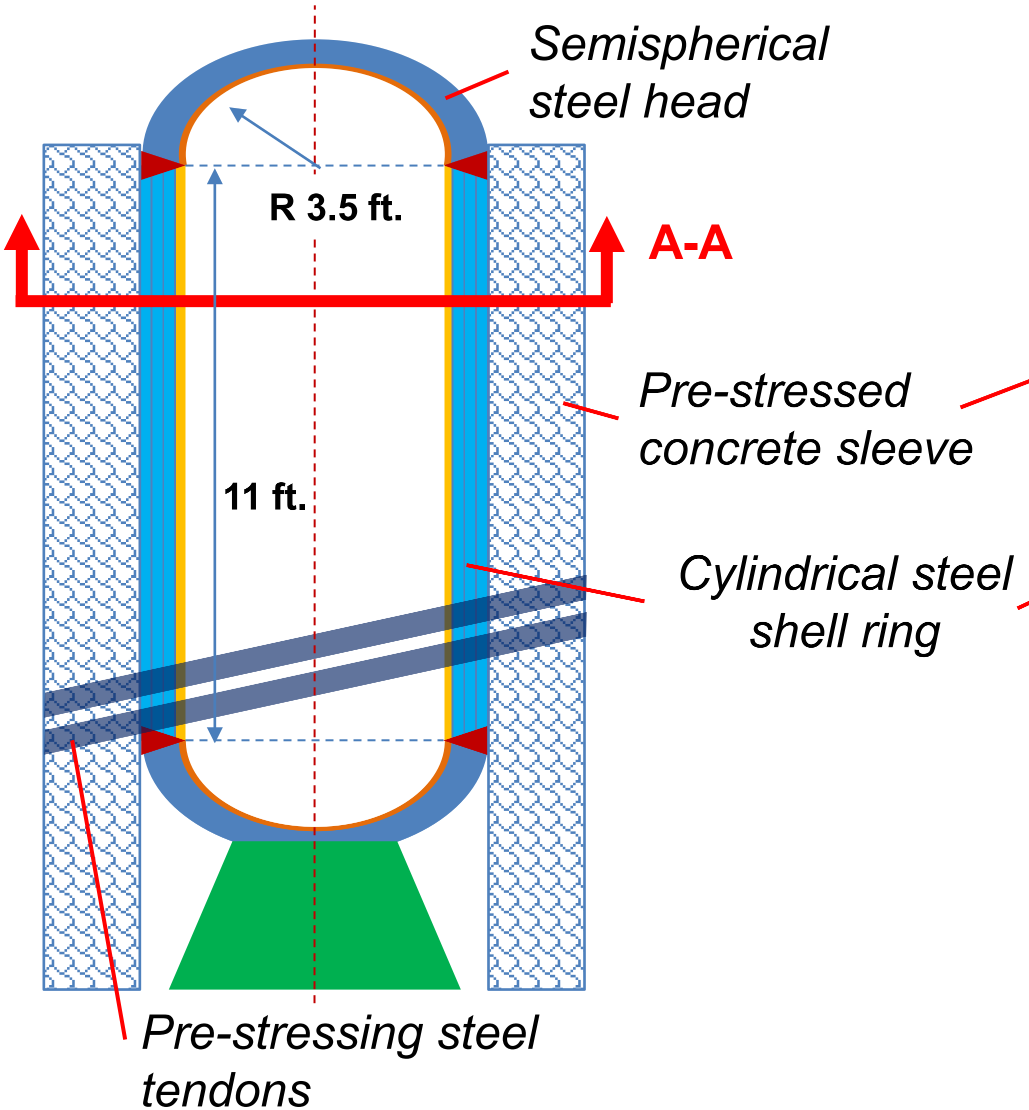
Case 3: Concrete and Steel “Liner”

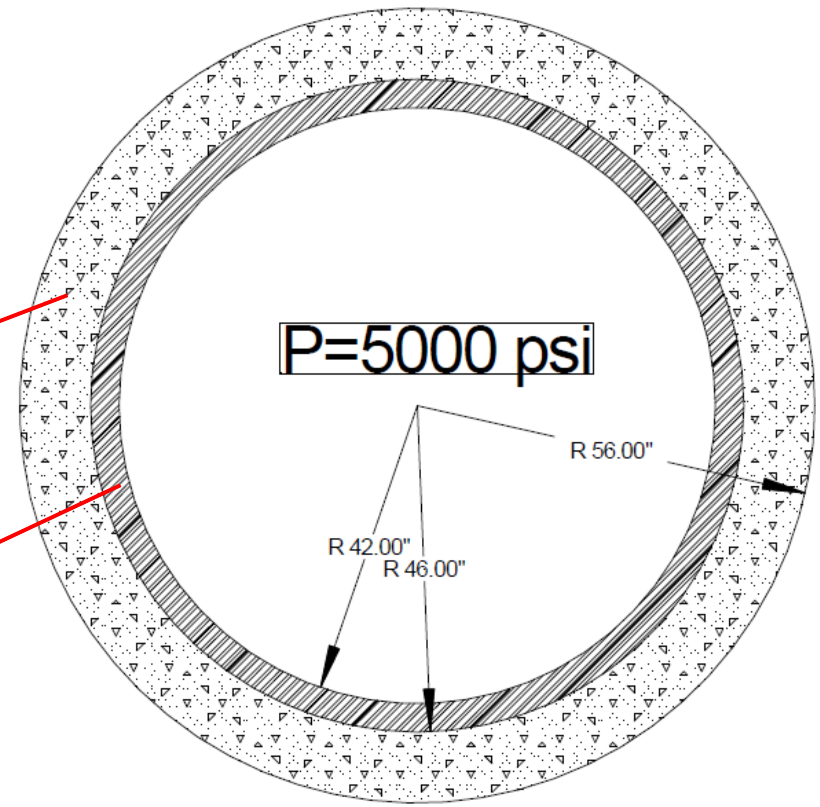
Pre-stressed concrete enclosure carrying 70% of hoop and axial stresses while steel liner carries 30% of the loads

Approach - Cost 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

Accomplishments - Engineering Calculations for 50% Steel + 50% Concrete Vessel

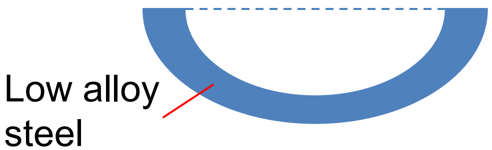




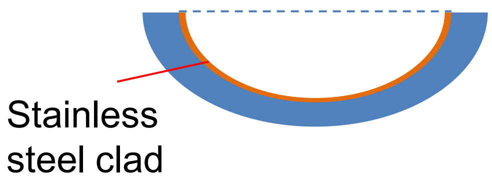
Section A-A

Baseline vessel design and not optimized for cost

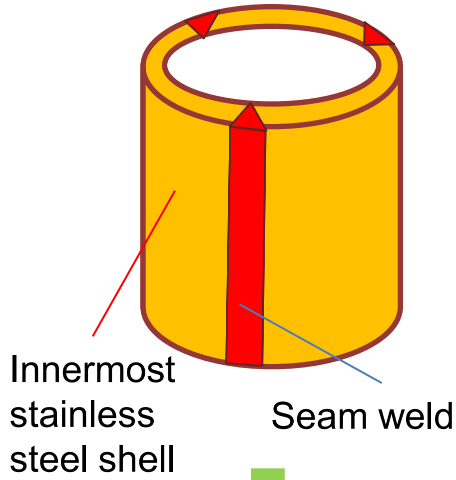
Accomplishments - Major Manufacturing Process Flow for Inner Steel Vessel

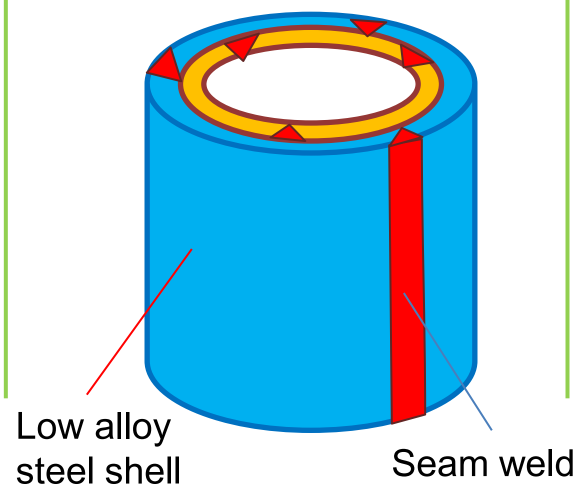


Purchase of two pieces of semispherical heads made of low-alloy steel

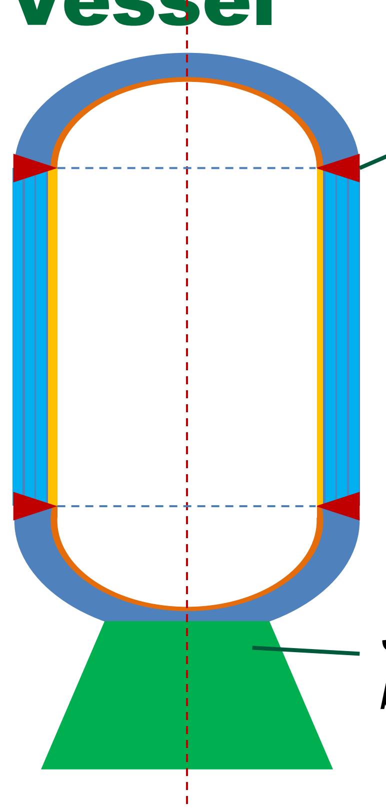


- Weld cladding of austenitic stainless steel layer on the head's inner surface
- Heat-treatment



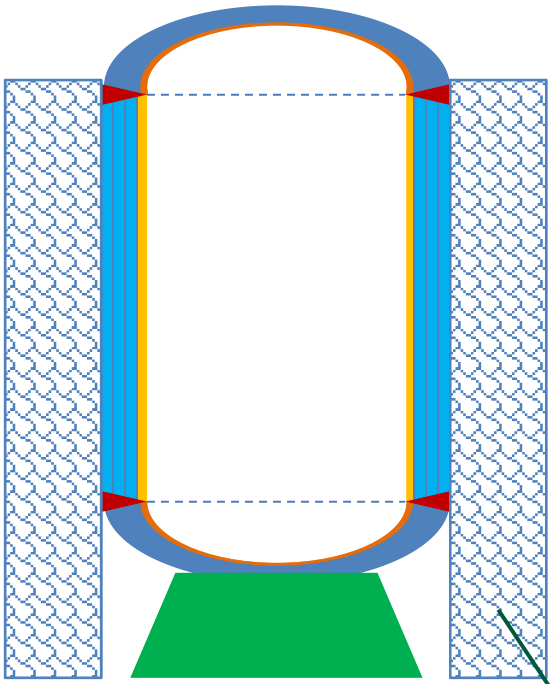


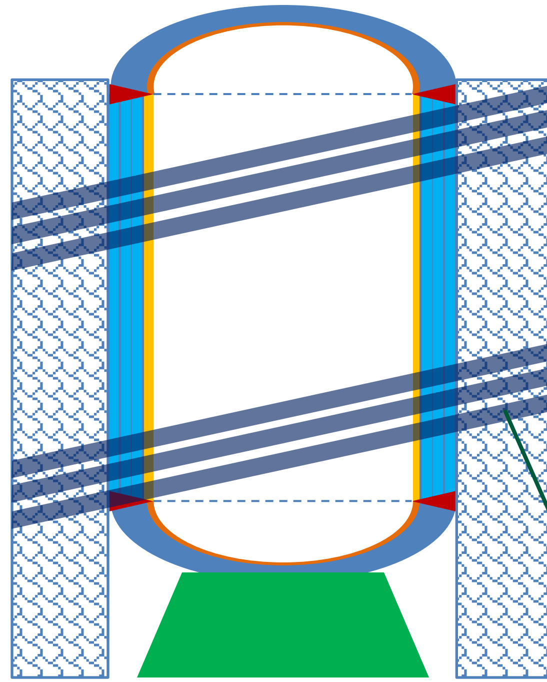
Fabrication of multi-layered steel ring by repeated wrapping and welding

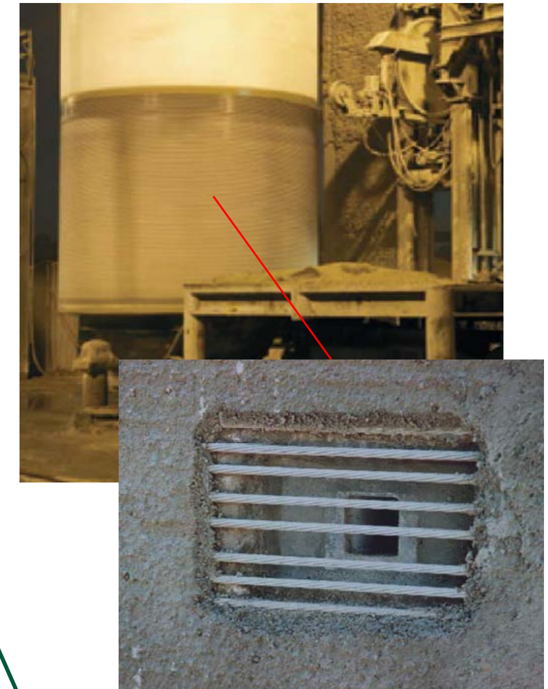


- Welding of heads to the layered cylinder
- Welding of skirt and base ring the lower head

Accomplishments - Manufacturing Process Flow for Outer Concrete Sleeve





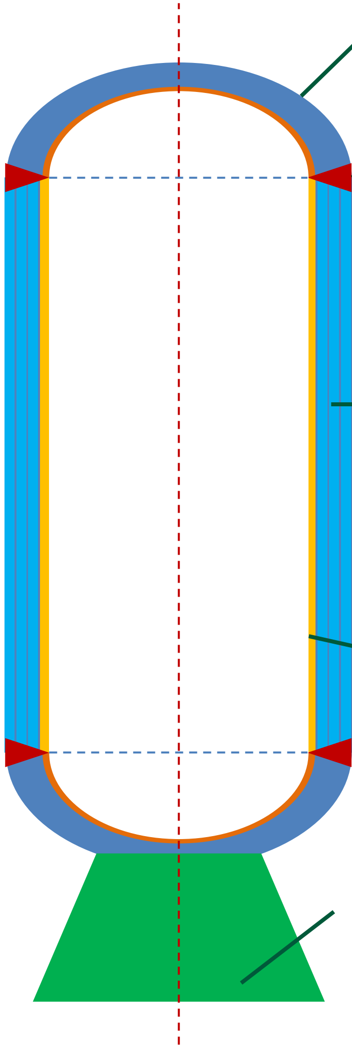


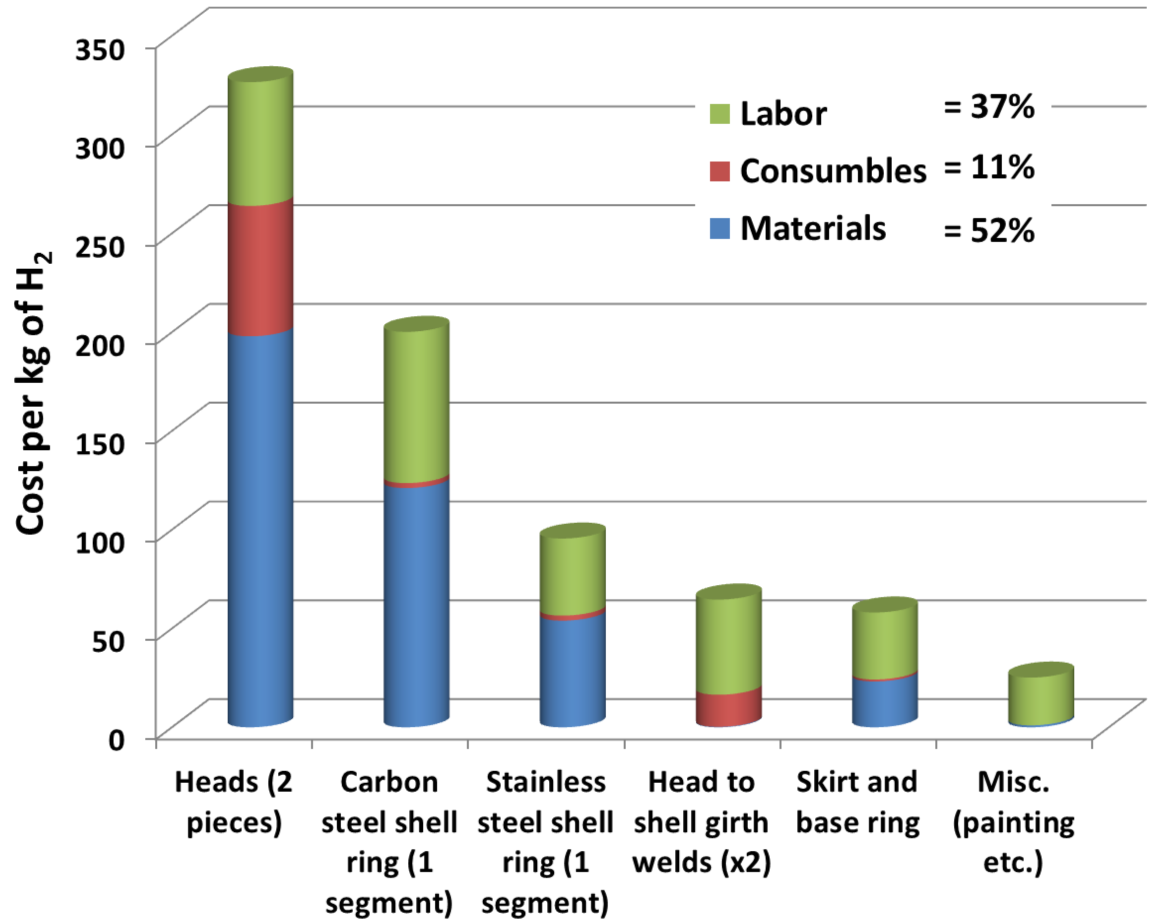
Winding and tensioning of steel tendons

Casting of a concrete core around the steel cylinder

Shotcrete application for corrosion prevention

Accomplishments - Estimated Cost for Inner Steel Tank

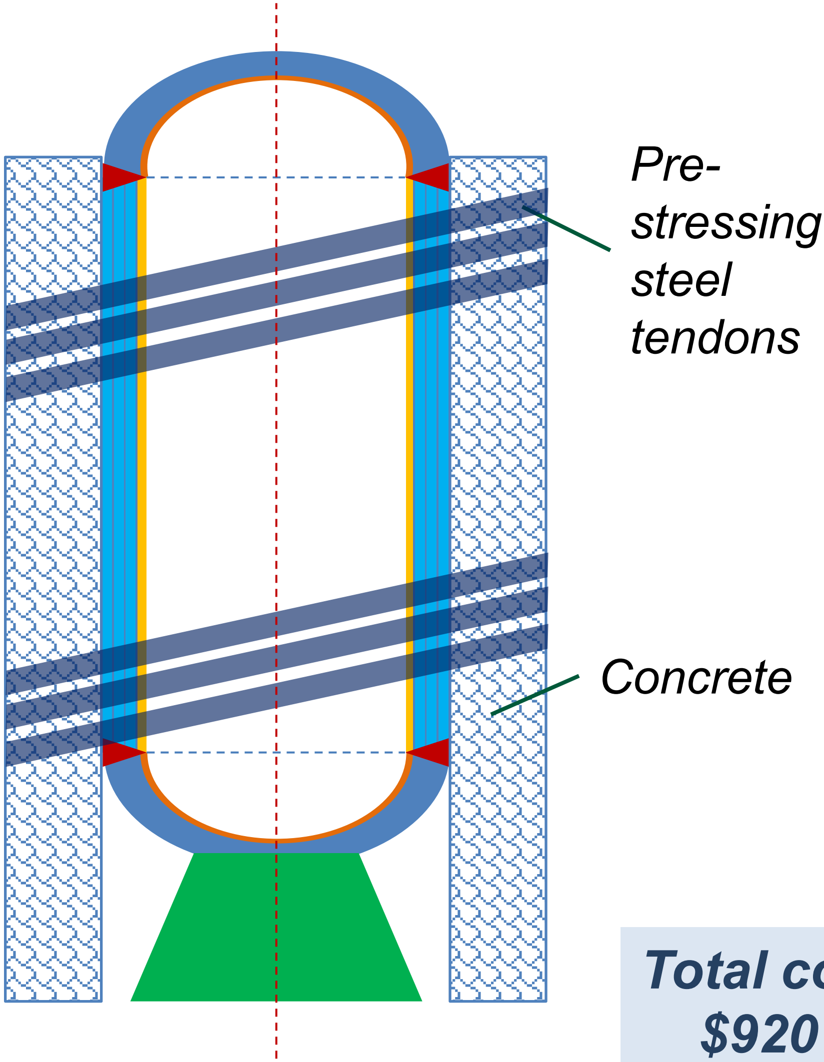


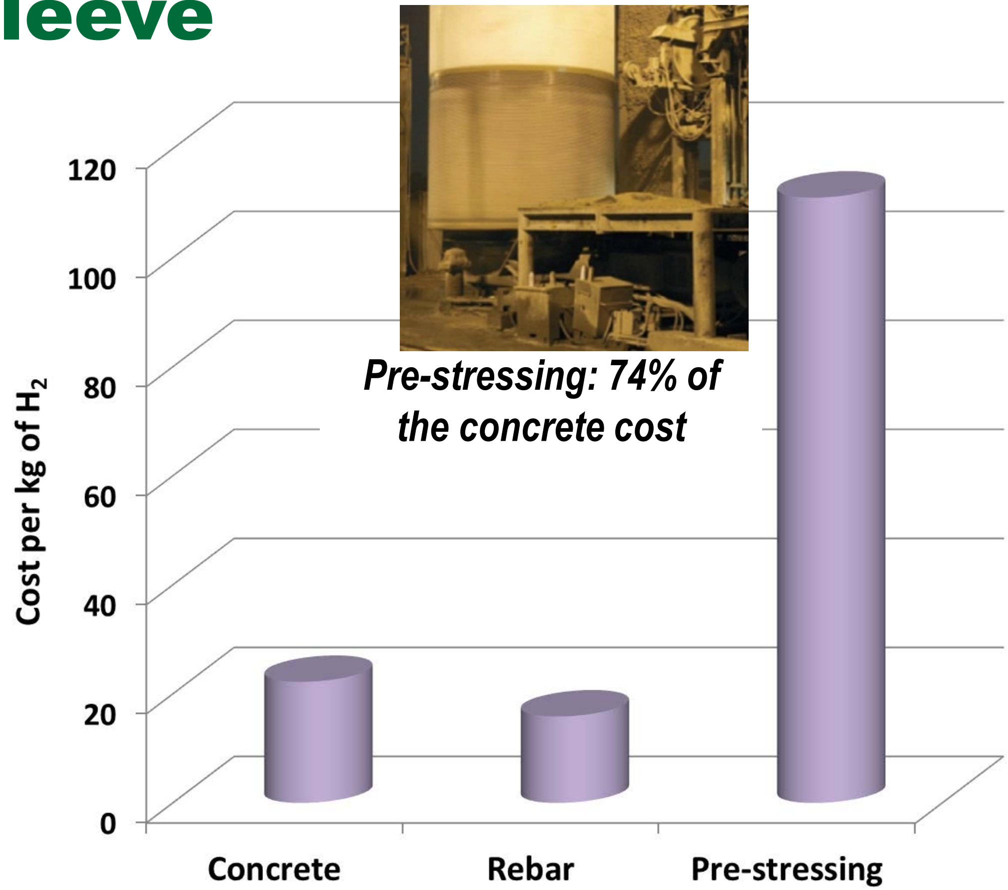


- *Consumables including welding filler wires and shielding gases, etc.*
- *Assumed labor rate: $75 per hour*

Baseline vessel design and not optimized for cost

Accomplishments - Estimated Cost for Pre-stressed Concrete Sleeve

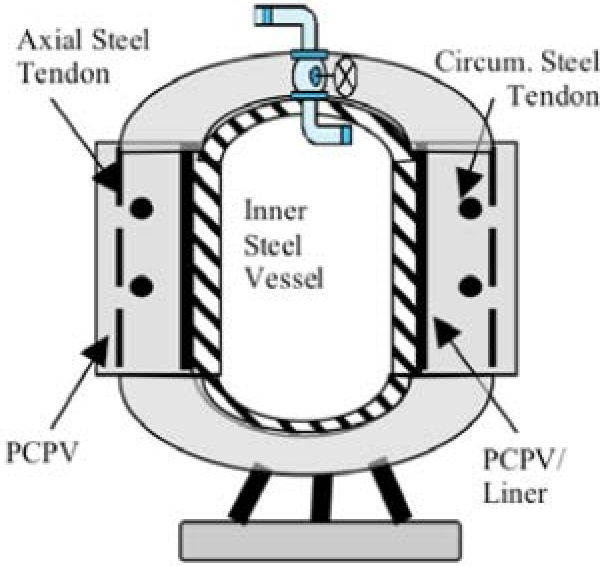




Total cost of baseline 50% + 50% vessel: $920 per kg of H_2 at 5,000 psi

Baseline vessel design and not optimized for cost

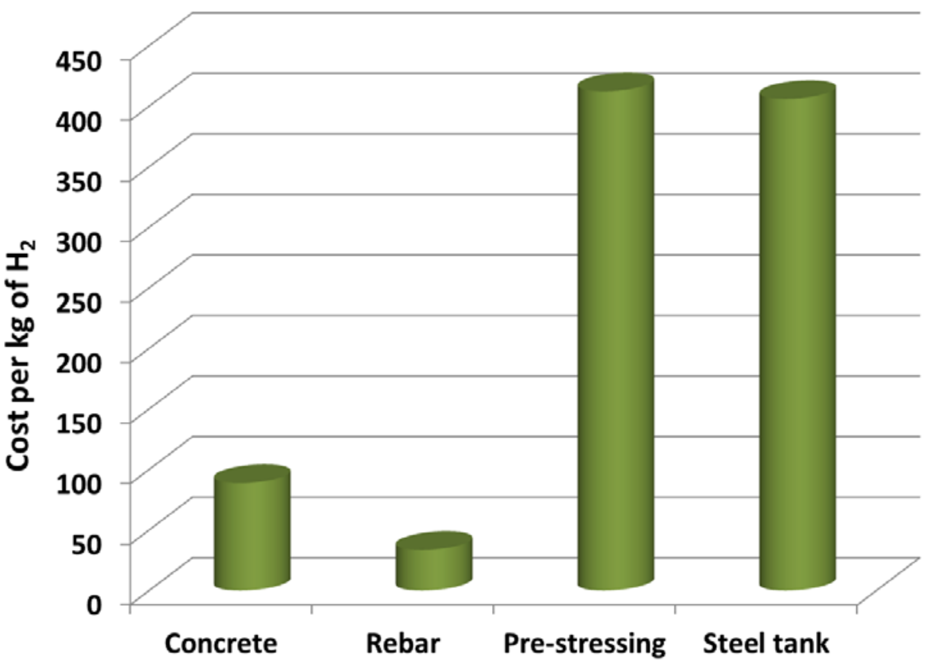
Accomplishments - Cost Assessment for Concrete and Steel Liner Composite Vessel



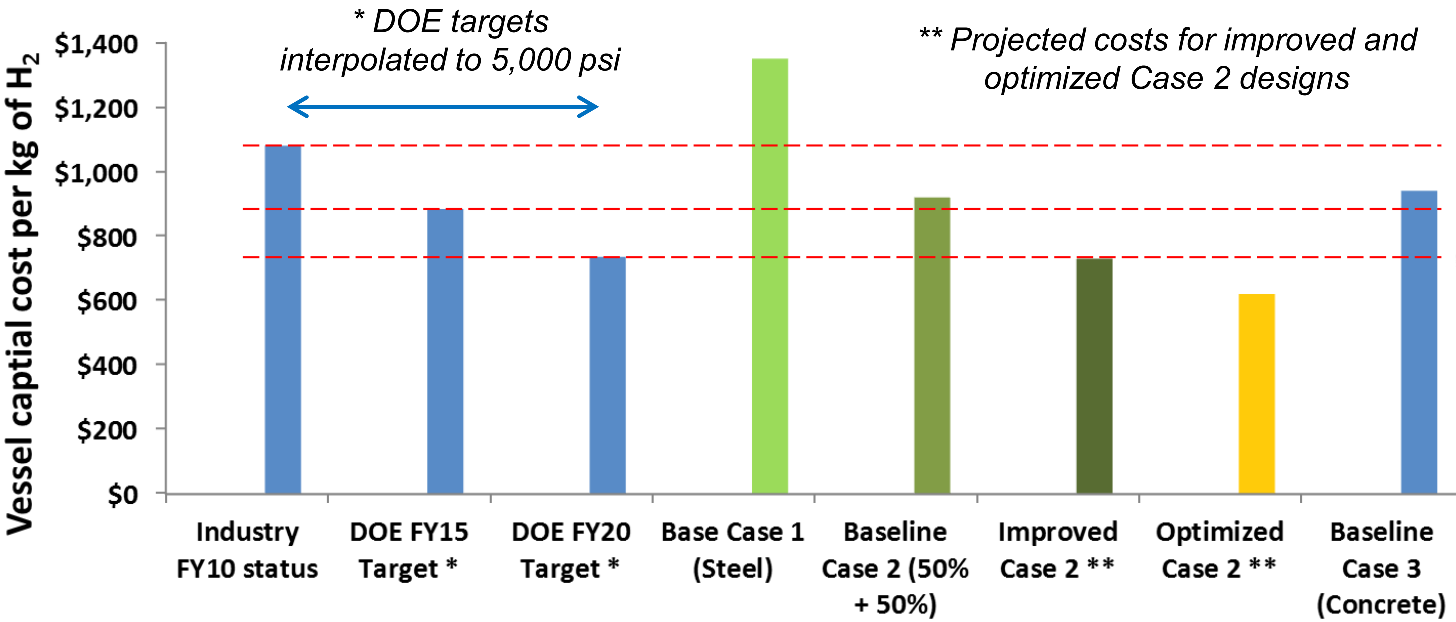
Case 3: Concrete and Steel "Liner"

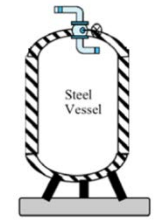
Pre-stressed concrete enclosure carrying 70% of hoop and axial stress while steel liner carries 30% of the loads

- Composite design making the most "aggressive" use of concrete.
- To avoid buckling during concrete pre-stressing, the steel liner has to have a minimal wall thickness.
- Preliminary cost estimate: \$940 / kg of H_2

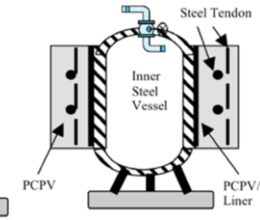


Accomplishments - Preliminary Cost Assessment for Various Composite Vessels

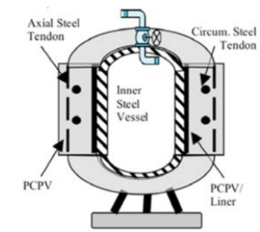




Case 1: Steel only

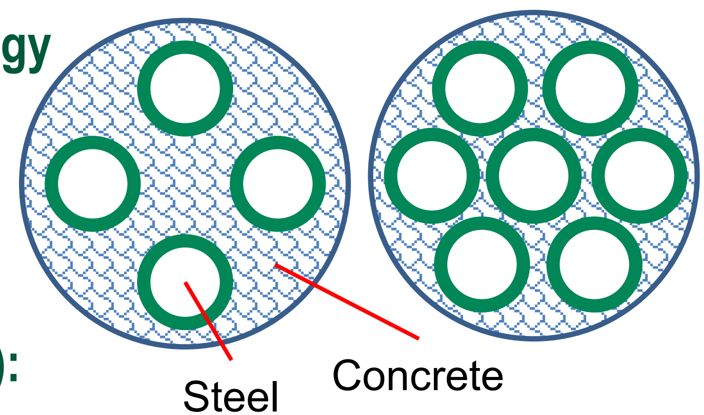


Case 2: 50% Steel + 50% Concrete



Case 3: Concrete and Steel "Liner"

- **Improved design (achievable with no or little technology development):**
  - Smaller diameter & thinner wall for reducing steel usage
  - Optimal use and fabrication of stainless steel liner
  - Layout of steel tanks vs. concrete enclosure
- **Optimized design (requiring technology development):**
  - Automated friction stir welding based vessel fabrication
  - Pre-stressing of steel tendons



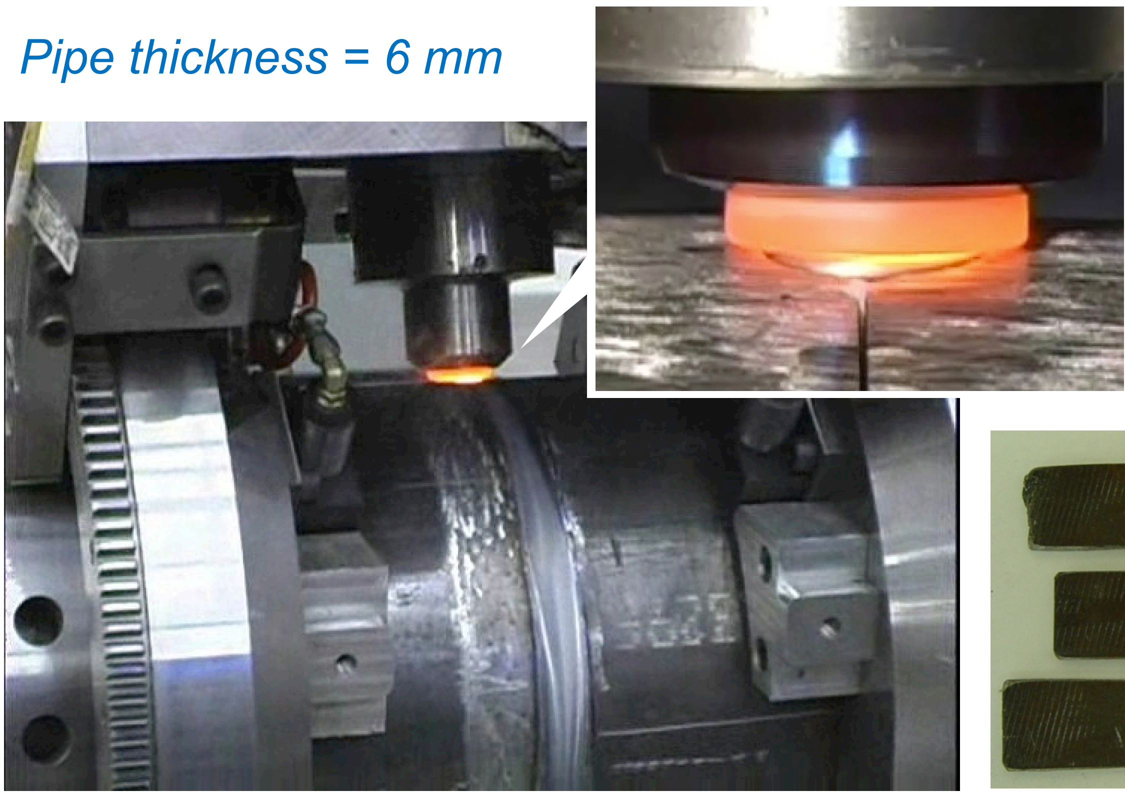
Diamond layout

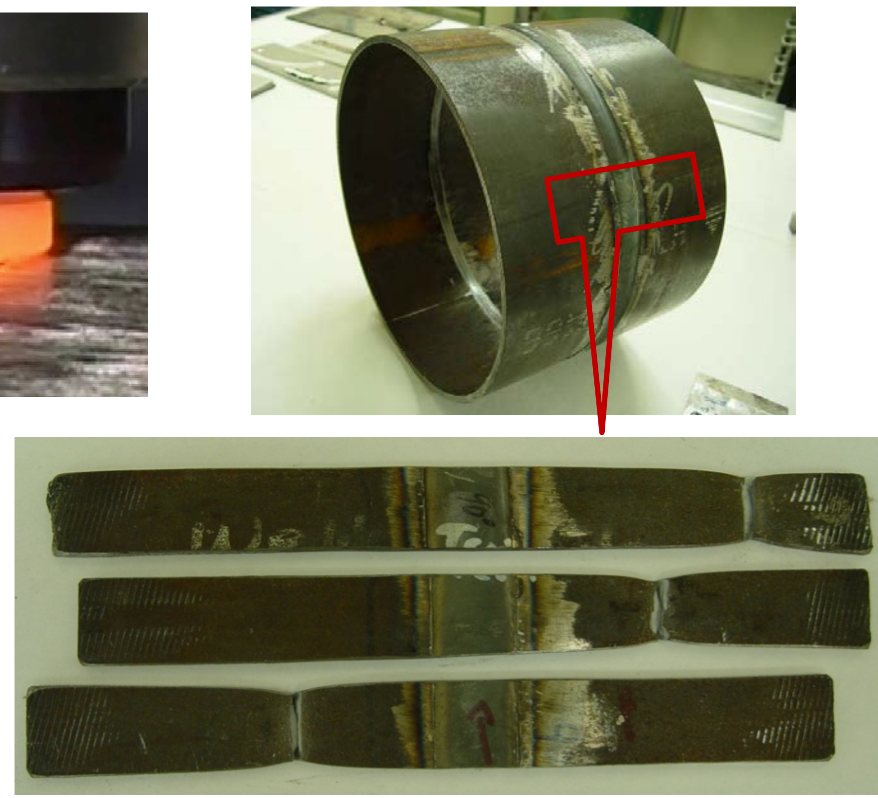
Hexagonal layout

Accomplishments - Fabrication Technology for Layered Steel Tank

- **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

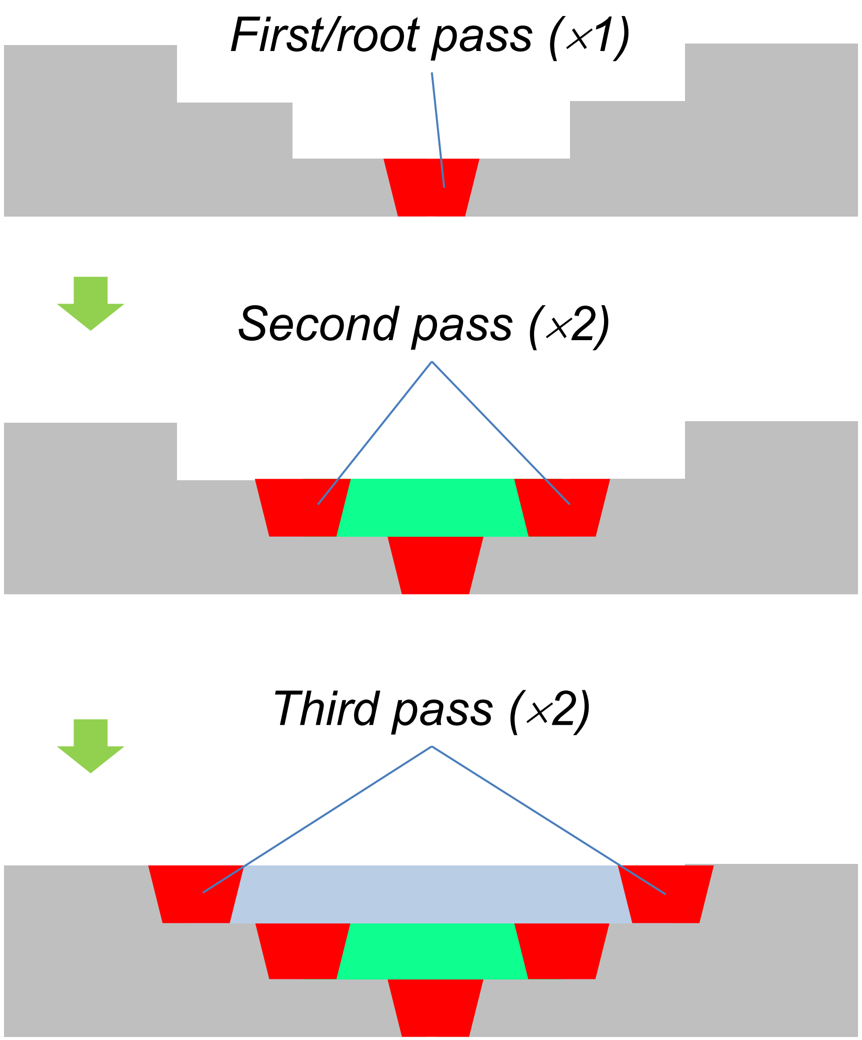
Pipe thickness = 6 mm

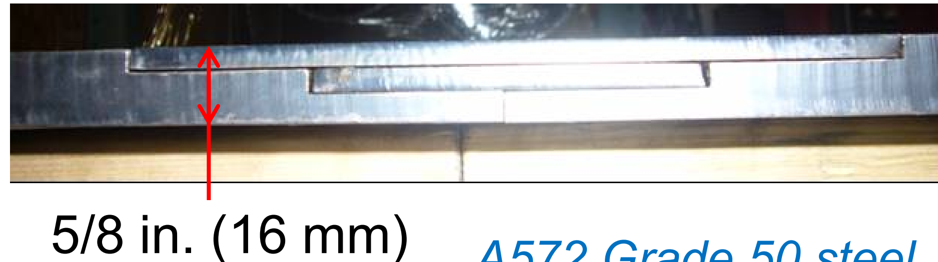




* Feng, Z. Steel, R. Packer, S. and David, S.A. "Friction Stir Welding of API Grade 65 Steel Pipes," 2009 ASME PVP Conference, Prague, Czech Republic.

Accomplishments - Multi-Layer, Multi-Pass Friction Stir Welding of Thick Steel Section





A572 Grade 50 steel

Typical weld transverse section showing a high-quality joint

Scale-up of friction stir welding for joining of thick-wall steel structures

Collaborations

Partners / Interactions	Extent of collaboration
• Global Engineering and Technology	Design and cost estimate of steel tanks
• Ben C. Gerwick, Inc.	Design and cost estimate of 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)	Hydrogen embrittlement to structural steels
• DOT	Qualification of stationary storage vessel for high-pressure hydrogen

Proposed Future Work

Major Tasks & Milestones	Schedule & Status
Task 2: Design, engineering and cost modeling •Complete the design optimization of composite vessel for cost reduction (including other pressures) •Study hydrogen embrittlement in layered steels (including welds) and pre-stressed concretes •Test performance of strain sensors exposed to hydrogen	**10/11 – 9/12**
Milestone #2: Composite vessel, designed using relevant industry codes and standards, that meets DOE's technical targets for stationary storage capital cost	*Ongoing*
Task 3: Construction and testing of mock-up vessel •Complete high-pressure hydrogen testing of coupons and components •Complete the mock-up vessel's drawings and its verification using structural finite element analysis •Subcontract manufacturers for construction of mock-up vessel •Identify testing site and acquire necessary approval •Conduct relevant tests and collect performance data	**10/12 – 9/14**
Milestone #3: Mock-up vessel passing relevant tests such as burst, pressure (and temperature) cycling, and hydrogen permeation	*Not started*

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	• Engineering calculations of composite vessels' dimensions based on relevant design codes (e.g., ASME BVP) • Step-by-step manufacturing process flow for composite vessels and cost assessment of various design options • High potential for exceeding DOE's FY2020 cost targets • Scale-up of friction stir welding for thick steel sections
Collaborations:	Active partnership with industry, university and other stakeholders
Future Research:	• Optimize composite designs for cost reduction • Complete high-pressure hydrogen testing of coupons and components • Complete the mock-up vessel's drawings and its verification using structural finite element analysis

Acknowledgements

- **Project Sponsor:** DOE Hydrogen and Fuel Cell Technologies Program
- K. Scott Weil, Sara Dillich and Monterey Gardiner (DOE)
- David Wood, David Stinton and Steve Pawel (ORNL)
- James Merritt (U.S. Department of Transportation)
- Louis Hayden (ASME B31.12)
- Hong Wang and Larry Anovitz (ORNL)