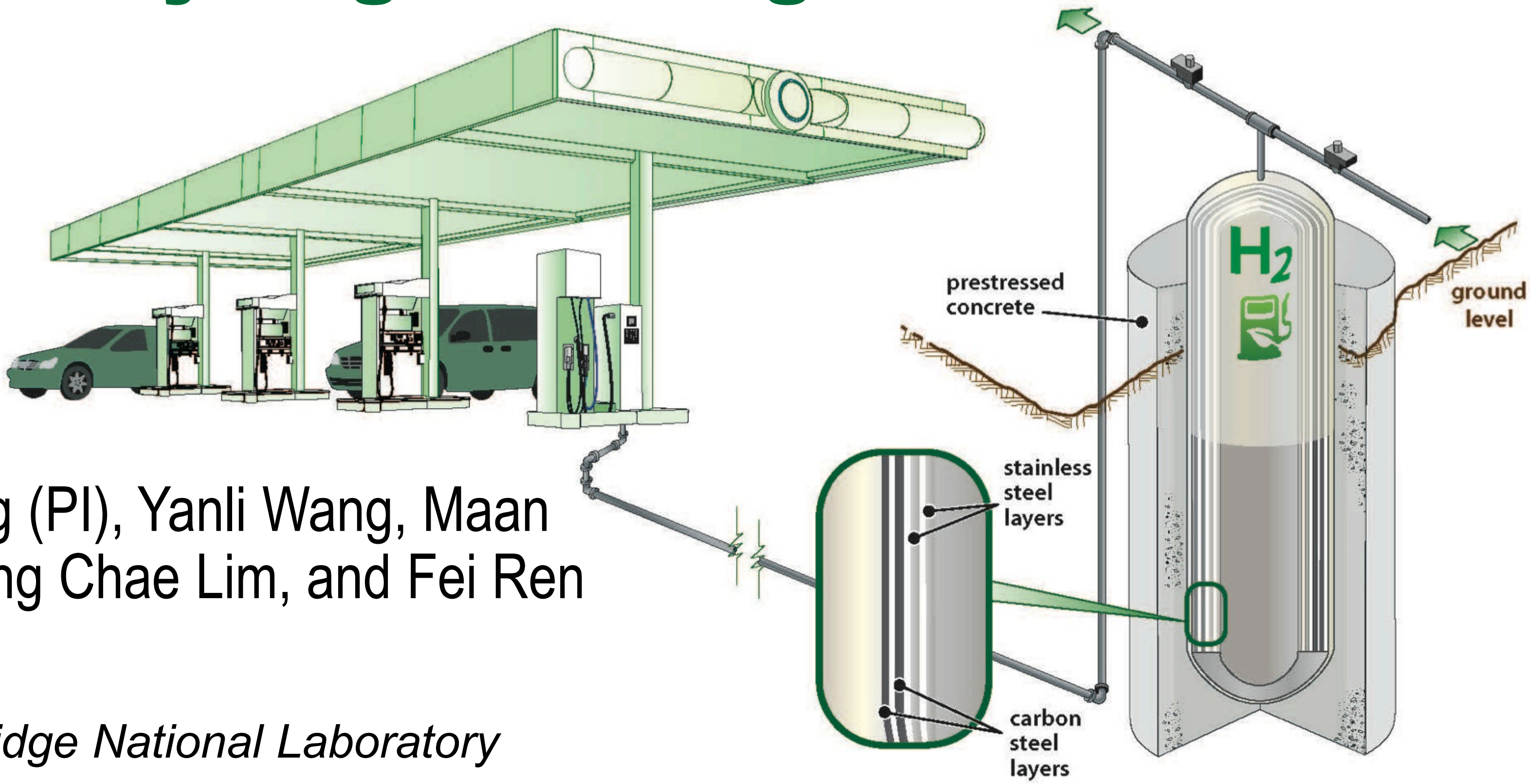
2015 DOE Hydrogen and Fuel Cells AMR

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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Overview

Timeline

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

Budget

- Total Funding Spent: $3,088K*
- Total Project Value: $3,600K
- FY15 DOE Funding: $700K
- Cost Share %: 20%

*as of 3/31/2015

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.
  - Hanson Pressure Pipe
  - Kobe Steel
  - Temple University
  - MegaStir Technologies
  - ArcelorMittal
  - U.S. Department of Transportation
- Project lead
  - Oak Ridge National Laboratory (ORNL)

Relevance – Project Objectives

Develop and demonstrate the novel steel/concrete composite vessel (SCCV) design and fabrication technology for stationary storage system of high-pressure hydrogen that meet DOE technical and cost targets

- Address the significant **safety** and **cost** challenges of the current industry standard steel pressure vessel technology

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

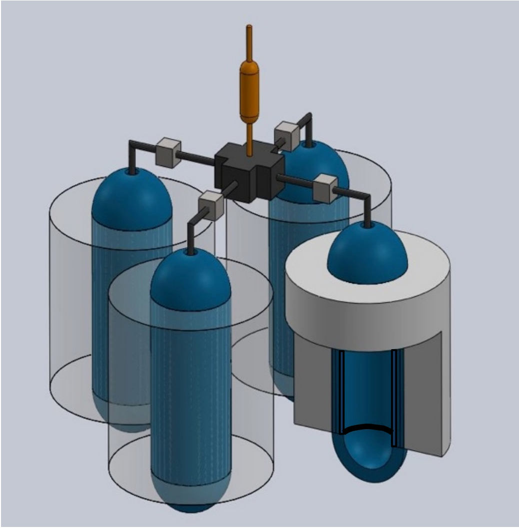
* *DOE FCT Multi-Year Plan updated 2-2013*
http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

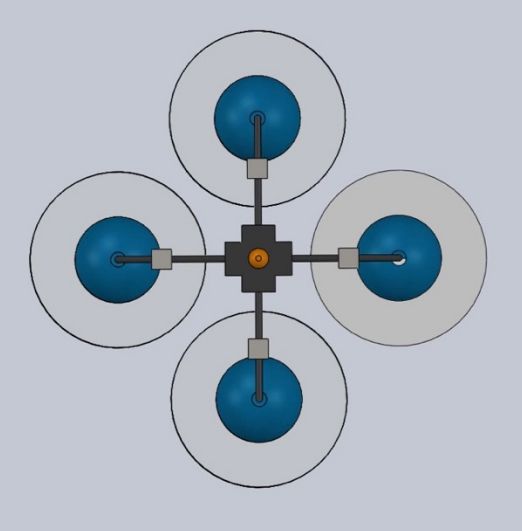
- By 2015: about 17% reduction
- By 2020: about 31% reduction

SCCV Technology

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

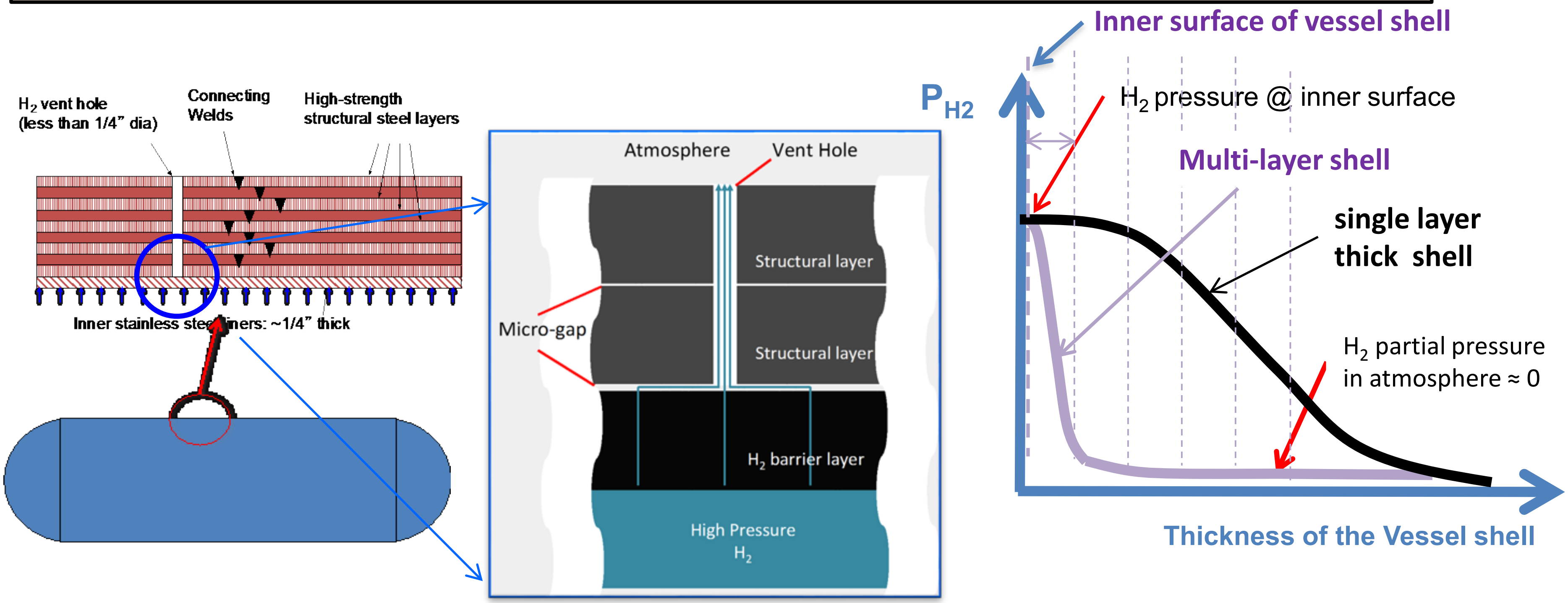
- Modular design of hydrogen storage system
  - Flexibility for scalability
  - Flexibility for cost optimization
  - System reliability and safety
  - Individual vessels are self contained and monitored.
- Combine steel/concrete to reduce cost
  - An inner multi-layered steel vessel encased in a pre-stressed outer concrete reinforcement
  - Use of cost-effective commodity materials (concrete and steel)
- Novel layered inner steel vessel design to eliminate hydrogen embrittlement (HE) *by design*
- Advanced fabrication and sensor technologies for cost reduction and improved operation safety





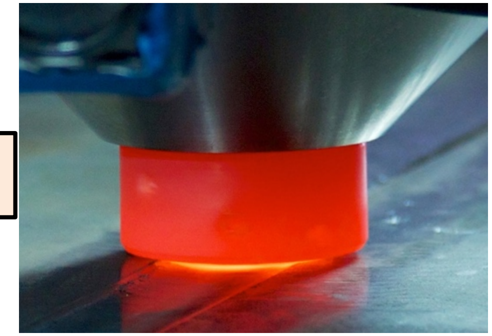
Approach:

Small hydrogen vent holes combined with multi-layered steel vessel uniquely solves the HE problem, by design



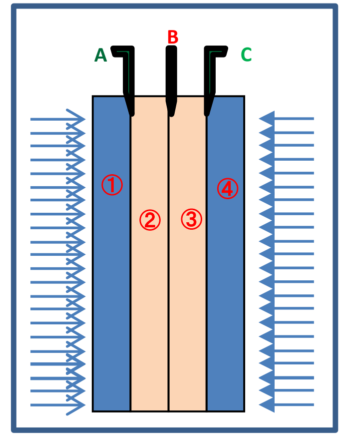
- Small vent ports are created on the 2nd and all the outer layers of the vessel without sacrificing the structure's mechanical integrity.
- Hydrogen migrated through the innermost layer will pass through the vent ports, resulting in little or no pressure buildup in the other layers. Thus, **hydrogen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

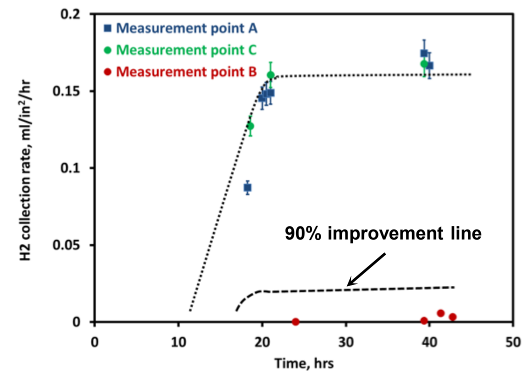
Past accomplishments

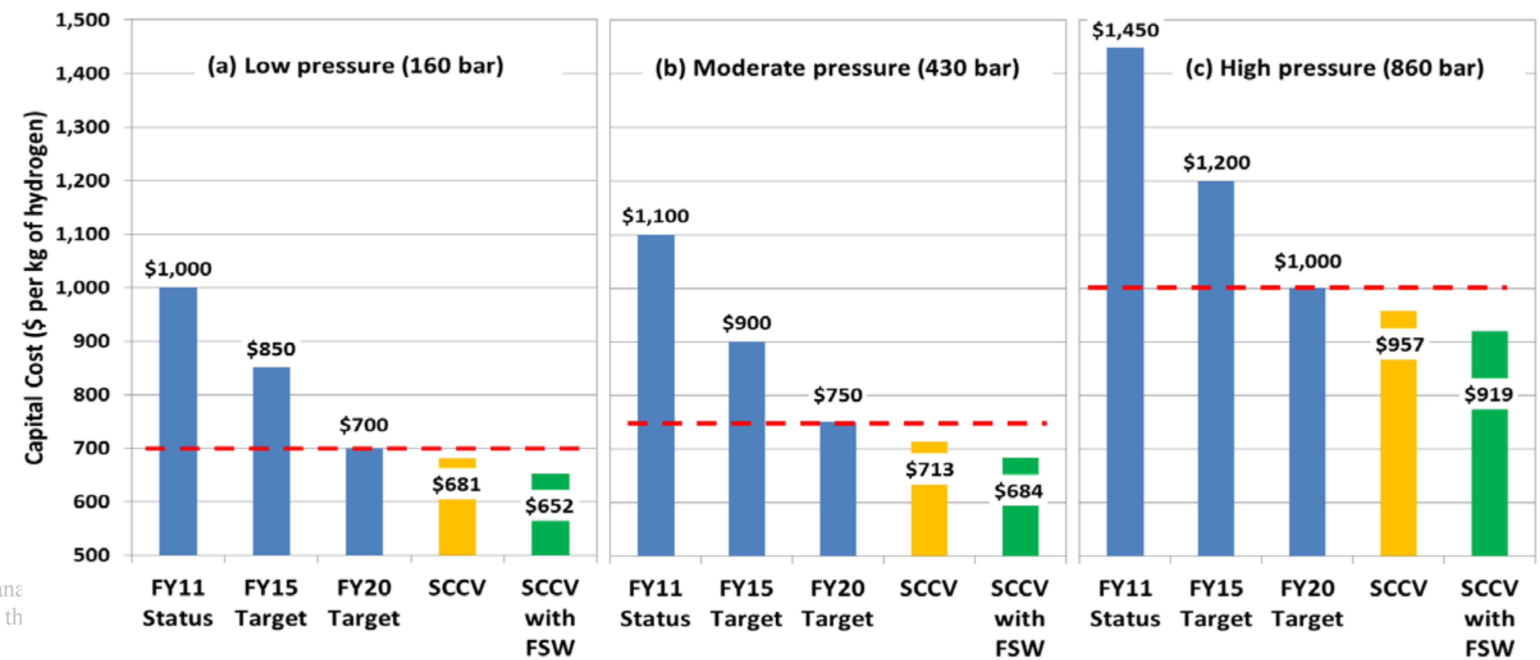


Demonstrated and validated individual SCCV innovations

- High-fidelity cost analysis demonstrated SCCV can exceed the relevant cost targets set forth by DOE
- Validated the technical basis for HE mitigation by design through lab scale experiments.
- Demonstrate the superior properties of friction stir welded multi-layer steel vessel.
- Received a US Patent on a novel low cost, high H_2 pressure low frequency fatigue test







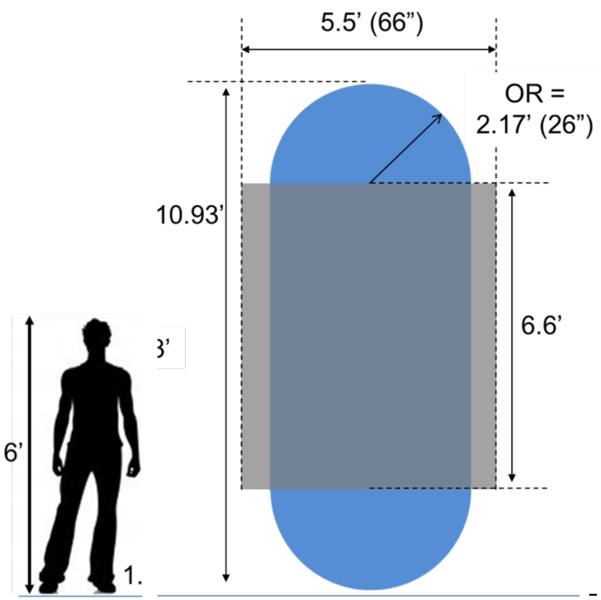
FY2015 Milestones/Deliverables

- Demonstrate and validate the entire SCCV design concept and manufacturability using today's industry scale manufacturing technologies and relevant codes/standards
  - Complete a SCCV prototype mockup capable of storing 90 kg gaseous hydrogen at 430 bar, which captures all major features of SCCV design and manufacturing requirement. (4/30/2015) Complete
  - Complete ASME hydro-static testing at 615 bar (1.43 times of the 430 bar design pressure) of the mockup SCCV to validate both the constructability and performance of the SCCV per ASME BPV code requirement. (6/15/2015) On-going
  - Complete the initial phase of long-term testing of the mockup SCCV performance under cyclic hydrogen pressure loading, simulative of hydrogen charging and discharging cycles of hydrogen re-fueling stations, at one to two cycles per day from 100 to 430 bar. (9/30/2015) Planned

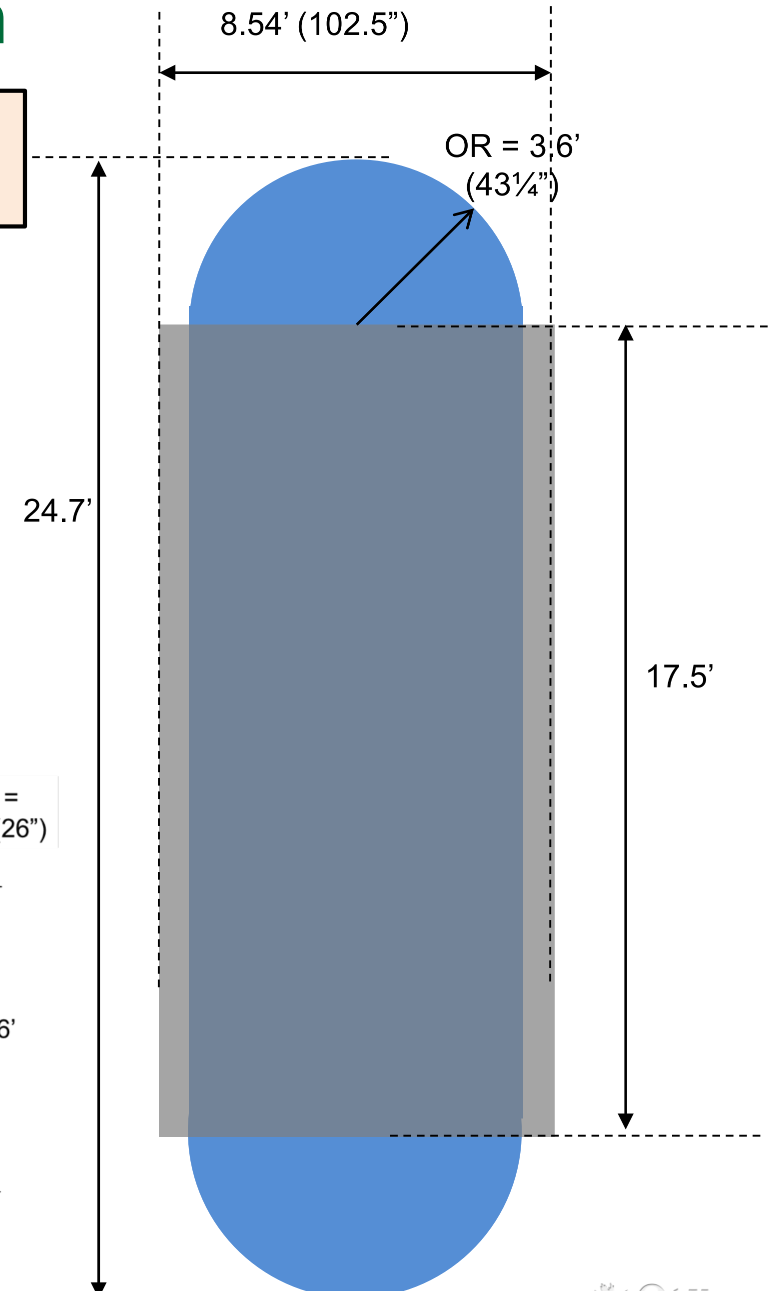
Technology Demonstration

Design, engineering and manufacture a small but representative prototype SCCV mockup

- Captures all major features of SCCV design and construction requirement with today's manufacturing technologies and code/standard requirements
- Obtain "real-world" performance data
- A mock-up with <u>manway</u>
  - Manway is needed in today's high-pressure vessel applications
  - For internal inspection per ASME BPV code
  - For today's manufacturing technology and future repair



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



Full-size: (564 kg of H_2)

Technology Demonstration

The SCCV mockup is designed, fabricated and tested for hydrogen storage per relevant codes and standards

- 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 hydrogen permeation barrier liner
- ACI design allowables for pre-stressed concrete
- Hydro-static testing at 1.43 times of design pressure as part of code acceptance (8940psi, 615 bar)
- Cyclic hydrogen pressure loading to simulate service conditions

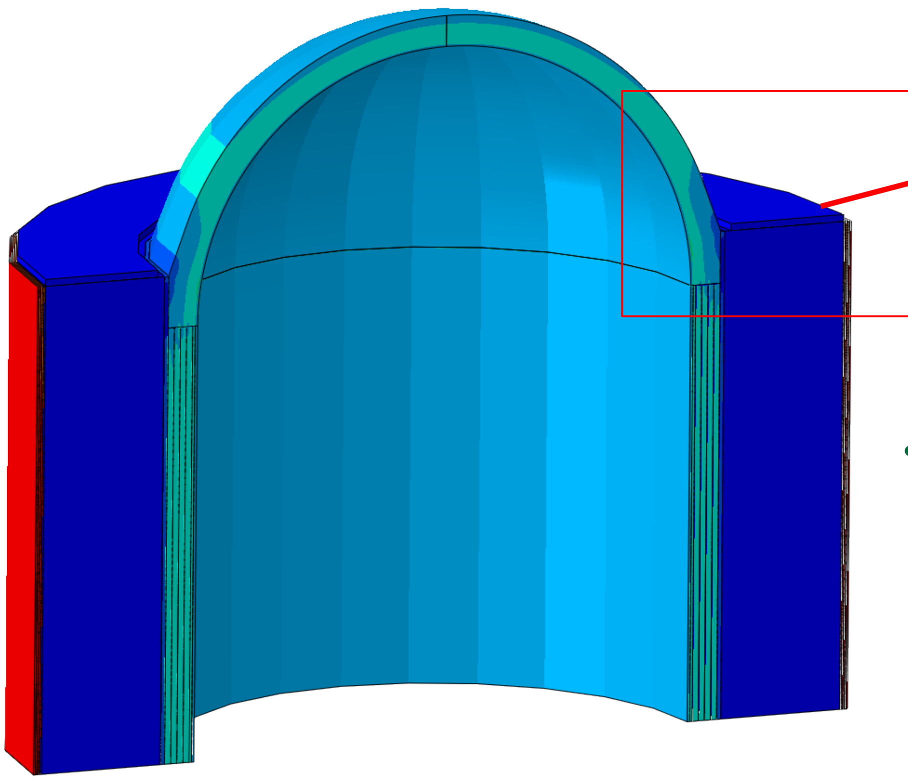
Status

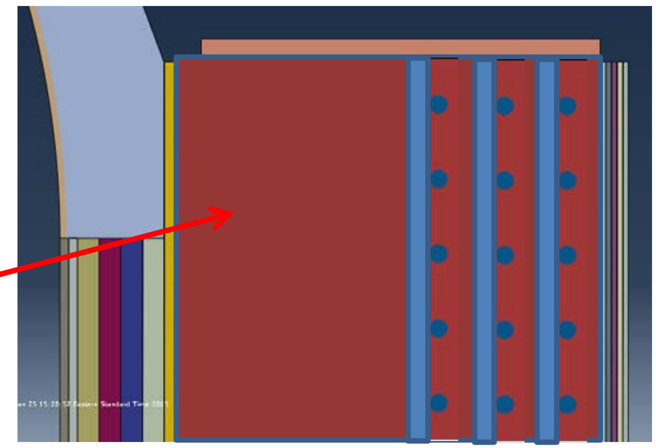
- Construction completed
- Hydro-testing to be performed
- Cyclic hydrogen loading test planned

Accomplishment:

Detailed finite element engineering analysis was used to optimize the SCCV design

- Design against buckling of inner vessel under compression load from pre-stressing
- Design against concrete cracking during service and hydro-testing
- Fabrication considerations

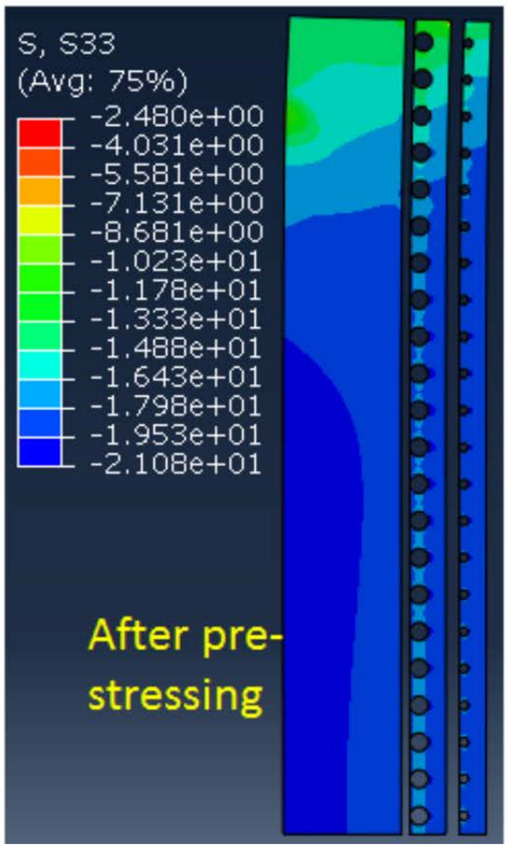


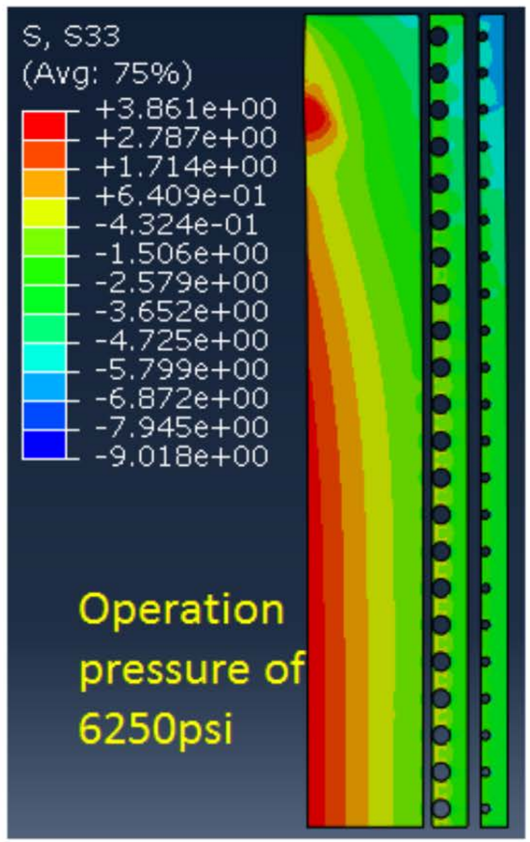


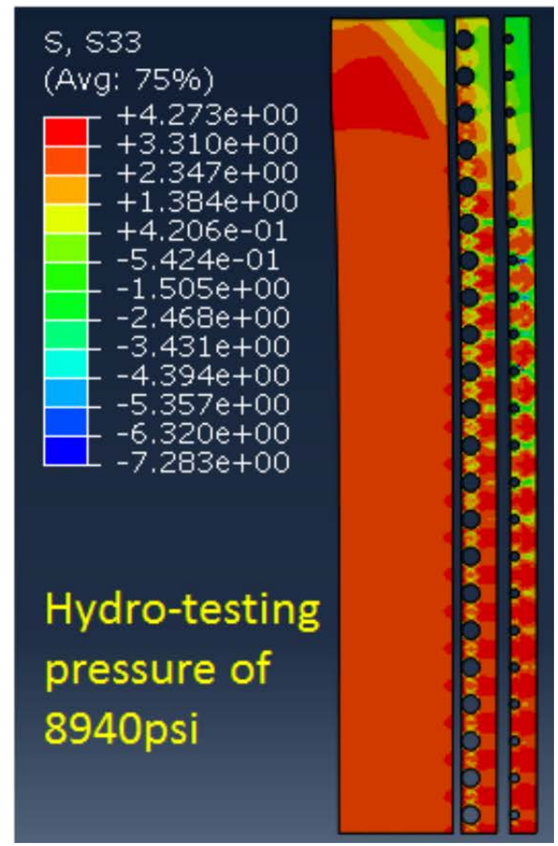
- A number of detailed design iterations
  - Rebars
  - Concrete thickness
  - Wire wrapping for pre-stressing
  - Fabrication issues, dimensional interference etc.

Accomplishment: Optimize stress in concrete by FEM modeling

Detailed finite element engineering calculations were used to drive design iterations of the pre-stressed concrete reinforcement to ensure acceptable stress levels in the concrete







Stresses in MPa

Accomplishment:

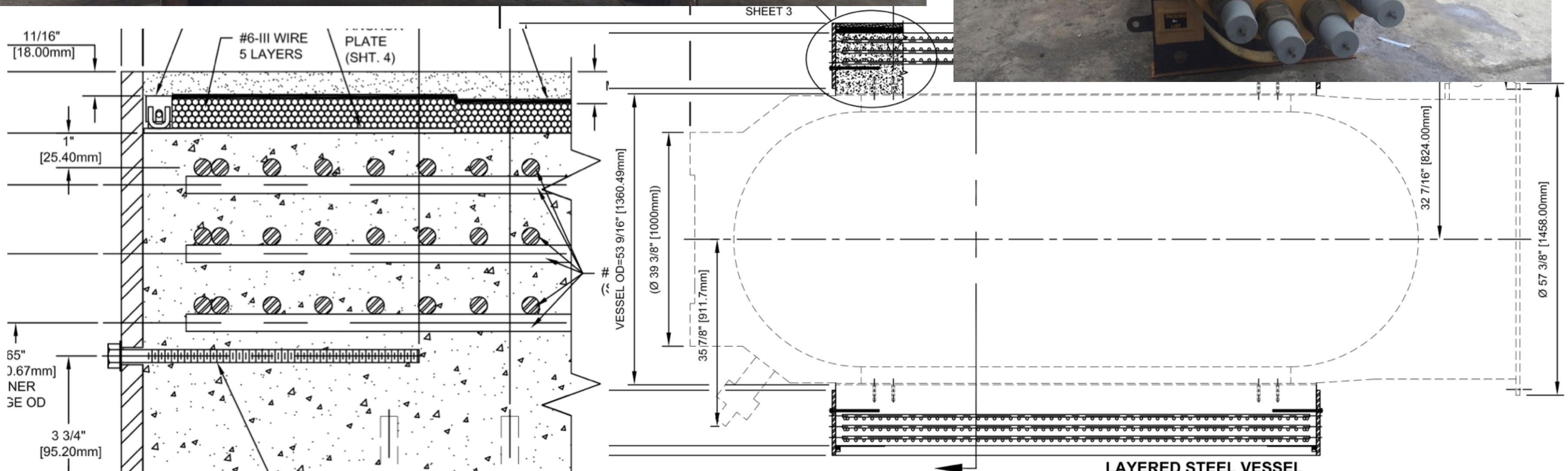
Detailed finite element engineering calculations ensured the circumferential stresses in the SCCV design are below the code allowable stresses

Range of the Hoop stresses		After pre-stressing	6250psi operation pressure	8940psi hydro-testing pressure
Inner steel vessel	Layered high strength steel shell (σ_a=39.6ksi)	-14ksi to -8ksi	21ksi to 12ksi	38ksi to 22ksi
	Inner stainless liner (σ_a=31ksi, and -36ksi for compression buckling)	-35.6ksi to -31.8ksi	-1.5ksi to -9.1ksi	7.8ksi to 0.5ksi
Inner cage spiral rebar (σ_a=32ksi)		-15.6ksi to -10.8ksi	1.4ksi to -3.0ksi	9.5ksi to 0.7ksi
Pre-stressing wire (σ_a=227ksi)		127ksi to 115ksi	140ksi to 125ksi	146ksi to 129ksi

Code allowable stress limits are in parentheses

Accomplishment:

Inner steel vessel was designed, constructed and hydro-tested per ASME BPV code at Kobe Steel



Final design of pre-stressed outer concrete reinforcement took into account the unexpected high-compressive stresses from layered inner steel vessel construction

Accomplishment:

Construction of the outer concrete at Hanson Pressure Pipe

Accomplishment:

Final steel wire wrapping to create the designed level of compressive stresses in the inner steel vessel at Hanson Pressure Pipe

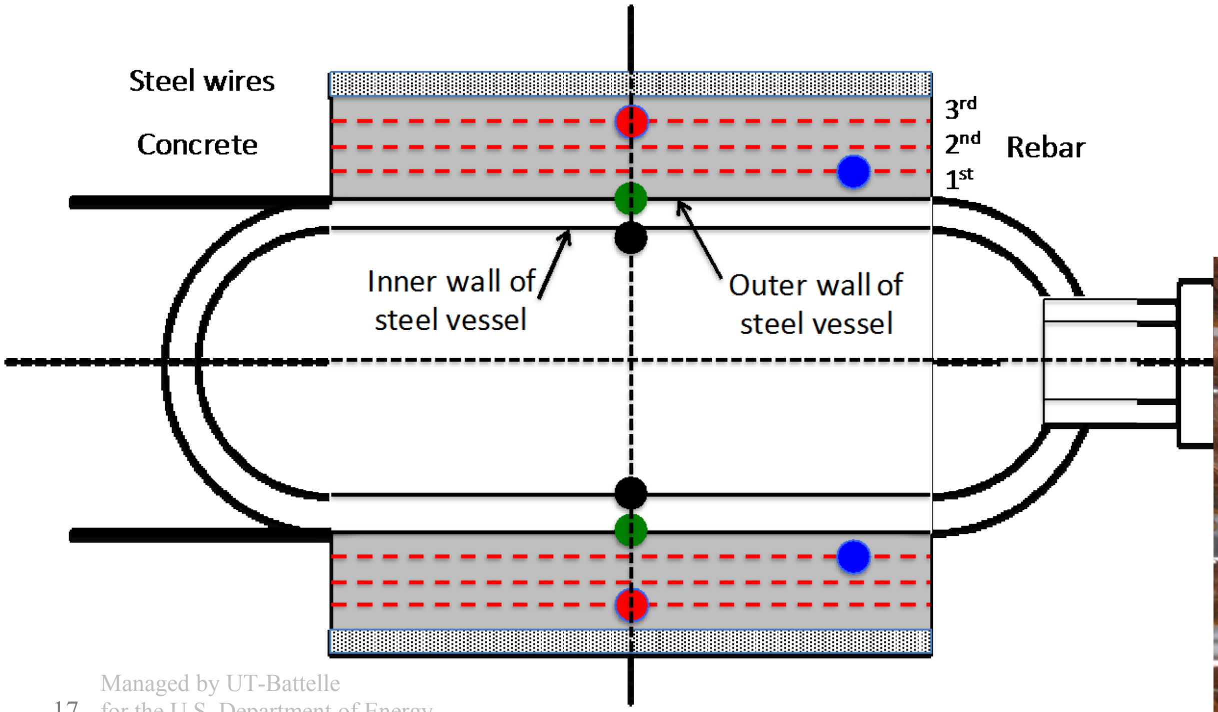
Accomplishment:

Completed entire mockup SCCV with multiple coatings and mortar protective layers to protect the vessel.

Accomplishment:

Strain gages were strategically placed throughout the mockup vessel to monitor the stresses during construction and subsequent testing

- Used during pre-stressing to control pre-stress levels to reach 50/50 load sharing,
- Will be used to monitor the health of vessel during hydrostatic test and cyclic hydrogen pressure loading test



Responses to reviewers' comments

- "The approach looks very practical." "The approach to diffusion experiment is simple and elegant. The team is addressing cost barriers toward the target and making good progress.
- "It is not evident that a manway is useful." "Perhaps it is possible to fabricate and inspect without a manway (a cost improvement)."
  - *Manway is currently required by ASME BPV code for in-service inspection and repair. It is also necessary in today's fabrication. We are working on options to eliminate manway in GEN II SCCV*
- Progress in imaging in the visible and infrared, together with developments in robotics, should counter the need for direct human observation and exposure. It would be preferable to see tests on multiple small mockups.
  - *We appreciated the suggestions from the reviewer. We are working on these recommendations for GEN II SCCV.*
- Installation cost
  - *Installation cost varies greatly and is highly dependent on a number of factors - location, location and location.*

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
• Kobe Steel	Construction of inner steel vessel
• Hanson Pressure Pipe	Construction of outer concrete reinforcement
• MegaStir Technologies	Friction stir welding for layered steel design
• ArcelorMittal	High-strength steels
• Temple University	Sensors and instrumentation
• ASME (B31.12)	Relevant code committee on high-pressure hydrogen services
• DOT	Qualification of stationary storage vessel for high-pressure hydrogen

Remaining Challenges and Barriers

- Anticipated long testing period of cyclic high pressure hydrogen loading, to simulate hydrogen charging and discharging cycles of hydrogen re-fueling stations
  - Obtain initial data in FY15 (~100 to 200 cycles)

Proposed Future Work

- **FY15**
  - Complete testing of the mockup SCCV under code required hydro-testing for final validation of the design, manufacturing and performance of the SCCV for hydrogen storage. Perform long-term evaluation of the mockup 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

Technology Transfer Activities

- Multiple Inquires from a number of companies for potential applications of the technology
  - Re-fueling stations
  - Underground storage
  - Development and application of ultra high-strength steels (beyond those in current ASME code)
- Potential future funding
  - Hydrogen Initiatives in California
  - Beyond hydrogen storage
- Patent and licensing
  - SCCV technology is patent pending (US20150014186A1)
  - US Patent No. 8,453,515B2: Apparatus and method for fatigue testing of a material specimen in a high-pressure fluid environment

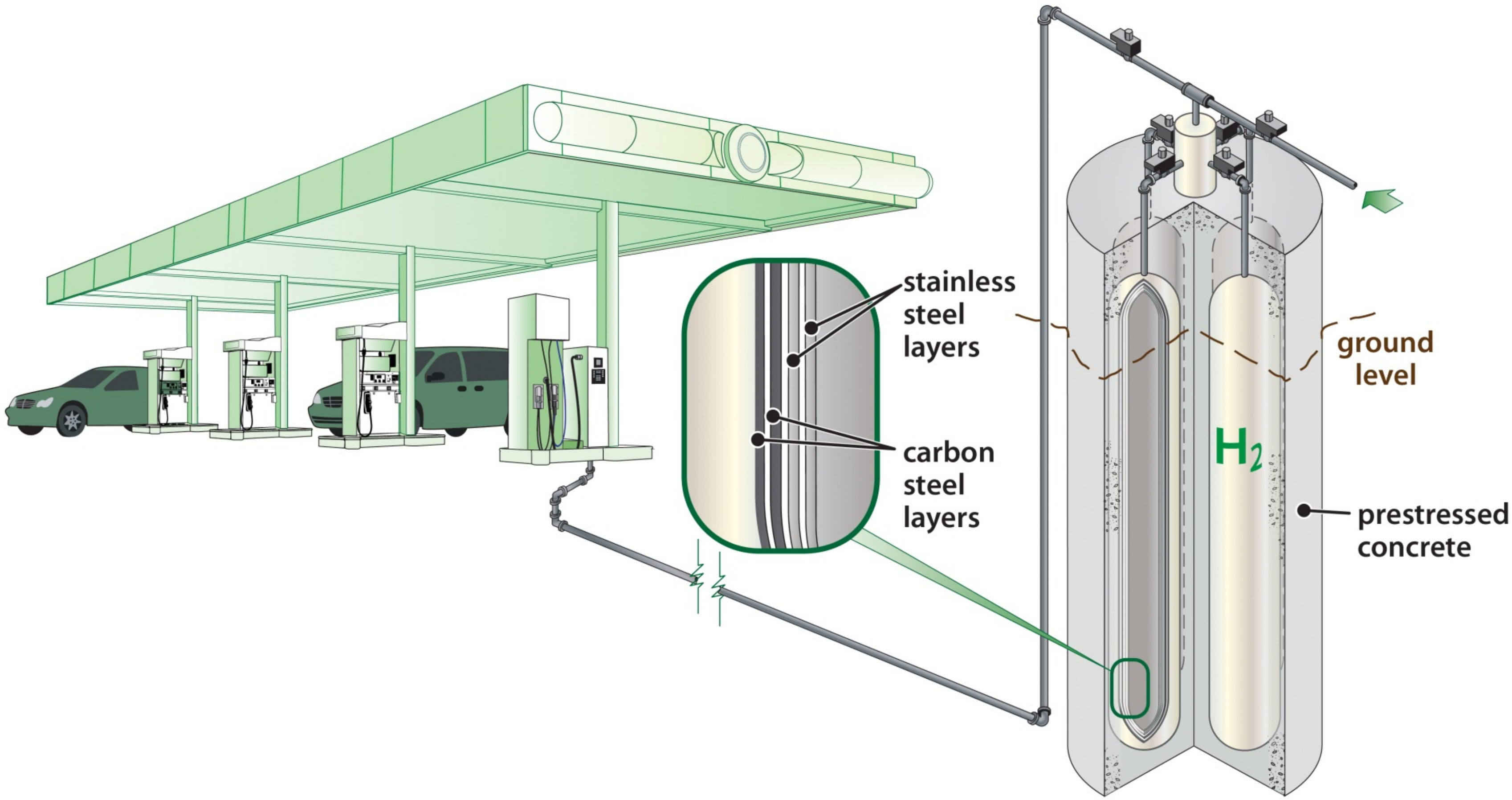
Project Summary

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 • Solve hydrogen embrittlement in high-strength steels by design • Advanced, automated manufacturing of layered steel tank
Technical Accomplishments	• A high fidelity cost analysis demonstrated that the SCCV technology can exceed the relevant cost targets set forth by DOE • Validated the technical basis for hydrogen mitigation by design through lab scale experiments. • Demonstrated the superior properties of multi-layer friction stir welds. • Validated manufacturability of SCCV with today's industry manufacturing capability and code compliance by the construction of ¼ scale mockup SCCV for near-term commercialization
Collaborations:	Active partnership with industry, university and other stakeholders
Future Plan:	• Perform technology validation testing of SCCV under cyclic hydrogen service conditions (FY15) • GEN II SCCV for further cost reduction and technology demonstration and transfer (FY15-FY17)

Summary: SCCV for High Pressure H_2 Storage

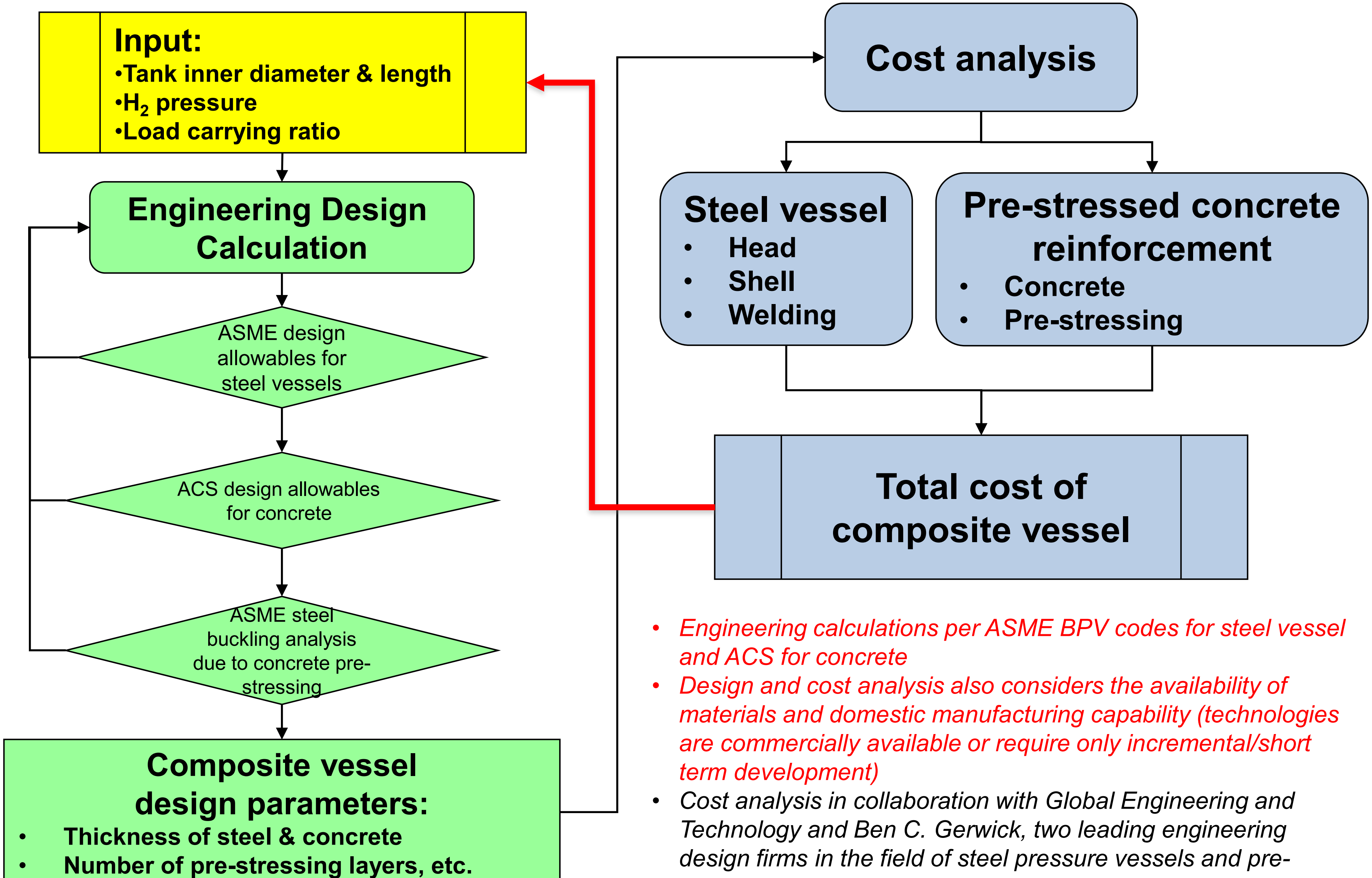
- Can be designed and constructed using mature and proven industry scale fabrication technologies and following pertinent codes/standards
  - Steel inner vessel designed and built per ASME Boiler and Pressure Vessel (BPV)
  - Outer concrete reinforcement per American Concrete Institute (ACI)
- Safety 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.)

SCCV for High-Pressure H_2 Storage



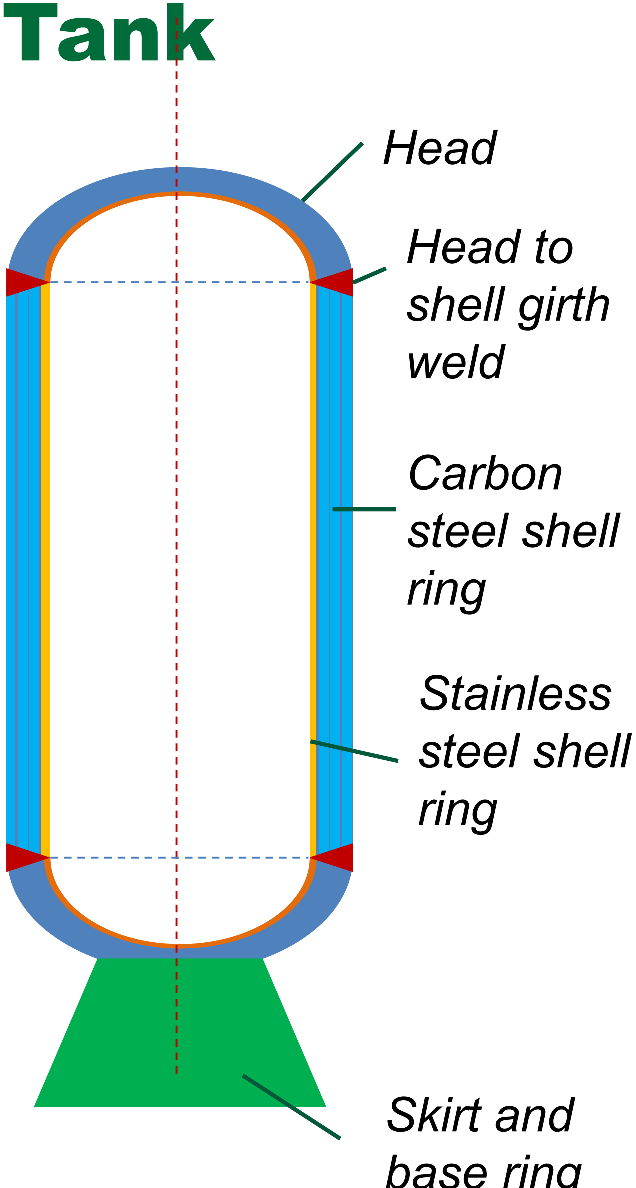
Technical Backup Slides

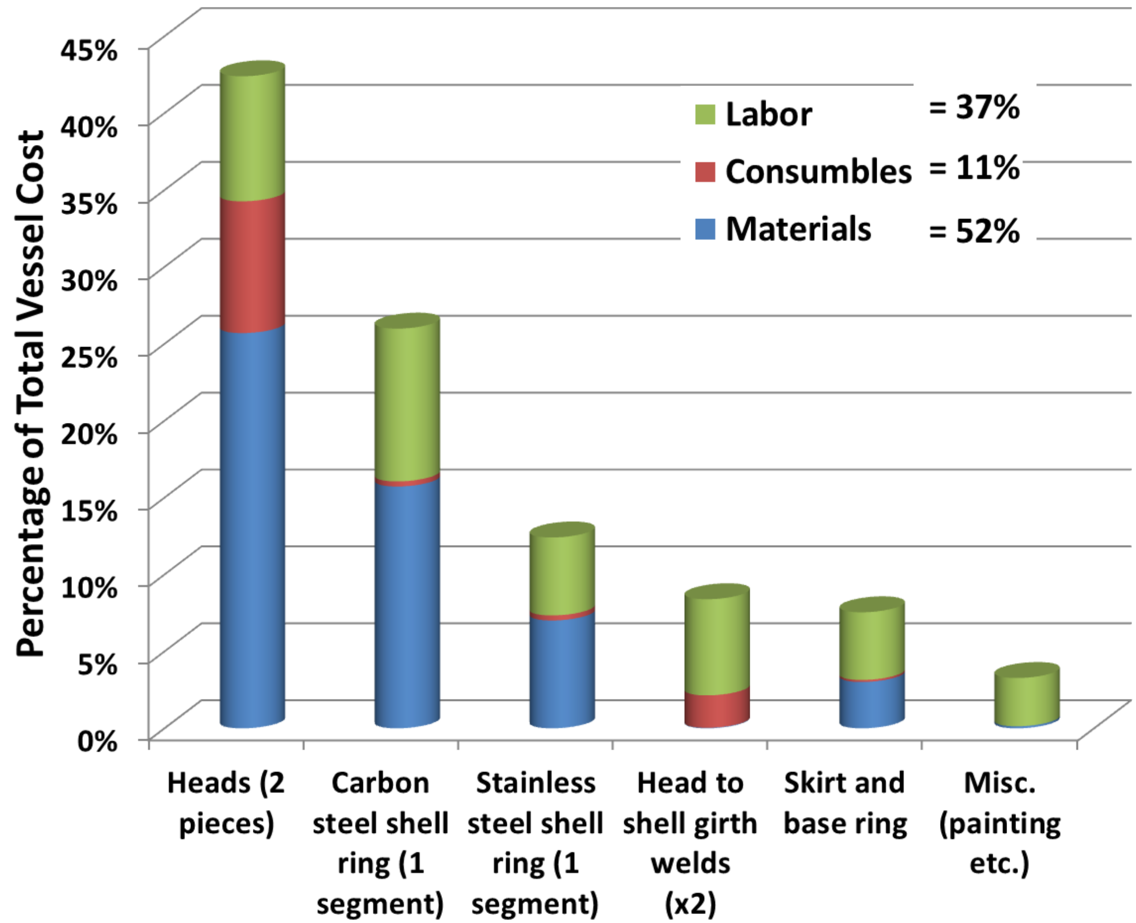
Overview of Cost Analysis Approach



- *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.*

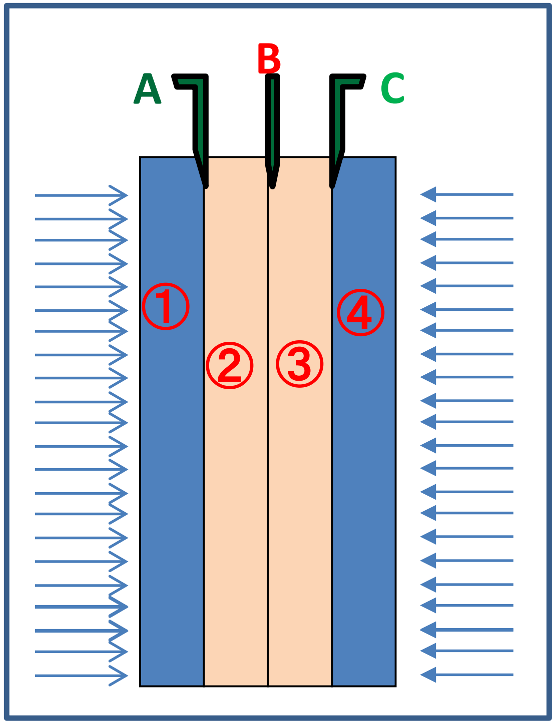
Example: Cost Analysis for Inner Steel Tank



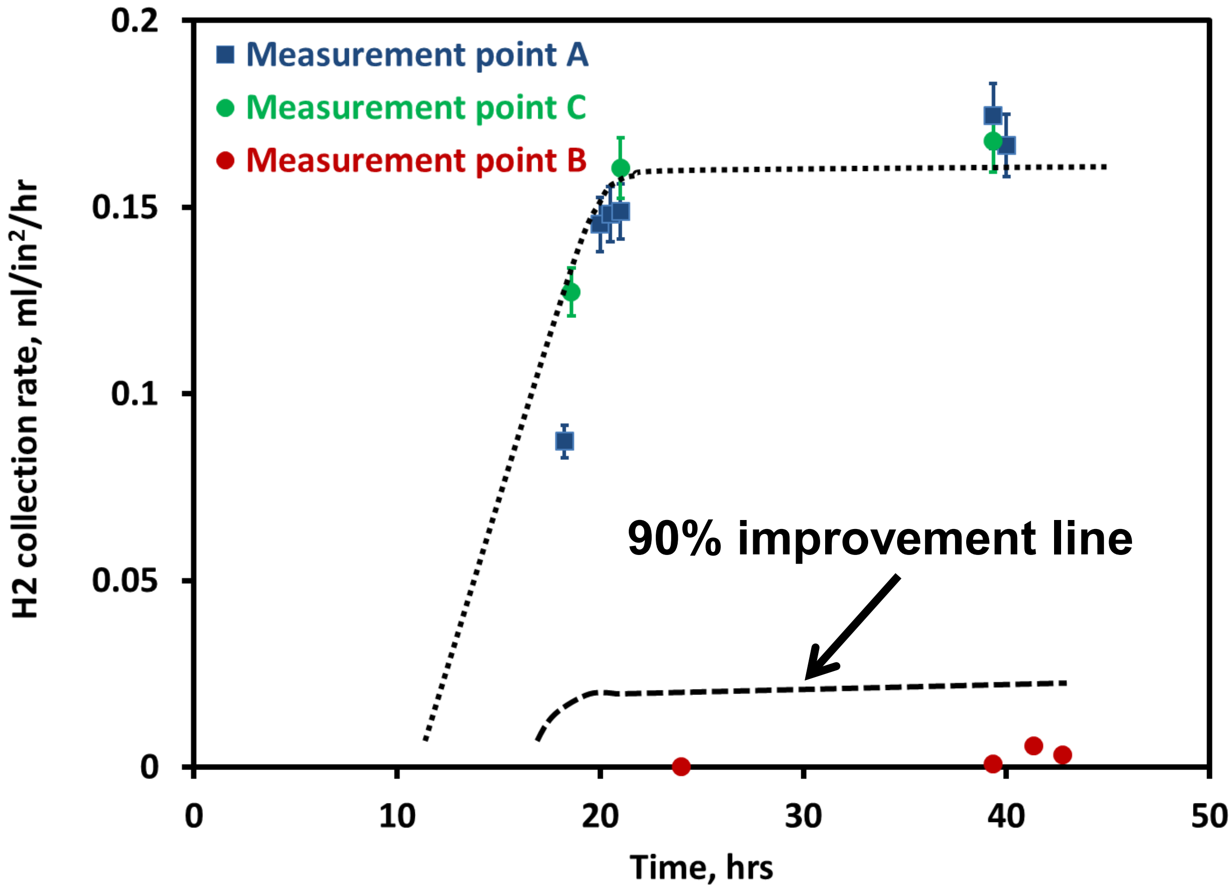


- *Consumables including welding filler wires and shielding gases etc.*
- *Assumed labor rate: $75 per hour*

Accomplishment: H_2 Permeation Experiment Validating Hydrogen Mitigation Technology



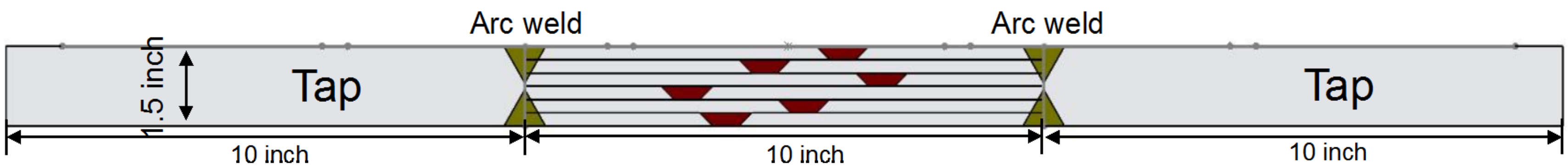
Tested at 150C, 2000Psi H_2

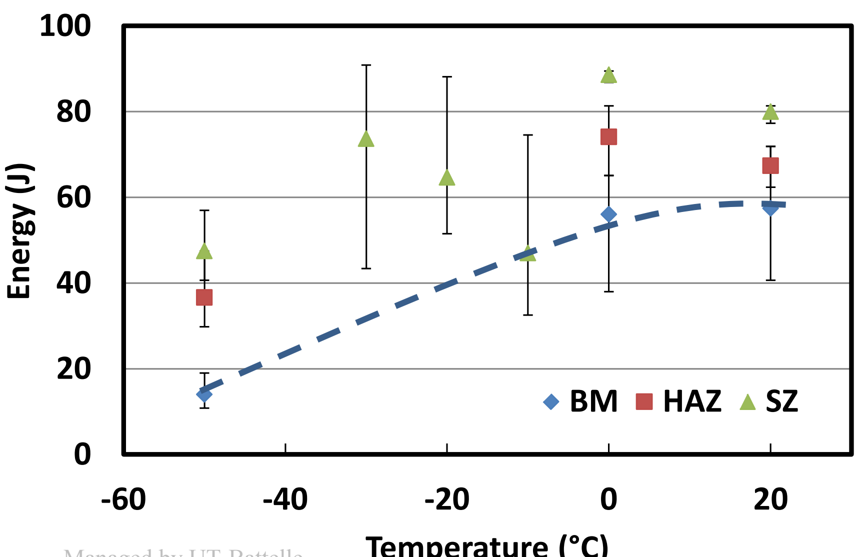


- H_2 permeation rate through the 2nd layer was reduced more than 95%
- Consistent with theoretical analysis results, validated the design basis based on theoretical analysis.

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

- 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





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