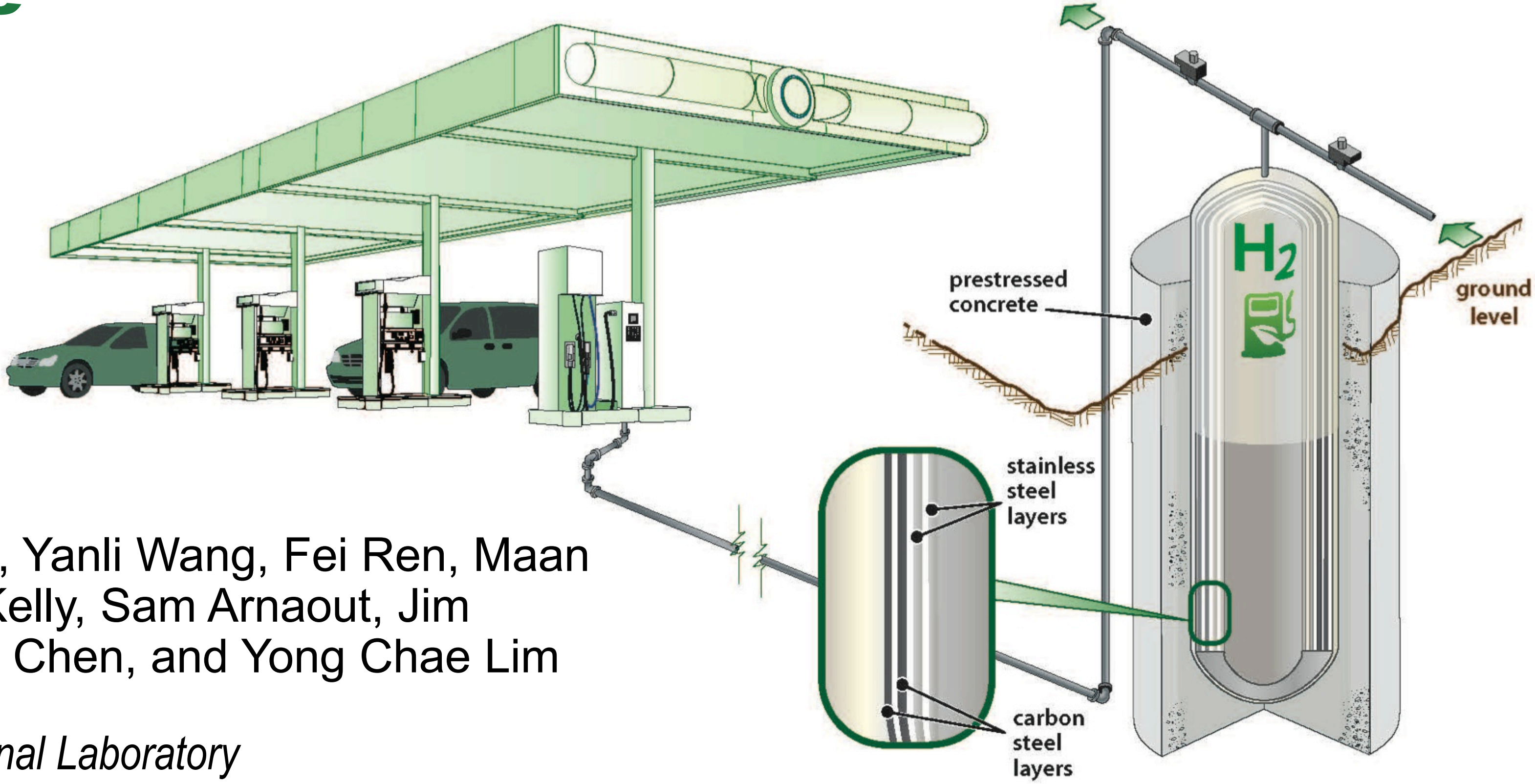
Vessel Design and Fabrication Technology for Stationary High-Pressure Hydrogen Storage



Zhili Feng (PI), Yanli Wang, Fei Ren, Maan Jawad, Mike Kelly, Sam Arnaout, Jim Nylander, Jian Chen, and Yong Chae Lim

Oak Ridge National Laboratory
Kobe Steel, Foterra Pressure Pipe, Global Engineering & Technology, Temple University, and Harris Thermal Transfer

PD088

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

Overview

Timeline

- Project start date: Oct. 2010
- Project end date: Sept. 2016

Budget

- Total Project Budget: $3,600K
  - Total Recipient share: $600K
  - Total Federal Share: $3,000K
  - Total DOE Funds Spent*: $3,587K

*as of 3/31/2016

Barriers

- Barriers addressed
  - E. Gaseous hydrogen storage cost.

Partners/Collaborators

- Oak Ridge National Laboratory (ORNL)
- Global Engineering and Technology
- Ben C. Gerwick, Inc.
- Foterra Pressure Pipe (formally Hanson Pressure Pipe)
- Kobe Steel
- Harris Thermal Transfer
- Temple University
- MegaStir Technologies
- ArcelorMittal
- U.S. Department of Transportation

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

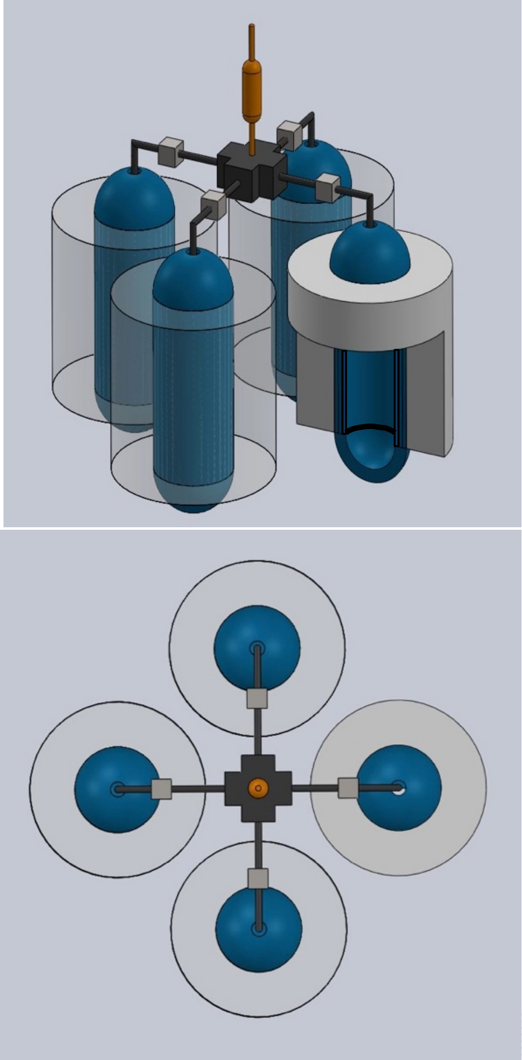
* *DOE FCT Multi-Year Plan updated 2-2013*
http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

OAK RIDGE
National Laboratory

Approach: SCCV Technology

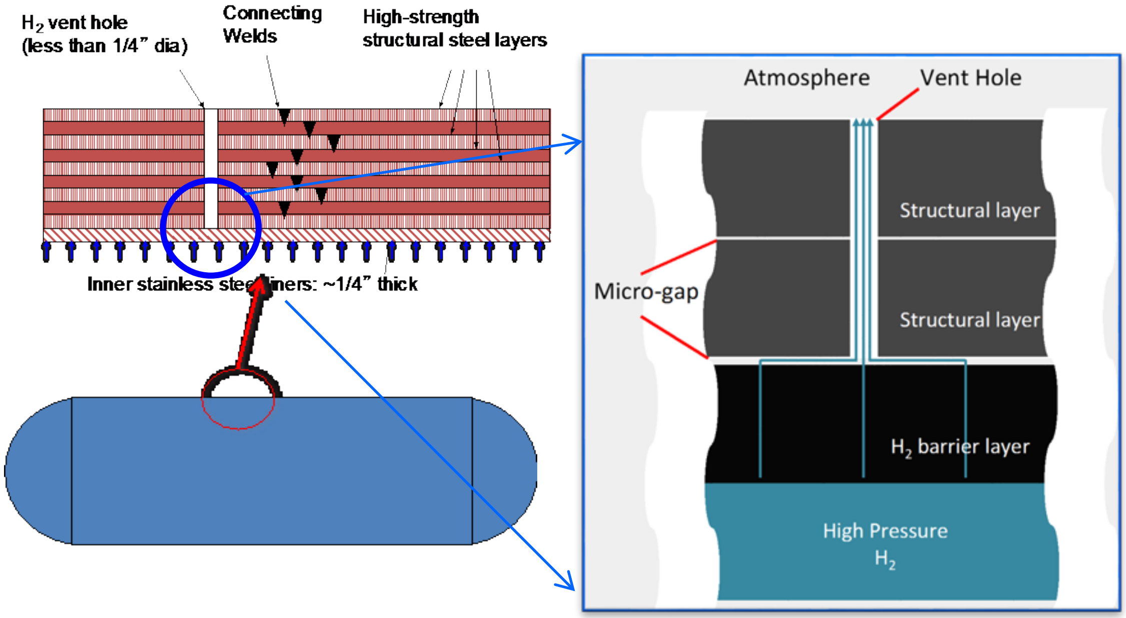
SCCV technology integrates four major innovations to optimize cost, scalability, durability, and safety.

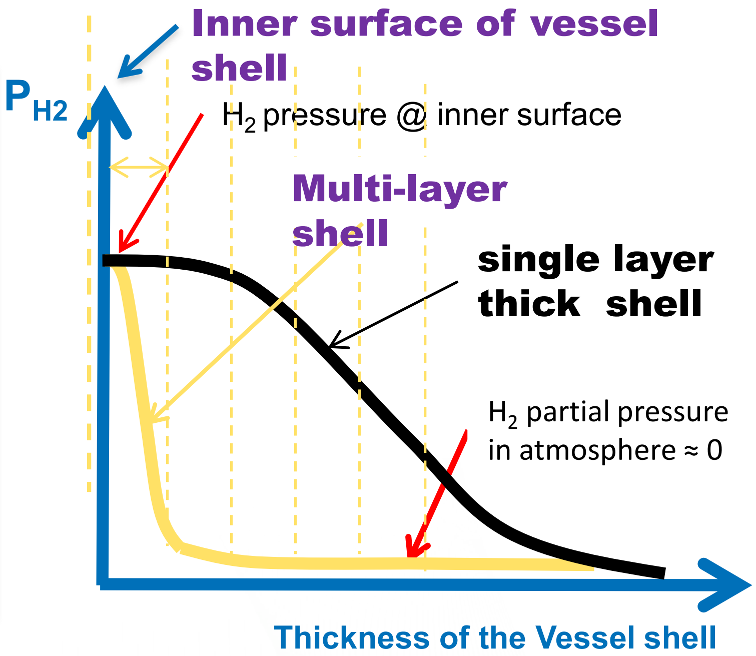
- Novel layered inner steel vessel design to eliminate hydrogen embrittlement (HE) ***by design***
- Combine steel/concrete to reduce cost
  - An inner multi-layered steel vessel encased in a pre-stressed outer concrete reinforcement for load sharing
  - Pre-stressed design for 50/50 load sharing between inner vessel and pre-stressed concrete
  - Use of cost-effective commodity materials (concrete and steel)
- Advanced fabrication and sensor technologies for cost reduction and improved operation safety
  - Unique pre-stress wire wrapping technology
- Modular design of hydrogen storage system
  - Flexibility for scalability
  - Flexibility for cost optimization
  - System reliability and safety
  - Individual vessels are self contained and monitored.



Approach: Solving HE *by Design*

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



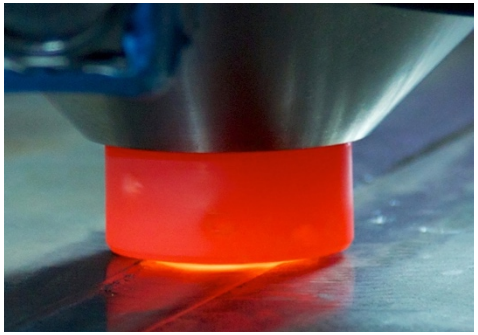


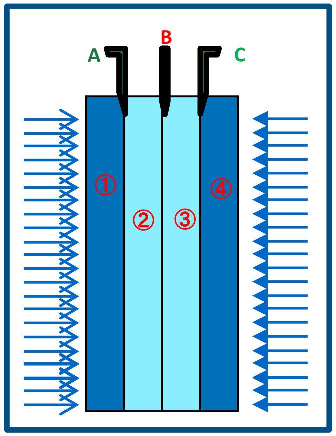
- Small vent ports are created on the 2nd and all the outer layers of the vessel without sacrificing the structure's mechanical integrity.
- Hydrogen migrated through the innermost layer will pass through the vent ports, resulting in little or no pressure buildup in the other layers. Thus, **hydrogen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

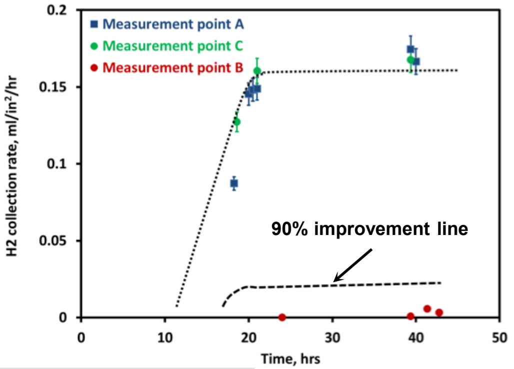
Past Accomplishment

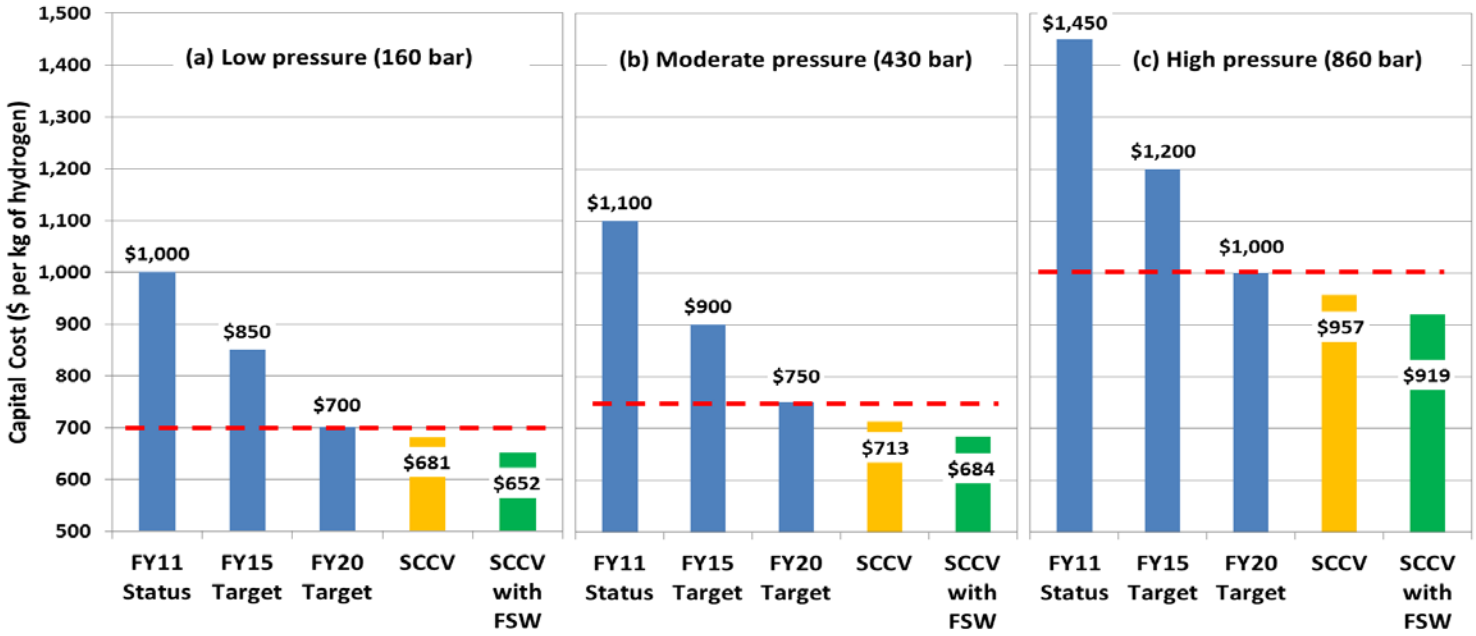
Demonstrated and validated individual SCCV innovations

- High-fidelity cost analysis demonstrated SCCV can exceed the relevant cost targets 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
- SCCV is patent pending







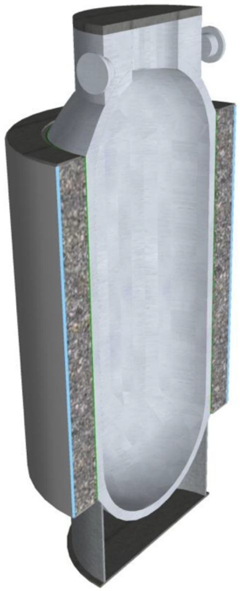


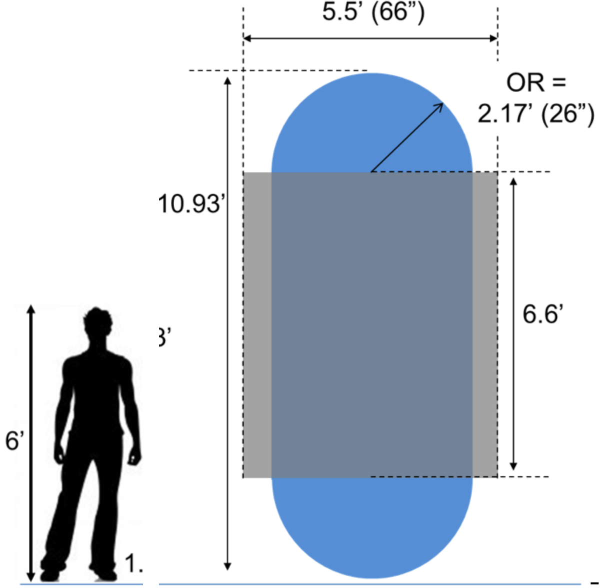
Note: Cost targets from 2013 DOE FCT Multi-Year Plan

Approach: Technology Demonstration

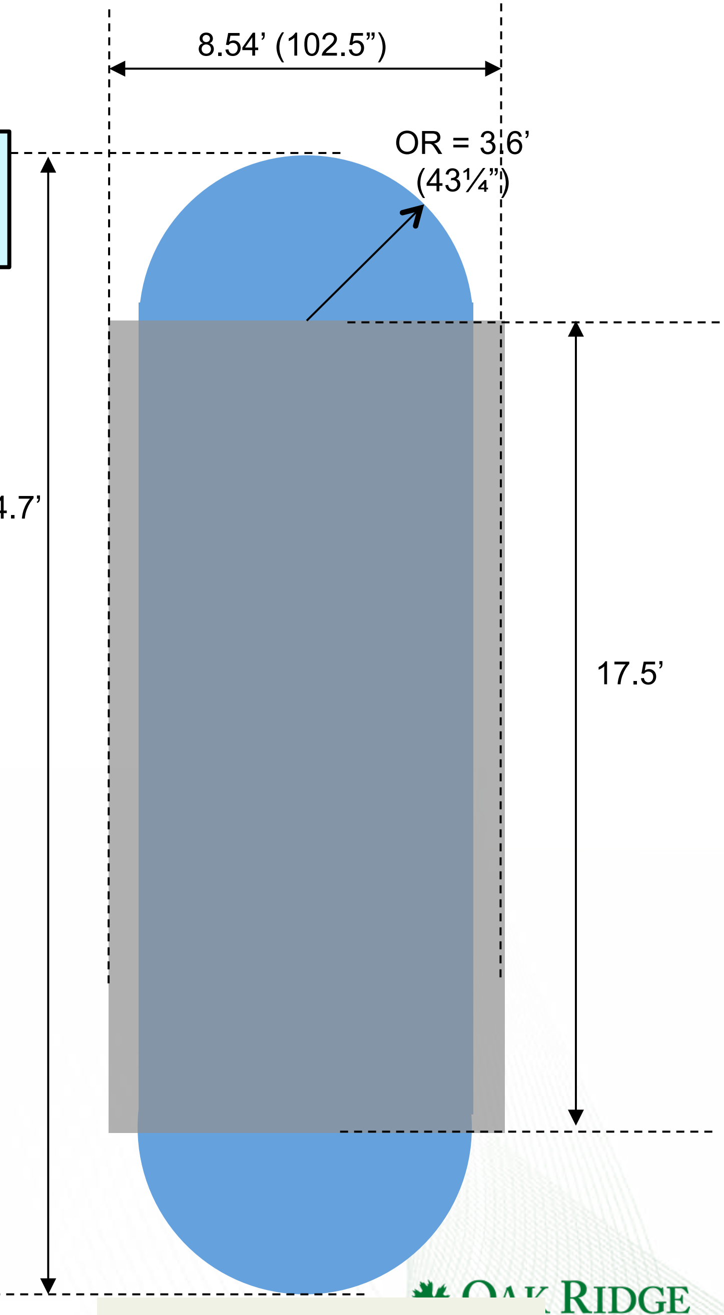
Designed, engineered and manufactured a small but representative SCCV

- 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 manway
  - 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)

Accomplishments

Construction and validation of demonstration SCCV

- Contains 90kg of H2 at 6250 psi (430 bar)
- Codes of construction
  - Steel inner vessel designed and built per ASME Boiler and Pressure Vessel (BPV) Section VIII Division 2, 2013 edition
    - ASME Steel: SA-765 Gr IV for head, SA-724 Gr B for layered shell
    - 3-mm thick 308/304 stainless steel hydrogen permeation barrier liners
  - Outer concrete reinforcement per American Concrete Institute (ACI)
- Constructed using mature and proven industry scale fabrication technologies
  - Unique pre-stressed wire wrapping technology
- 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 successful
  - Cyclic hydrogen loading on-going

Movie: Pre-stressed wire wrapping technology

Developed the technology to control the tension of the steel wire during wire wrapping to achieve 50/50 load sharing

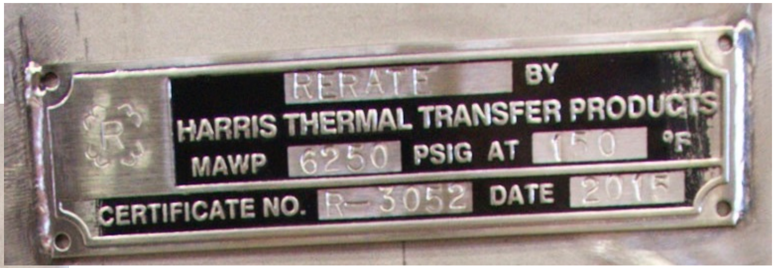
Accomplishment

Successfully passed hydrostatic test per ASME BPV code requirement

RERATE BY
HARRIS THERMAL TRANSFER PRODUCTS
MAWP 6250 PSIG AT 150 °F
CERTIFICATE NO. R-3052 DATE 2015

1137
CERTIFIED BY KOBE STEEL, LTD.
TAKASAGO EQUIPMENT PLANT
U2
M.A.W.P. 3620 PSIG
AT 150 °F
M.A.E.W.P. — PSIG
AT — °F
M.D.M.T. -20 °F
AT — PSIG
WL
PHT
SERIAL NO. 140057
YEAR BUILT 2014
CODE EDITION & ADDENDA 2013 EDITION

KOBELCO
LAYERED STEEL VESSEL
PURCHASER'S ORDER NO.
4000130021
RADIOGRAPHY PER CODE
VOLUME 3.1 m^3
KOBE STEEL, LTD.

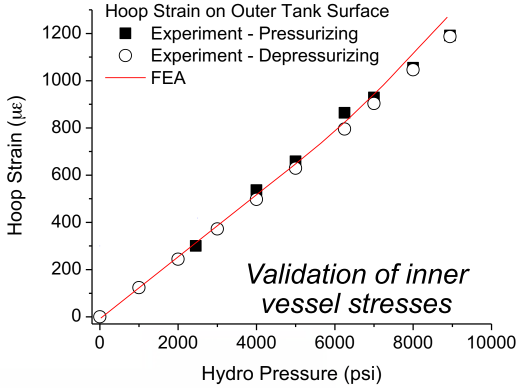


RERATE BY
HARRIS THERMAL TRANSFER PRODUCTS
MAWP 6250 PSIG AT 150 °F
CERTIFICATE NO. R-3052 DATE 2015

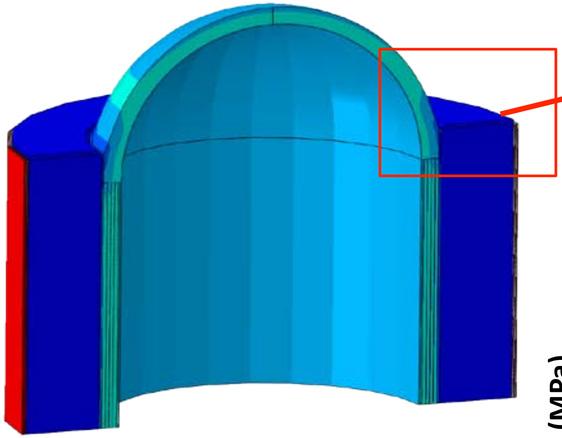
Accomplishment

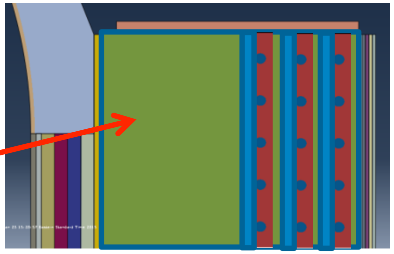
Validated finite element based design and engineering tool for SCCV design

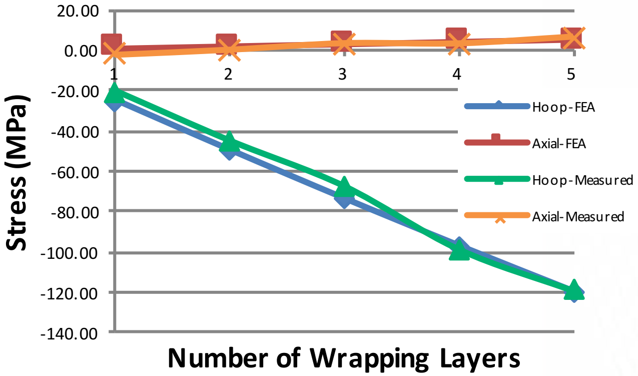
- Strain gages were strategically placed throughout the demonstration SCCV
- Measurements from strain gages provided valuable insights to SCCV construction and operation.
- The FEM design tools were validated using measured strain gage results.
- Modeling tool covers a number of design parameters
  - Rebars
  - Concrete thickness
  - Wire wrapping for pre-stressing
  - Fabrication issues, dimensional interference etc.

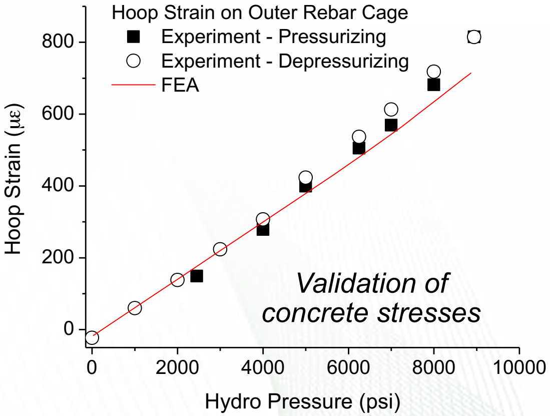


Validation of inner vessel stresses









Validation of concrete stresses

Validated design approach for pre-stress wire wrapping

Progress

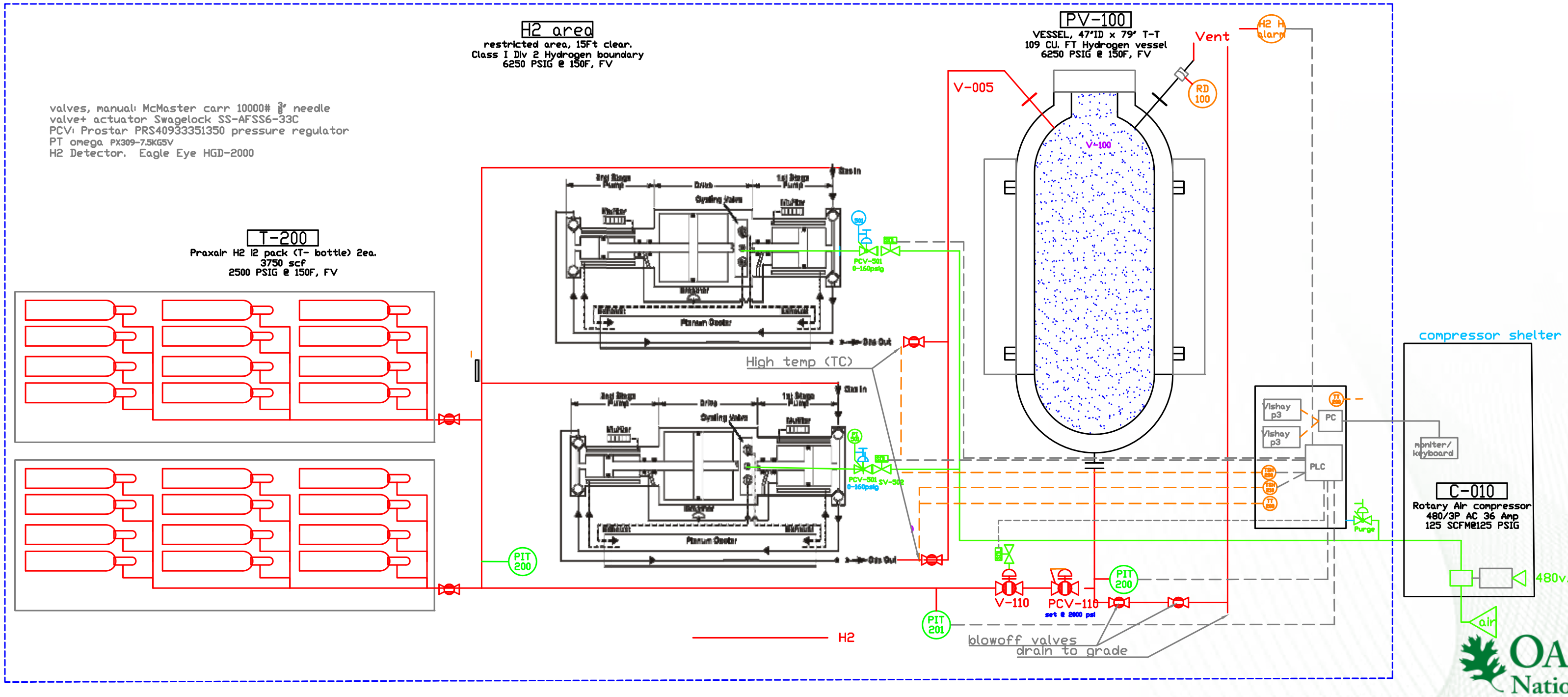
On-going: Long-term evaluation of demonstration SCCV performance under cyclic hydrogen pressure loading simulative to service pressure cycling.

- Cyclic hydrogen pressure loading from 2000 to 6000 psi, for a total of 250 cycles (Phase I). One to two pressure loading cycles per day.
- Cyclic testing is monitored with strain gages and other temperature and pressure sensors
- Permission from the Fire Marshal of the local jurisdiction has been obtained prior to performing the H2 testing. Personnel have been trained to perform the test. The procedure utilize pumps, compressors, and valves specifically suited for hydrogen to assure safe loading and unloading of the H2 during and in-between cycle testing

Accomplishment

Designed and assembled testing system

- Use glass beads to reduce the effective H_2 gas volume for test to 30kg
- High purity hydrogen cylinders are connected to pressure boosters to provide hydrogen and regulated for cyclic hydrogen pressure changes
- Recycling of hydrogen to reduce testing cost and safety risk of discharge hydrogen to environment
- Automated control of pressure cycling and charging rate
- Remote access to sensor reading and recording from ORNL and other sites for monitoring and data analysis



Progress

Cyclic testing protocol was developed, reviewed and approved that covers system requirement, testing operation, data collection and analysis, safety and protection.

- Pre-test: N2 to check leak at 2850psi(passed)
- Determine effective volume with glass beads fill (verified reduced to ~30%)
- System function test (passed)
  - Control, sensor readout, etc
- System purge (passed)
  - Purge with N2
  - Purge with industry grade H2 (99.95%), 4 times between 500 to 50 psi
  - Vacuum vessel to 5psi
  - Purge with high purity grade H2 (99.9999%)
  - Analyze purity of H2 in vessel
  - Issues of hydrogen purity from suppliers identified and resolved
- Cyclic loading test (on-going)
  - Control the rate of charge and discharge so temperature change is within -28C to 65C (-20F to 150F)
  - H2 purity analysis
  - Continuous data collection for data analysis and decision making
- Completion
  - Final analysis of H2 impurity in vessel
  - Targeted H_2 purity during cyclic testing per SAE J2719 (same as for fuel dispensed)

Accomplishments and Progress: Responses to Previous Year Reviewers' Comments

The roles of concrete. It's functionality and cost.

As shown in technical backup slides, the cost of concrete and rebar only amounts to less than 3% of total cost. Pre-stressed concrete provides a means to share the hoop stress in the vessel. The use of concrete is primarily a manufacturing consideration. We were constrained with the manufacturing technology available at the time we initiated the project. Pre-stressed concretes is used in construction of nuclear power plants. In retrospect, we now recognize that load sharing can be done by means of direct wire wrapping on the inner vessel, *in design*. But this will require developing or modifying the pre-stressing technologies. Two options are investigated in Gen II SCCV.

Use strain gage measurement results to compare and validate the finite element design model. <u>An invalidated model is not nearly as useful as a validated one.</u>

The finite element model has been validated with the strain gage measurement during different stages of SCCV construction and testing, in this reporting period

Hydrogen cyclic testing will be very informative. It would be good to cycle this vessel for a few years to develop a base case and this could probably be achieved with a relatively small amount of funding

Good suggestion. We are looking means to support continued testing after the completion of this project.

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
• Foterra 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
• Harris Thermal Transfer	Specialize in hydrostatic testing for code requirement and cyclic hydrogen pressure testing
• 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

- Unexpected hydrogen purity issue from hydrogen supplier caused ~6 months delay
- The sources of contamination have been identified and corrected

FY2016 Milestones/Deliverables

- Demonstrate and validate the entire SCCV design concept and manufacturability using today's industry scale manufacturing technologies and relevant codes/standards
    - Validate the modeling approach for SCCV design and engineering. Completed
    - Complete the initial phase of long-term testing of the demonstration 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. On-going

Proposed Future Work

- As a follow-on project, develop second generation SCCV for underground hydrogen storage for forecourt fueling stations at 875 bar with significant further cost reduction
  - Meet the cost targets of <\$800/kg H_2 stored at pressures of 875 bar or greater.
  - Show compatibility of design materials with hydrogen, and durability under pressure
  - Achieve 30-year designed service life.
  - Construct and test a prototype system of sufficient size to adequately demonstrate the capability of the technology to be scaled to storage volumes of > 1000 kg of hydrogen.
  - Scalability and footprint of the storage system for versatility in applications

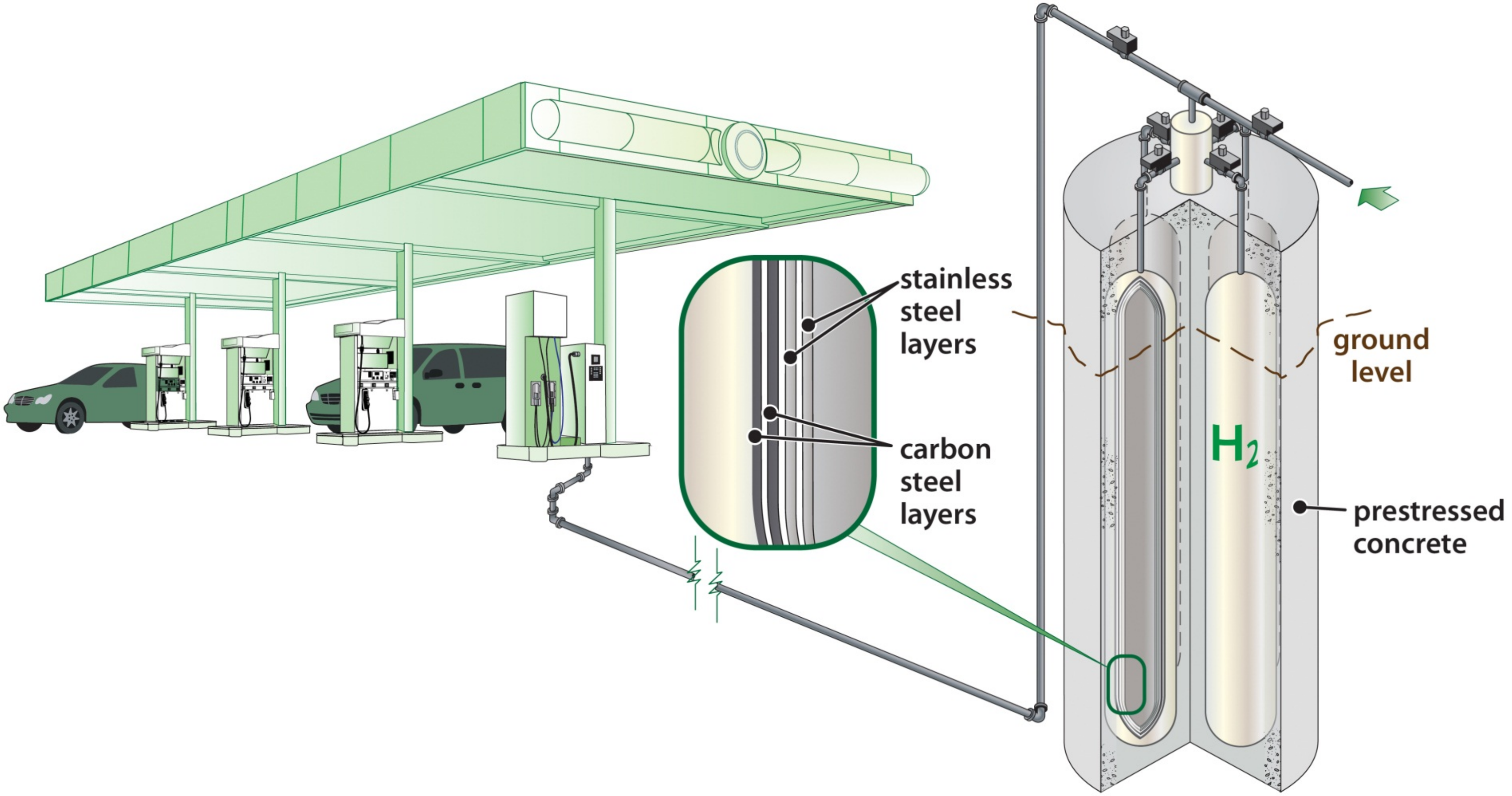
Technology Transfer Activities

- 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 • Address 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 a 90kg H2 430 bar demonstration SCCV for near-term commercialization
Collaborations:	Active partnership with industry, university and other stakeholders
Future Plan:	• Complete technology validation testing of SCCV under cyclic hydrogen service conditions (FY16) • GEN II SCCV for further cost reduction and technology demonstration and transfer (FY15-FY17)

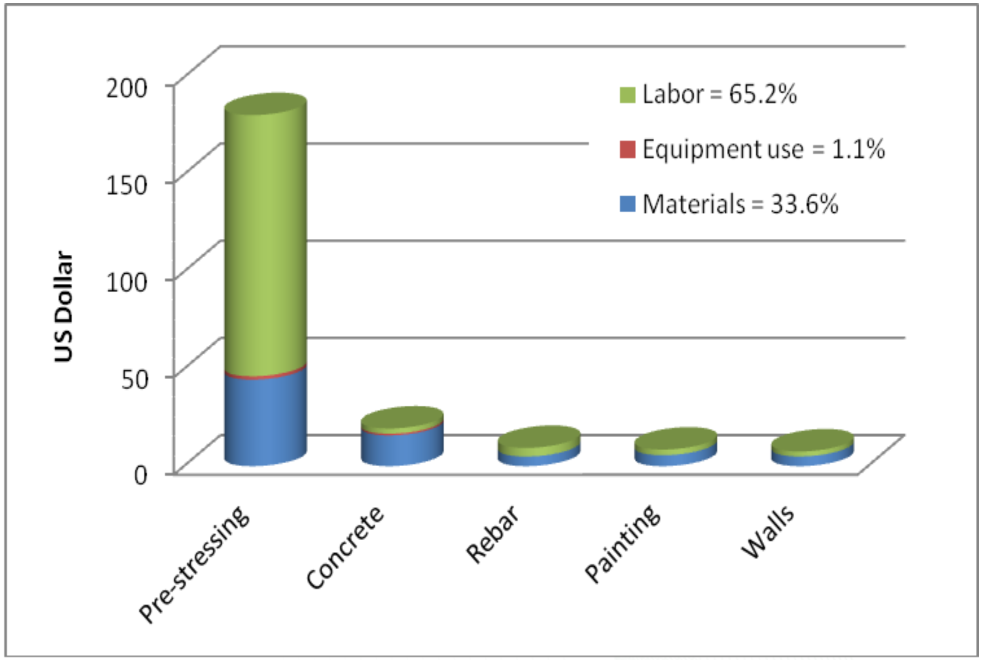
SCCV for High-Pressure H_2 Storage



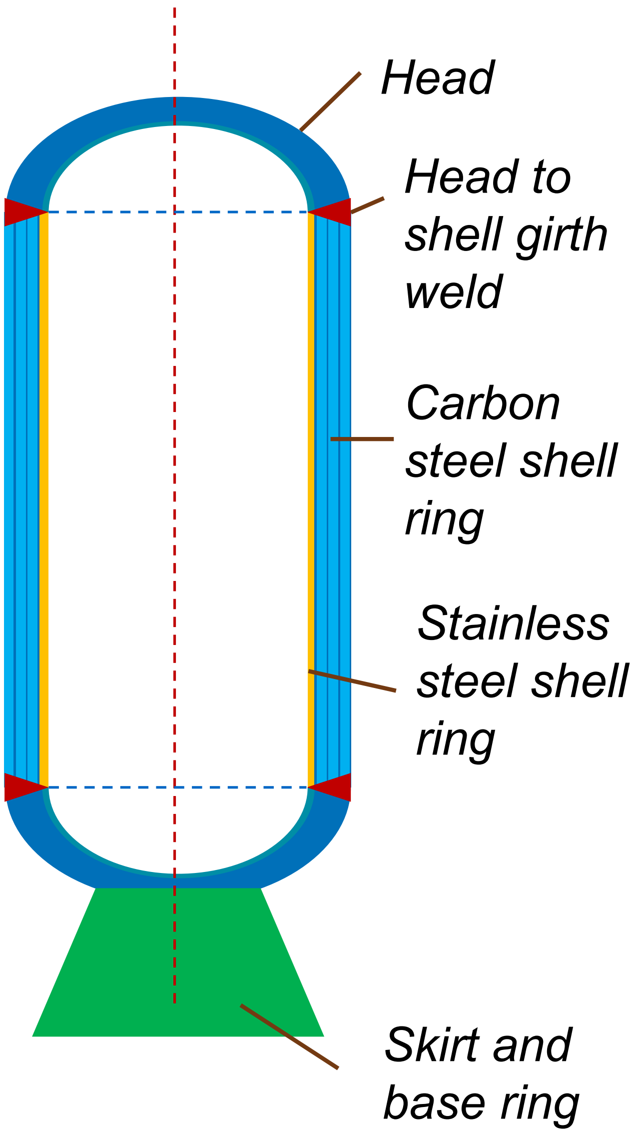
Technical Backup Slides

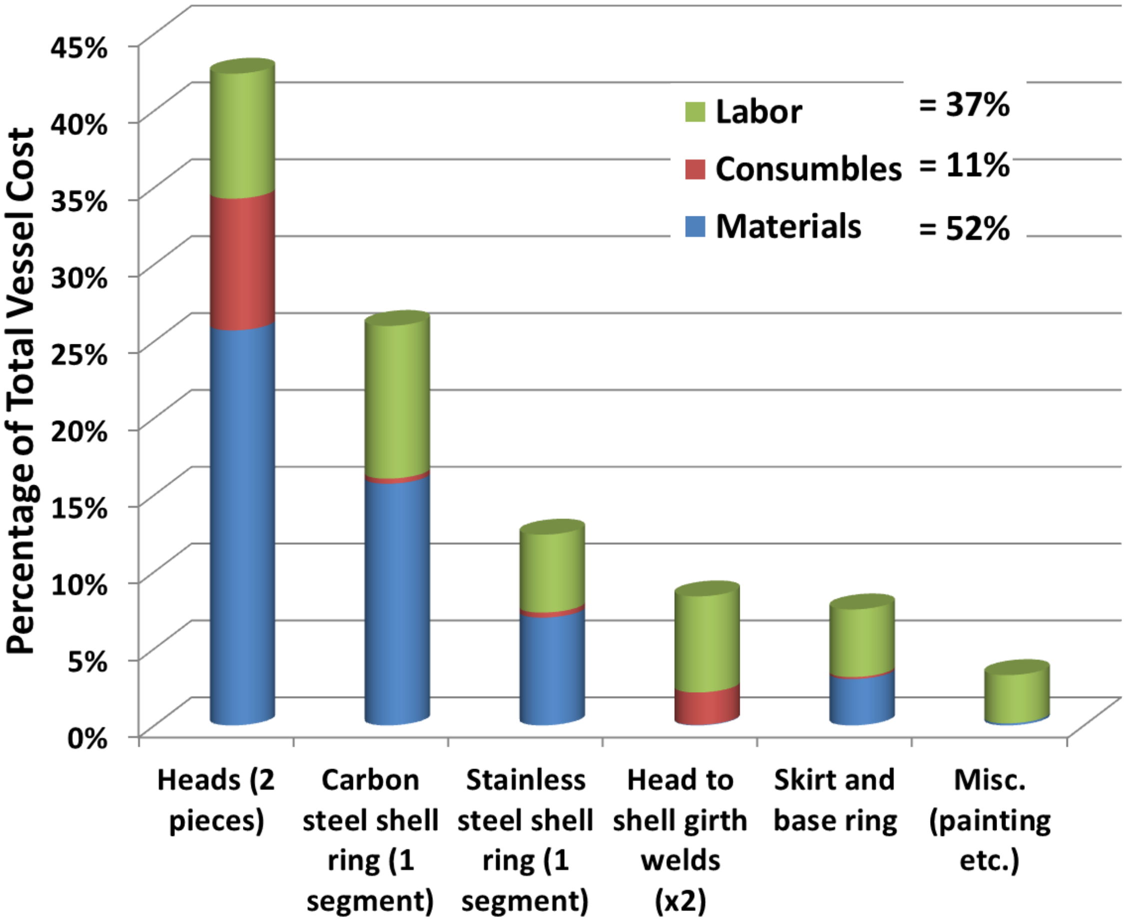
Example: Cost Analysis for Concrete

- 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



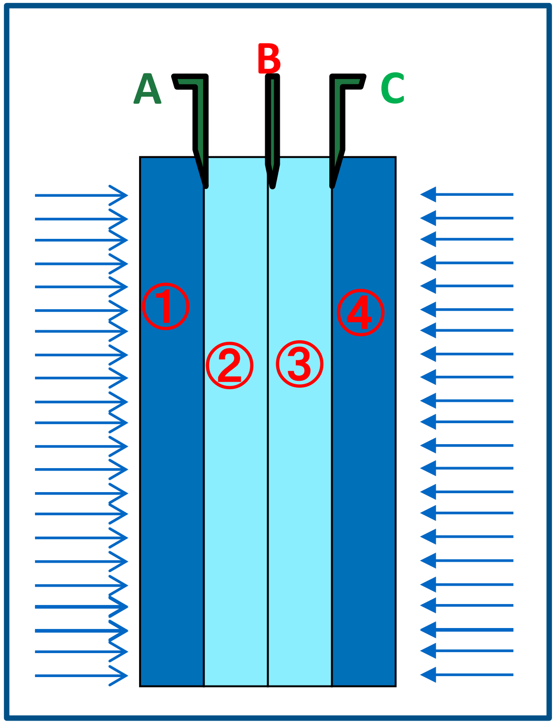
Example: Cost Analysis for Inner Steel Tank



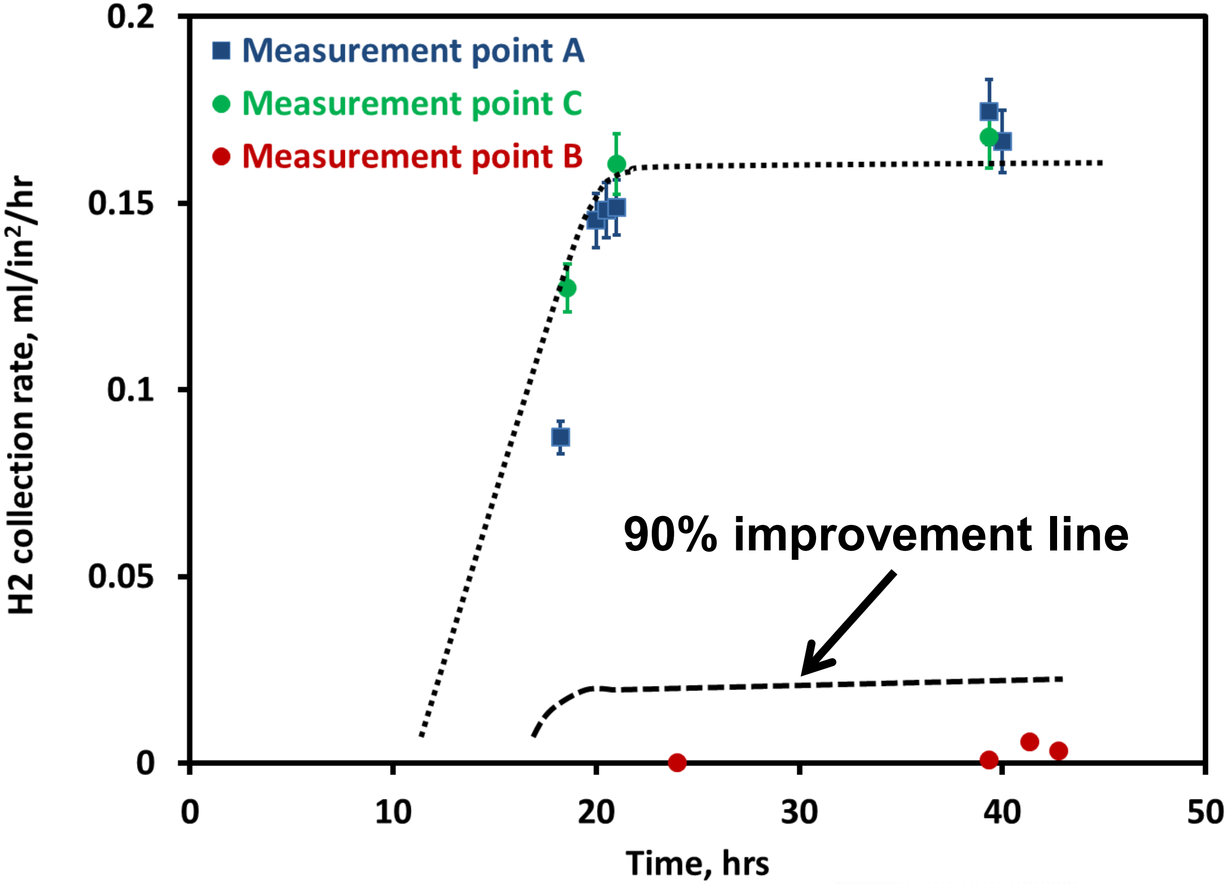


- *Consumables including welding filler wires and shielding gases etc.*
- *Assumed labor rate: $75 per hour*

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.

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**