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

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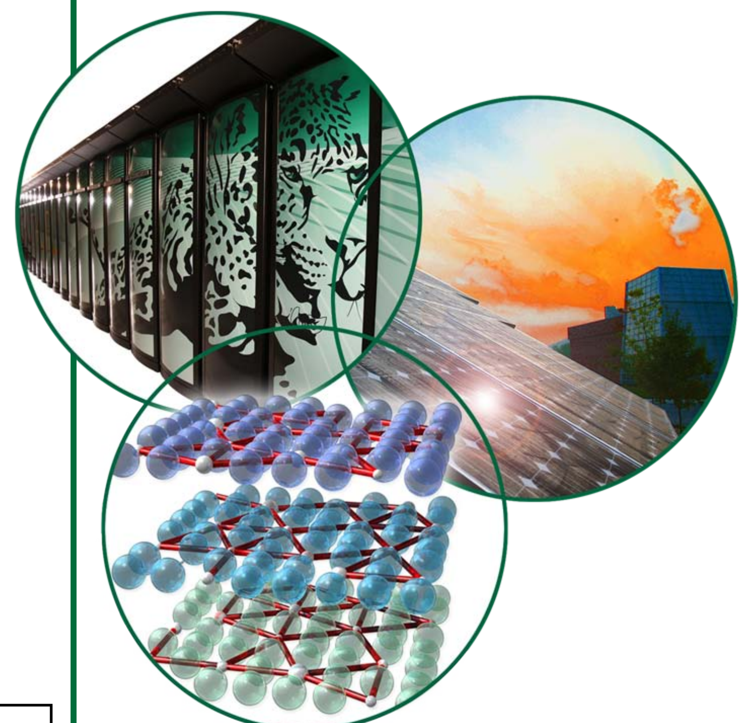
May 10, 2011



Project ID # PD088

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Overview

Timeline

- Project start date: Oct. 2010
- Project end date: Sep. 2013
- Percent complete: *10%*

Budget

- Total project funding
  - DOE share: $3,000K
  - Contractor share: 20%
- Funding received in FY10: $89K
- Funding for FY11: $400K

Barriers

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

Partners

- Project lead
  - ➢ ORNL (Oak Ridge National Laboratory)
- Interactions / collaborations
  - ➢ University of Michigan
  - ➢ MegaStir Technologies
  - ➢ ArcelorMittal
  - ➢ Others
  - ➢ Details in Slide 19

Relevance

- Overall project objective:
  - Develop designs and fabrication technology for cost-effective high-pressure hydrogen storage system for stationary applications
- Relevance to DOE FCT Program:
  - Meet or exceed DOE capital cost target of $300/kg H_2 for off-board gaseous hydrogen storage tanks (DOE 2007 Target)

Table 3.2.2 Technical Targets for Hydrogen Delivery

Category	2005 Status	FY 2012	FY 2015
Storage Tank Purchased Capital Cost ($/kg of H_2 stored)	$820	$500	$300

Ref.: Hydrogen Delivery, *Multi-Year Research, Development and Demonstration Plan*, 2007.

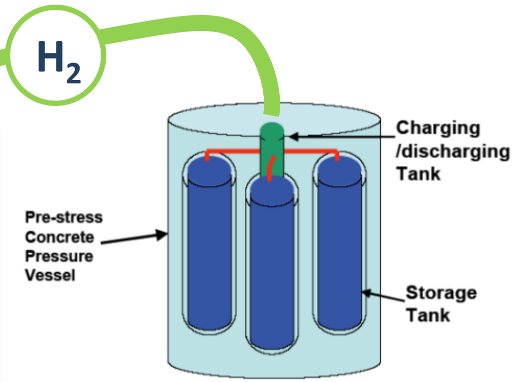
- Specific objectives during the current project year:
  - Develop conceptual engineering design of a bulk storage vessel for hydrogen capable of sustaining 5,000 psi design pressure
  - Demonstrate technical proof-of-feasibility for key design concepts and construction technologies

Potential Application - Fueling Stations

- Amount of H_2 in a stationary vessel = 1,500 kg
  – Refill 260 passenger cars per day (*based on 5.6 kg H_2 tank per car*)
- Baseline storage vessel:
  – Interior volume = 2,300 ft^3 (65.1 m^3)
  – Pressure = 5,000 psi (345 bar) @ room temperature

Refueling of a fuel cell lift truck

H_2 refueling station

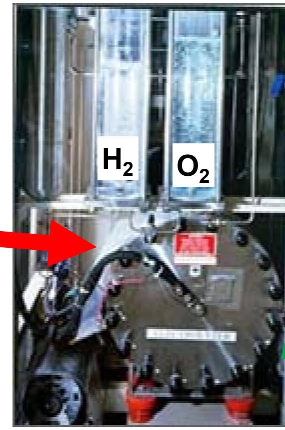


Cost-effective storage vessel

Pictures from DOE Fuel Cell Technologies Program Literature

Potential Application - Utility-scale Load Leveling and Peak Shaving in Renewable Energy Generation

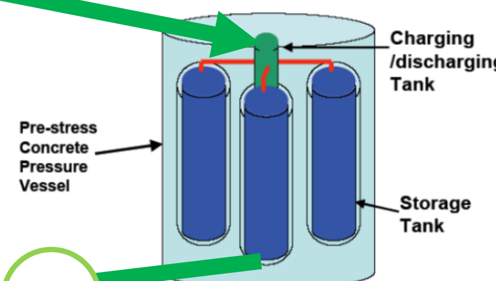
Excess electricity



PEM or solid oxide electrolyzer

H_2

- **Biomass gasification**
- **Other sources for H_2**



Cost-effective storage vessel (1,500 kg H_2)

H_2

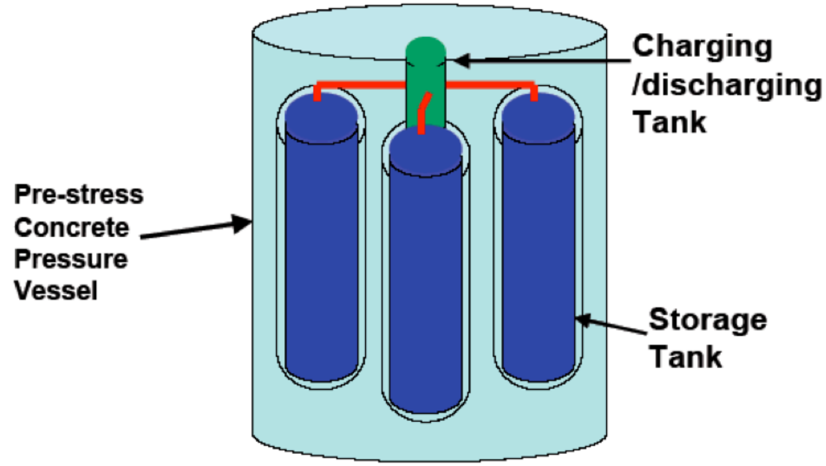
Stationary fuel cells

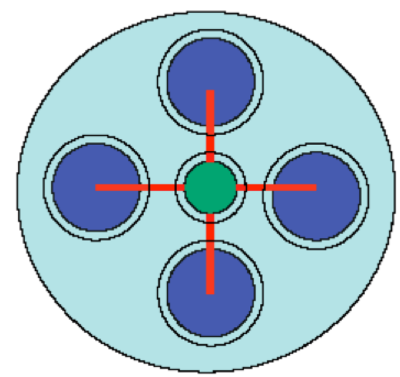
- ***24,200 kWh (3 MW for daytime) back into electrical grid***
- ***Powering 780 homes per day***

Ref.: *An Integrated Strategic Plan for the Research, Development, and Demonstration of Hydrogen and Fuel Cell Technologies, 2010 draft.*

Approach - Overall Engineering Concept

- **Modular design**
  - Scalability and flexibility for cost optimization
  - Individual vessels are self-contained and monitored for improved system safety
- **Use of commodity materials (structural steels and concretes) for cost-effectiveness**
  - Composite structure combining an inner steel pressure vessel with an outer pre-stress concrete pressure vessel
- **Novel vessel design to avoid hydrogen embrittlement of high-strength structural steels**
- **Advanced fabrication technology for steel vessel**
- **Engineering of concrete / steel interface**
- **Embedded sensors to ensure the safe and reliable operation**





Top View

Ballpark Estimate of Construction Cost

	All Steel Layered Vessel				Composite Vessel with Concrete Carrying 50% Hoop Stress Only			Composite Vessel with Concrete Carrying 85% Hoop and Axial Stresses		
Target	2005 Status	2010 Target	2015 Target		2010 Target	2015 Target		2010 Target	2015 Target	
H2 Pressure, psi	5000	7000	8700	10000	7000	8700	10000	7000	8700	10000
H2 Weight, kg	1400	1820	2125	2340	1820	2125	2340	1820	2125	2340
Steel Vessel										
Wall thickness, in	7.7	11.0	14.0	16.4	5.3	6.6	7.7	1.5	1.9	2.2
Weight, lb	194,500	285,700	370,400	439,900	185,500	236,300	276,900	51,900	64,900	75,000
Steel Vessel Cost, $k	$933.7	$1,371.5	$1,777.7	$2,111.7	$895.7	$1,141.4	$1,337.4	$250.6	$313.7	$362.5
PCPV										
Wall thickness, in					24	24	24	48	48	48
Concrete, $k					$13.5	$13.7	$13.8	$48.5	$48.8	$49.0
Steel Tendon, $k					$109.8	$143.9	$171.5	$224.3	$284.2	$330.6
Rebar & Liner, $k					$61.0	$62.0	$62.8	$117.0	$117.7	$118.2
PCPV Cost, $k	$0	$0	$0	$0	$184.3	$219.6	$248.1	$389.8	$450.7	$497.8
Total Purchase Cost, $k	$933.7	$1,371.5	$1,777.7	$2,111.7	$1,080.0	$1,361.0	$1,585.5	$640.4	$764.4	$860.3
Cost per kg H2, $	***$667***	***$754***	***$837***	***$902***	***$593***	***$640***	***$678***	***$352***	***$360***	***$368***

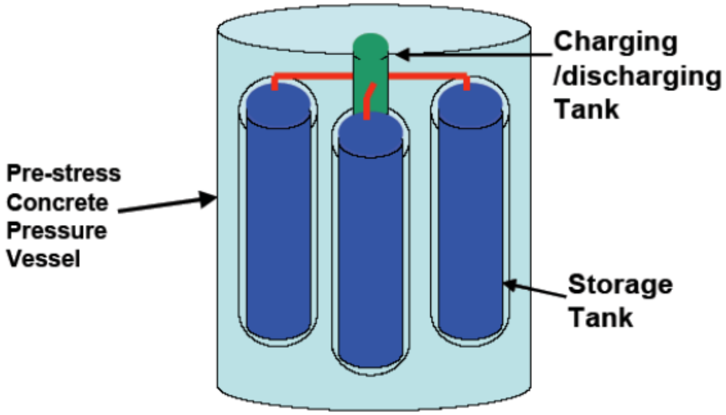
- *The basic premises in cost analysis. (1) Reference vessel: a cylindrical vessel with semi-sphere heads, 12 ft diameter and 21.7 ft long (2000 ft^3 storage volume), with piping attachment and maintenance access; (2) 50ksi inner steel vessel design allowable stress (SA724 100ksi grade high-strength steel) and 190ksi steel tendon design stress (Grade 270 steel), per ASME BPV Section VIII Division III design rules and material specification; (3) ASME BPV stress formulas to determine steel vessel wall thickness; (4) Layered steel vessel: steel plate cost at $2/lb, labor cost at $100/hr, and 6000 hours to fabricate the reference vessel, estimated by a major steel vessel construction; (5) PCPV: material and construction cost for rebar, high-strength tendon, and high-strength concrete are $2.5/lb, $3.5/lb, and $400/cubic yard, respectively, based on 2007 steel and concrete market price; (6) The estimated costs do not include the expected additional cost reduction by FSW process, the flat steel ribbon cross-helical wound construction, and use of modern ultra-high strength steels.*

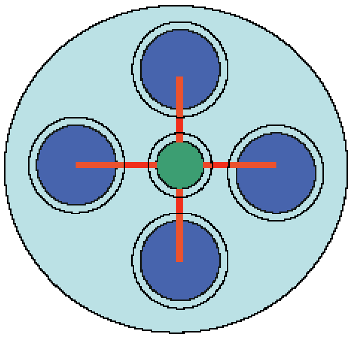
Proposed composite vessel design and fabrication technology have a sound basis to meet or exceed DOE cost target for FY2010 ($500/kg H_2) and FY2015 ($300/kg H_2).

Technical Accomplishments - Modular Design for Scalability and Safety

- Four inner steel tanks per stationary storage vessel
- Interior volume for each tank
  - 574.8 ft^3 at 5,000 psi (i.e., 375 kg of CGH_2 @ room temperature)
- Tanks can be shut-down individually for improved reliability and safety

CGH_2 = Compressed gas hydrogen

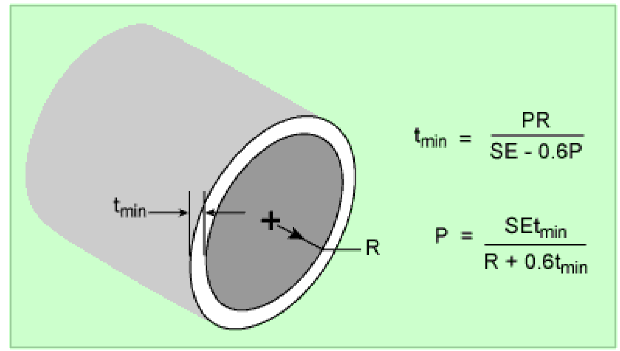




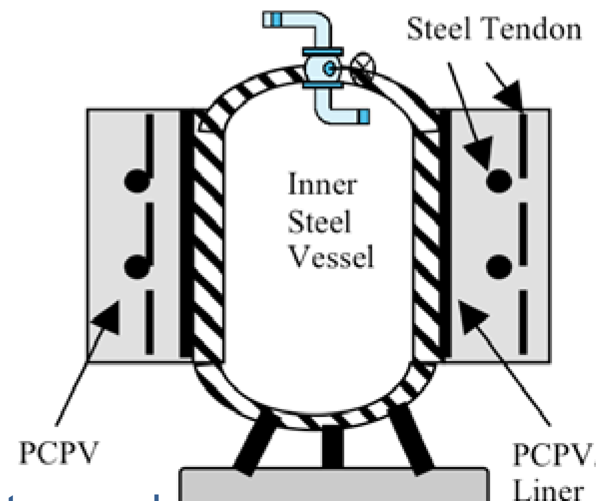
Top View

Lowering Cost by Integration of Steel Vessel and Concrete Vessel

- ASME BPV Section VIII Codes:
  - Steel wall thickness dictated by the hoop stress induced by the CGH_2 pressure (P)



- Steel vessel with concrete reinforcement
  - **Pre-stressed concrete designed to take 50% of the hoop stress**
  - **As a result, steel wall thickness reduced by half**
  - **Hoop stress split between steel and concrete as a design variable in cost modeling**
  - **Both structural steels and concrete are cost-effective commodity materials**



Prestressed concrete

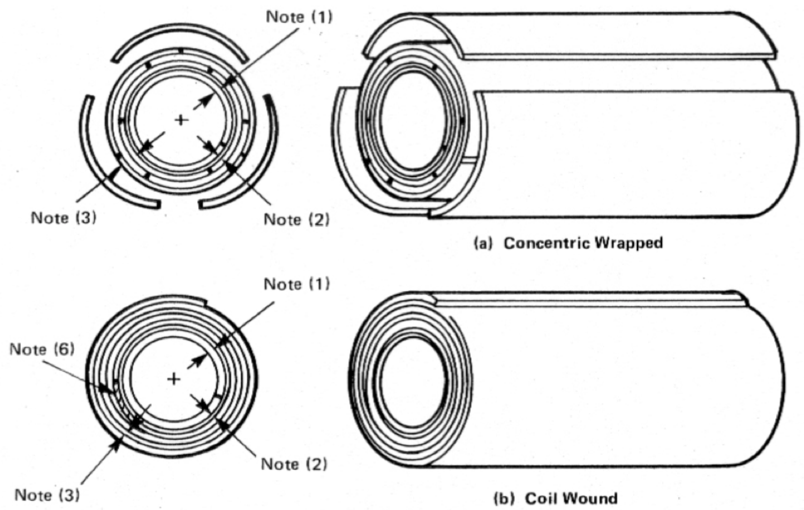
Basis of Design – Steel Vessel

- Advantages:
  - Codes and Standards available for safe design and construction of high-pressure steel vessels
  - Well-characterized mechanical properties
  - Many decades of construction and operating experience (inspection, maintenance, etc.)
- Challenges:
  - Structural steels (especially high-strength grades) susceptible to hydrogen embrittlement (HE)
  - Cost going up non-linearly (e.g., parabolic) with increase of steel thickness

H_2 assisted fatigue of a steel tank

Layered Steel Vessels for further Cost Reduction and Ease of Fabrication

- History:
  - Since 1932
  - High-pressure ammonia synthesis for nitrites production
  - Aircraft carriers
- Relative low cost fabrication
- Acceptable code case by ASME BPV codes
- Autoclaves (ORNL's hydrogen permeation system)

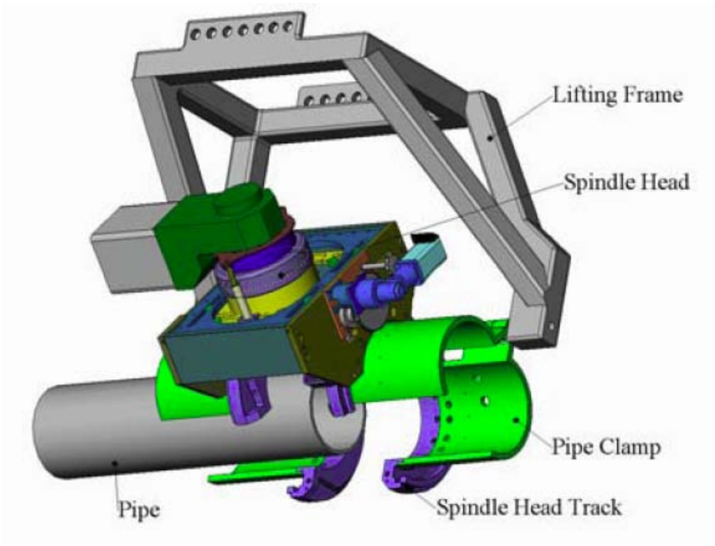


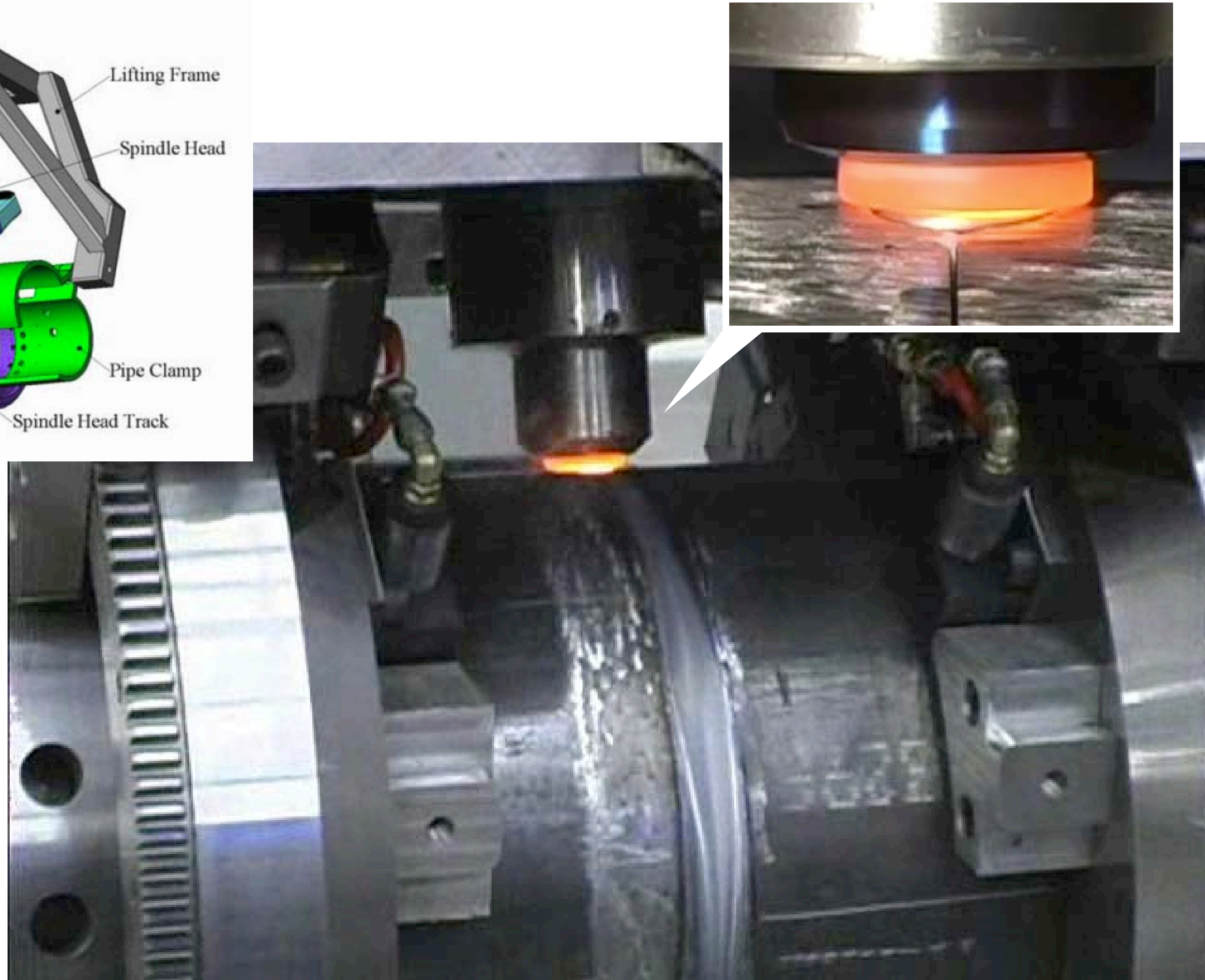
Layered vessel construction from AMSE BPV Code Section VIII and an actual layered section welded to a solid section

Example of High-Pressure Layered Steel Vessel

- Picture showing a 96-ft long layered high-pressure steel vessel for ammonia conversion with operating pressure of 4000 psi and temperature of 450 F.

Fabrication Technology for Layered Steel Vessel based on Friction Stir Welding



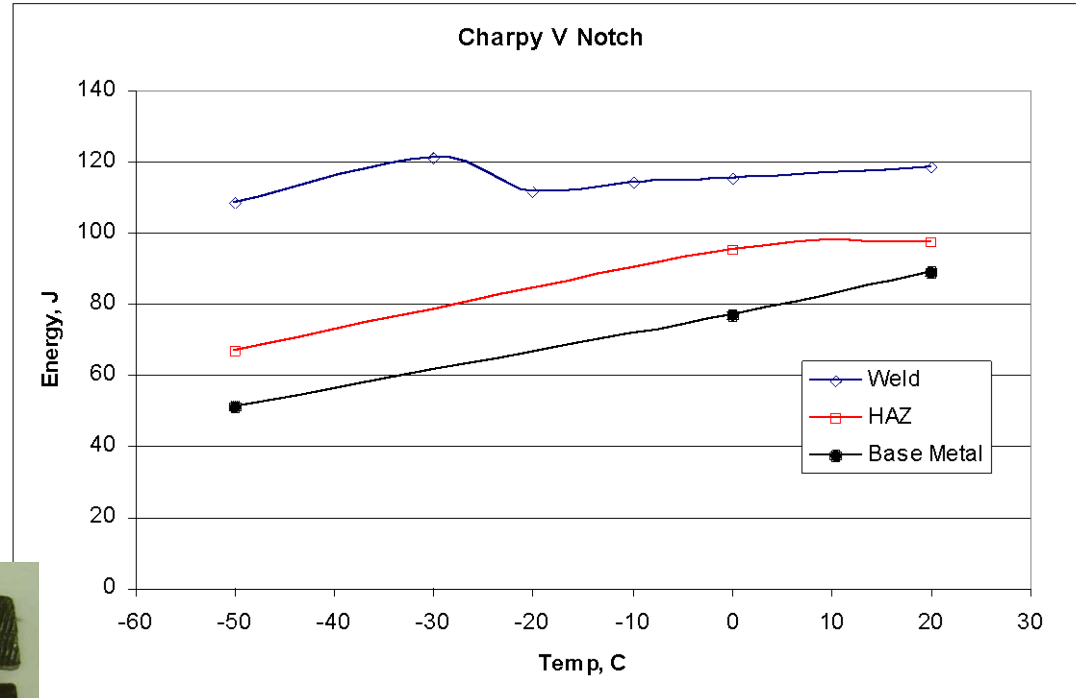


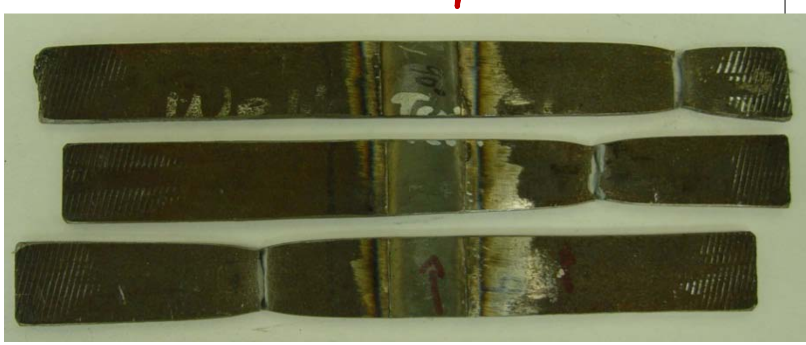
Fully-Automated and Field-Deployable Friction Stir Welding System for Joining Steel Sections

Click the image to play a movie clip of friction stir welding

Example showing girth weld of API X65 steel pipe for natural gas transmission (collaboration with MegaStir)

Superior Joint Strength and Toughness attained by Friction Stir Welding



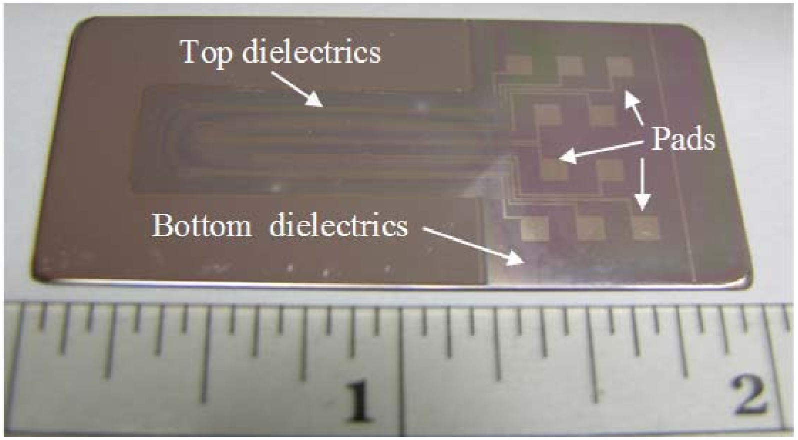


Charpy impact test results show the improved toughness of weld regions compared to base metal.

Weld regions exhibit better tensile strength compared to base metal.

Vessel Safety Monitoring

- Layered steel vessel enables vessel safety/health monitoring
- Embedded sensors
  - Hydrogen sensors
  - Strain and stress sensors
  - Temperature sensors



Picture of thin-film sensor which is under evaluation for monitoring of strain and stress

Overview of Current Project Status and Future Work

- First year of substantial development
  - Developing the preliminary design and engineering analysis of the integrated hydrogen storage pressure vessel.
    - Cost modeling
    - Design trade-off and optimization studies
  - Investigating structural material performance and design at interface between steel core vessel and pre-stressed concrete containment vessel.
  - Developing the high-pressure permeation testing protocol for validation of hydrogen embrittlement mitigation.
  - Working with industry partners to finalize the work scope and cost-share.
- Years 2 and 3
  - Detailed design and engineering.
  - Mock-up vessel construction, testing and demonstration.

Collaborations - Project Team

Oak Ridge National Laboratory
- Technology lead
- Project management
- System integration
- High-pressure H2 testing

Shell Global Solutions
- Vessel design review
- Materials selection
- Validation testing

MegaStir Technologies
- FSW hardware
- FSW process
- Tool materials

University of Michigan
- Concrete/steel interface design

Mittal Steel USA
- Steel R&D

Hydrogen Producer
- Design review
- Fabrication assistance

Steel Vessel Fabricator
- Forging
- Vessel fabrication

Global Engr & Tech. LLC
- Layered steel vessel design
- Code compliance

Fabricator for Prestressed Concrete Vessel

Project Summary

Relevance:	**Demonstrate off-board high-pressure storage vessel for CGH_2 that can meet or exceed the relevant DOE cost target**
Approach:	**Develop composite vessels combining inner steel tanks and outer prestressed concrete pressure vessels**
Progress to date:	• **Overall vessel design and cost modeling** • **Technical proof-of-feasibility studies:** ➢ **Hydrogen mitigation** ➢ **Advanced fabrication based on friction stir welding** ➢ **Embed sensors**
Collaborations:	**Active partnership with university and industry companies**
Future research:	• **Detailed design and engineering** • **Mock-up vessel construction, testing and demonstration**

Acknowledgements

- **Project Sponsor:** DOE Fuel Cell Technologies Program
- Sara Dillich, Monterey Gardiner and Scott Weil (DOE)
- Dave Stinton and Steve Pawel (ORNL)