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Hydrogen Storage Engineering
CENTER OF EXCELLENCE

Development of Improved Composite Pressure Vessels for Hydrogen Storage

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Project ID# ST047

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Overview

Timeline

- Phase 1 start 1 Feb 2009
- Phase 1 end 30 Apr 2011
- 30% complete

Budget

- Project funding $2,000,000
- Phase 1 funding $761,466
  - DOE share $609,156
  - Contractor share $152,290
- FY08 = $ 0
- FY09 = $305,000
- FY10 = $250,000 (plan)

Barriers

- Barriers addressed
  - A. System Weight and Volume
  - B. System Cost
  - G. Materials of Construction
- Targets (2010)
  - Gravimetric capacity > 4.5%
  - Volumetric capacity > 0.045 kg H_2/L
  - Storage system cost - TBD

Partners

- HSECoE
  SRNL, PNNL, LANL, JPL, NREL, UTRC, GM, Ford, LC, Oregon State Univ, UQTR
- Project lead = Don Anton, SRNL

Objectives - Relevance

- Meet DOE 2010 and 2015 Hydrogen Storage Goals for the storage system by identifying appropriate materials and design approaches for the composite container

	2010	**2015**
Gravimetric capacity	> 4.5%	> 6%
Volumetric capacity	> 0.045 kg H_2/L	> 0.081 kg H_2/L
Storage system cost	TBD	TBD

- Maintain durability, operability, and safety characteristics that already meet DOE guidelines for 2010 and 2015
- Work with HSECoE Partners to identify pressure vessel characteristics and opportunities for performance improvement
- Develop high pressure tanks as are required to:
  - Enable hybrid tank approaches to meet weight and volume goals
  - Allow metal hydrides with slow charging kinetics to meet charging goals

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Phase 1 Approach

- *Establish and document baseline* design, materials, and manufacturing process
- Evaluate potential improvements for design, material, and process to achieve cylinder performance improvements for weight, volume, and cost
- Down select most promising engineering concepts
- Evaluate design concepts and ability to meet Go/No-Go requirements for moving forward
- Document progress in periodic reports and support HSECoE Partner meetings and teleconferences

Phase 1 Milestones

- Establish/document baseline design and identify options for improvement – **Complete**
- Report on Phase 1 evaluation of design, material, and process improvements
- Identify most promising engineering concepts
- Report on Phase 1 selection of most promising design, material, and process improvements
- Document revised baseline design summary
- Evaluate likelihood of composite container meeting system and DOE objectives

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Progress – Baseline Design/Materials

- Design
  - Fiber reinforced composite structure
  - Plastic liner /permeation barrier
  - Metallic end bosses
  - 350 bar pressure capability
- Materials
  - Carbon fiber
  - Epoxy resin
  - HDPE liner
  - AA 6061-T6 bosses

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Progress – Baseline Design/Materials

Table 1: Service conditions and nominal cylinder properties

Service Pressure	5,000 psi (344.7 bar)
Gas Settling Temperature	59 °F (15 °C)
Maximum Fill Pressure	6,500 psi (448 bar)
Service Life	20 years
Gas Fill Temperature Limits	-40 to 149 °F (-40 to 65 °C)
Operating Temperature Limits	-40 to 180 °F (-40 to 82 °C)
Proof Test Pressure	7500 psi (517 bar)
Minimum Rupture Pressure	11,700 psi (807 bar)
Cylinder Diameter	21.4 inches (543.4 mm)
Cylinder Length (unpressurized)	63.0 inches (1600 mm)
Cylinder Length at Maximum Fill Pressure	63.34 inches (1609 mm)
Cylinder Empty Weight (excluding hardware)	231 lbs (105 kg)
Cylinder Volume	15,865 in^2 (260 L)
Cylinder Volume at Service Pressure	16,132 in^2 (264.4 L)
Cylinder interior diameter	19.2 inches (488 mm)

Note: Future improvements will be evaluated against this baseline

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Progress - Alternative Fibers

- Investigate alternative carbon fibers
  - Relative to fiber strength
  - Relative to impact tolerance
- Baseline Fiber - Toray T700
- Five alternate fibers tested
- Vessels wound using same parameters for each
  - Mandrel
  - Wind patterns
  - Tooling
  - Process
- Tow count adjusted, per fiber, to maintain consistent band cross sectional area

Progress - Alternative Fibers, Strength

- One vessel constructed of each fiber hydrostatically burst
- Stress in fiber at failure calculated based on fiber certifications and normalized to Toray T700
- Drop/cycle/burst testing is in progress
- Strength versus cost will need to be evaluated following completion of testing

Alternate Fiber	Normalized Strength
Toray T700	1.00
Fiber A	1.19
Fiber B	0.90
Fiber C	0.98
Fiber D	0.77
Fiber E	0.90

Future Work - Alternative Fibers, Impact Tolerance

- Future Actions (Phase 1)
  - One unit of each fiber to be drop and cycled per NGV 2-2007
  - 5 of 6 units have been drop tested and are beginning the cycling portion of the testing
  - All 6 units will be cycled and then burst
  - Report will be written at the conclusion of testing and data gathering

Progress - Alternative Boss Material

- Investigate methods to create bosses with 7075-T73 Aluminum
  - Properties difficult to acquire through the entire thickness
  - High strength would allow reduction in boss size and allow Aluminum use at high pressures
- Accomplishments
  - Near net shaped bosses machined from 7075-T6 Aluminum
  - 4 bosses have been machined and surface finished to influence quench rate
    - Smooth machining
    - Rough machining
    - Sand blasted
    - Chemical etching
  - Bosses have been heat treated to a T73 condition
  - Harness versus strength evaluation is in progress

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Future Work - Alternative Boss Material

- Future Actions (Phase 1)
  - Bosses in process of being sectioned for review
  - Each boss cross section will be hardness mapped
  - Hardness mapping will be used to create cross sectional strength profile
  - Sections will be reviewed to evaluate effectiveness of relative surface finishes in achieving T73 condition

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Progress - Resin Toughening

- Accomplishments
  - Identified and gathered candidate material specifications for resin toughening
  - Received samples of candidate materials for testing
  - Acquisition of equipment/materials for making test specimens
  - Developed procedure for preparing test specimens
  - Preliminary screening (Viscosity, Tg) of alternate hardener
  - Sent baseline formulation and alternate hardener specimens for testing (ASTM D5045)
  - Awaiting tooling for completion of ASTM D638 testing on baseline formulation and alternate hardener

Future Work - Resin Toughening

- Future Actions (Phase 1)
  - Determine which hardener will be used for testing (Based on ASTM D5045 and ASTM D638)
  - Preliminary screening (Viscosity, Tg) of candidate materials – select down
  - Begin testing to determine mechanical and environmental/chemical properties – select down
  - Coupon impact test – select down
  - Build full scale parts for qualification testing

Progress – Alternate Liner Materials (Permeation)

- Coatings and surface treatments do not look viable to date
  - Coatings show blistering following hydrogen soak and blow down
  - Surface treatments have not been effective
- HDPE with nanoclay filler was not successful
  - Molecular properties of HDPE did not promote dispersion
  - Improvement seen with new vendor material
  - HDPE with titanium dioxide resulted in a 25% reduction in permeation
- HDPE/EVOH
  - Problems with layered materials including welding
  - Have looked at adding EVOH as an outside layer to avoid weld region, but have had adhesion problems
  - Looking at EVOH that has been modified to increase ductility

Progress – Alternate Liner Materials (Permeation) - continued

- Nylon
  - Have seen lower permeation rates but will have a large increase in cost (4X to 10X) in reference to standard HDPE
  - EVA did not show an improvement
- Domes have been molded
  - HDPE
  - HDPE/standard nonclay
  - HDPE/development nanoclay
  - HDPE/titanium dioxide
- Domes have been molded together to begin winding vessels

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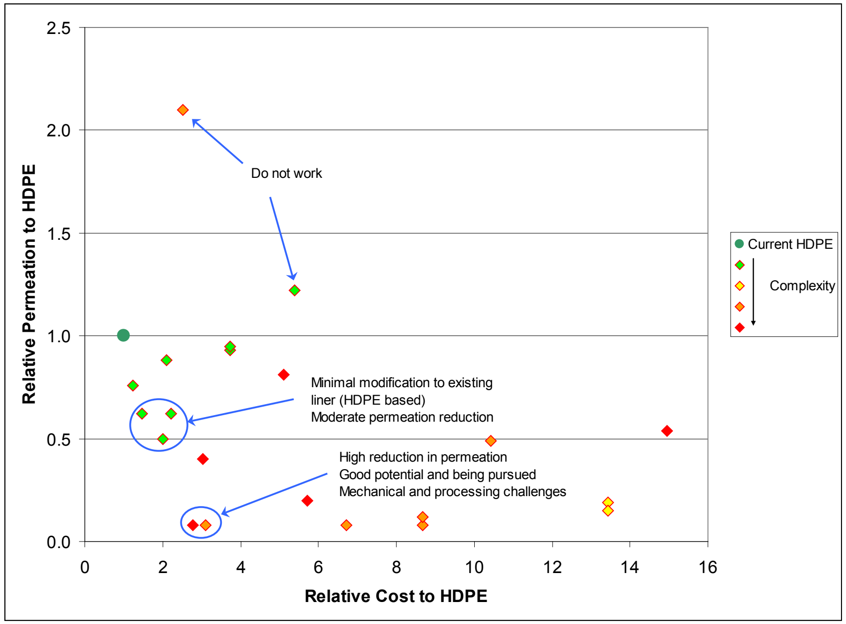
Progress – Alternate Liner Material Permeation versus Cost

- HDPE is baseline (1,1)
- Comparison of relative cost and permeation rates
- HDPE fillers show 40% reduction with limited cost increase
- Alternate materials show promise of significant permeation reduction
- Some alternate materials are prohibitively expensive



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Future Work – Alternate Liner Materials (Permeation)

- Future Actions (Phase 1)
  - Wind liners with the current designated additives as stated on previous slide
  - Permeation testing will follow on complete vessels
  - Working to get domes molded in nylon and EVOH if this looks promising in coupons
  - Plan to test with 100% hydrogen at Powertech Labs
  - Further testing to confirm mechanical and physical properties will need to be evaluated as well to capture data with respect to fatigue and cold fast fill

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Progress – Reduced Safety Factors

- Improved data base for stress rupture of carbon fiber may allow reduced safety factors
  - Maintain projected reliability
  - Reduce cost and weight, increase volumetric efficiency, with thinner walls
- Stress rupture project presented at industry workshop to gain feedback and support
  - Project is being refined
  - Some collaborators and funding has been identified
  - Additional collaboration and funding is being sought
  - Considering stress rupture, fatigue and damage tolerance
  - Evaluate damage vs. impact to characterize safety and ability to remain in service after damage
  - Evaluate NDE as a means of monitoring the structural integrity, allowing thinner laminates and removal from service before rupture

Future Work – Overall Project

- Continue progress on evaluating potential improvements
- Down select most promising engineering concepts.
- Evaluate design against DOE 2010 and 2015 Hydrogen Storage Go / No Go Criteria
- Phase 2 – continuation of container development in support of system requirements
- Phase 3 – fabrication of subscale containers to support assembly of prototype systems for evaluation

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Collaborations

Hydrogen Storage Engineering Center of Excellence

D. Anton, SRNL
T. Motyka, SRNL

Materials Operating Requirements

D. Herling, PNNL

- Materials Centers of Excellence Collaboration – SRNL, LANL, NREL
- Reactivity – UTRC
- Adsorption Properties – UQTR
- Metal Hydride Properties – SRNL
- Chemical Hydride Properties - LANL

Transport Phenomena

B. Hardy, SRNL

- Bulk Materials Handling – PNNL
- Mass Transport – SRNL
- Thermal Transport – SRNL
- Media Structure - GM

Enabling Technologies

J. Reiter, JPL

- Thermal Insulation – JPL
- Hydrogen Purity – UTRC
- Sensors – LANL
- Materials Compatibility – PNNL
- Pressure Vessels - PNNL

Performance Analysis

M. Thornton

- Vehicle Requirements– NREL
- Tank-to-Wheels Analysis – NREL
- Forecourt Requirements - UTRC
- Manufacturing & Cost Analysis - PNNL

Integrated Power Plant/ Storage System Modeling

D. Mosher, UTRC

- Off-Board Rechargeable - UTRC
- On-Board Rechargeable – GM
- Power Plant – Ford

Subscale Prototype Construction, Testing & Evaluation

T. Semelsberger, LANL

- Risk Assessment & Mitigation – UTRC
- System Design Concepts and Integration - LANL
- Design Optimization & Subscale Systems – LANL, SRNL, UQTR
- Fabricate Subscale Systems Components – SRNL, LANL
- Assemble & Evaluate subscale Systems – LANL, JPL, UQTR

Technology Area

Technology Area Lead

- Technology Team – TT Lead
- Technology Team – TT Lead
- Technology Team – TT Lead

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Collaborations

Enabling Technologies
Joe Reiter, JPL

- ***Thermal Insulation***
  - **JPL**
- ***Hydrogen Purity***
  - **UTRC**
  - SRNL, PNNL, LANL
- ***Sensors***
  - **LANL**
- ***Thermal Devices***
  - **JPL**
  - PNNL, LANL, UTRC
- ***Containment and Pressure Vessels***
  - **PNNL**
  - Lincoln, SRNL, UTRC

Collaborations

Subscale Prototype Construction, Testing, & Evaluation

T. Semelsberger, LANL

Risk Assessment & Mitigation

UTRC
All Other Partners

Design & Optimize Subscale Systems

LANL, SRNL, UQTR
JPL, UTRC, PNNL, OSU

Fabricate Subscale System Components

SRNL, LANL
Lincoln, OSU, PNNL, UTRC

Assemble & Evaluate Subscale System

LANL, JPL, UQTR

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Accomplishments

- Kick-off meeting in December 2008, Washington DC
- IP agreement signed January 2009
- Face to Face Meeting February 23-25, 2009, Golden, CO
- Face to Face Meeting September 28-October 1, 2009, Charleston, SC
- Face to Face Meeting March 2-4, 2010, Pasadena, CA
- Collaborating on technical paper with John Khalil (UTRC)(Lead), Kevin Simmons (PNNL) and Daniel Dedrick (SNL)

Summary

- Lincoln Composites has initiated work under the DOE contract funding the HSECoE
- Design, material and process improvements have been identified that show potential to meet DOE 2010 and 2015 goals for the storage system
- Work is progressing on schedule with expectation of meeting go/no-go criteria to proceed to Phase 2
  - 4 of the DOE 2010 numerical system storage targets must be fully met
  - The status of the remaining numerical targets must be at least 40% of the target or higher