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Hydrogen Storage Engineering
CENTER OF EXCELLENCE

Development of Improved Composite Pressure Vessels for Hydrogen Storage

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Hexagon Lincoln

10 June 2015

Project ID#
ST047

Overview

Timeline

- Project Start Date: 2/1/09
- Project End Date 6/30/15

Budget

- Total Project Value: $1,781,251
- Cost Share: $356,251
- DOE Share: $1,425,000
- Total DOE Funding Spent*: $1,187,215

* as of 3/31/15

Barriers

- Barriers addressed
  - A. System Weight and Volume
  - B. System Cost
  - G. Materials of Construction
- Targets (2020)
  - Gravimetric capacity > 5.5%
  - Volumetric capacity > 0.040 kg H_2/L
  - Storage system cost < $12/kWh

Partners

- HSECoE

  SRNL, PNNL, LANL, JPL, NREL, UTRC, GM, Ford, HL, Oregon State Univ, UQTR, Univ of Michigan, BASF
- Project lead = Don Anton, SRNL

Objectives - Relevance

- Meet DOE 2020 Hydrogen Storage Goals for the storage system by identifying appropriate materials and design approaches for the composite container

	2020 Goal
Gravimetric capacity	> 5.5%
Volumetric capacity	> 0.040 kg H_2/L
Storage system cost	< $12/kWh

- Maintain durability, operability, and safety characteristics that already meet DOE guidelines for 2020
- Work with HSECoE Partners to identify pressure vessel characteristics and opportunities for performance improvement, in support of system options selected by HSECoE Partners
- Develop high pressure tanks as required to:
  - Contain components and materials of the selected hydrogen storage system
  - Operate safely and effectively in the defined pressure and temperature range

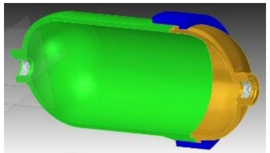
Approach

- *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 as applicable to HSECoE selected systems
- 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

Approach/Results

- Phase 1
  - Material evaluation for cost and weight reduction, internal volume increase
    - Projected cylinder improvements: 11% lower weight, 4% greater internal volume, 10% lower cost
  - Evaluate design and materials against operating requirements of storage systems selected by HSECoE Partners
    - Baseline design approach established
    - Liner material development is most significant issue
    - Maintain durability, operability, and safety

- Phase 2
  - Subscale Type 1 and Type 4 tanks designed and tested
  - Focus on cryo-adsorbant system
  - Trade studies compared design and material options
  - Decision made to use 3-piece Type 1 tank for Phase 3 testing
  - Agreed to make monolithic Type 1, and cryo capable Type 3 and Type 4
  - Agreed to demonstrate vacuum shell for insulation and fill



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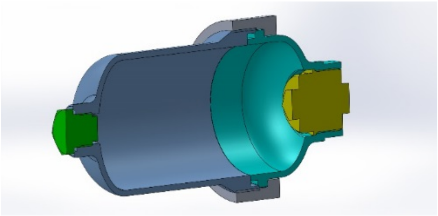
Phase 3 S*M*A*R*T Milestones - #1

- Report on ability to design and manufacture a baseline, separable Type 1 tank in accordance with:
  - size (2L - 6L),
  - pressure (100 bar service pressure),
  - operating temperatures (80K – 160K) and
  - interfaces specified by HSECoE team members, and
  - with a 10% reduction in weight per unit volume compared with the Type 1 tank tested in Phase 2.
  - Status – complete.
    - Tanks delivered to project partners for assembly of internal components and testing

Planned 3-piece Type 1 design




- New design to meet team needs for demonstration of MATI approach
  - Larger port, plug inserted from inside
  - Wall thickness reduced for lighter weight
  - Existing cryo-seals could be used
- Seals leaked at service pressure at cryo temperatures
  - Several new sealing concepts tried, limited success
  - Seal manufacturer redesigned seals, still leaked
- New Type 1 cylinder design chosen for system test purposes

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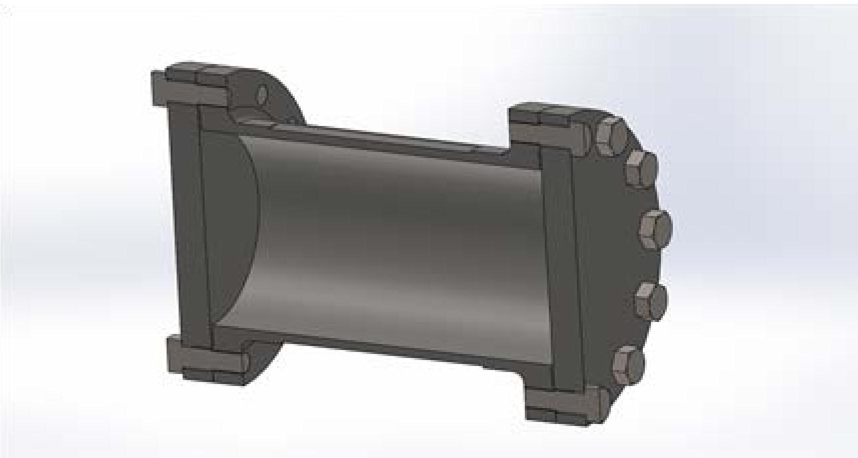
Type 1 Design for System testing



- Inner diameter of 4.40 inches
- Nominal wall thickness of 0.25 inch
- Cylinder length 8.50 inches
- End plates 0.75 inch thick, 7.0 inch dia
- 12 ½-20 x 1.5-inch bolts

- Design worked for system test purposes
- No leakage
- Not intended to be reflective of a production design

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Phase 3 S*M*A*R*T Milestones - #2

- With other HSECoE partners, report on the ability to design:
  - a full scale thermos bottle concept tank
  - with the LN2 tank cooling
  - with a modeled cooling rate and transient heat loss for dormancy determination meeting the DOE technical targets.
  - Status – in work.
    - Initial testing of prototype tank in early April in vacuum insulated thermal shell provided supporting data
    - Second set of testing in late April
    - Data being evaluated, first data indicates DOE technical targets will be met
    - Full scale tank with cooling concept to be designed

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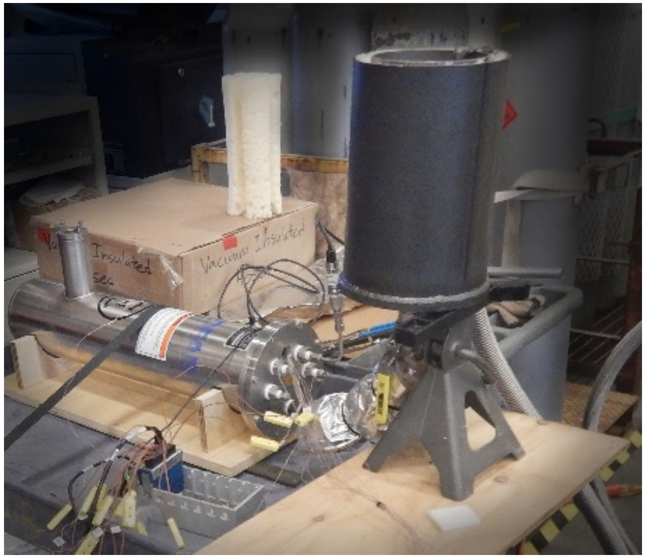
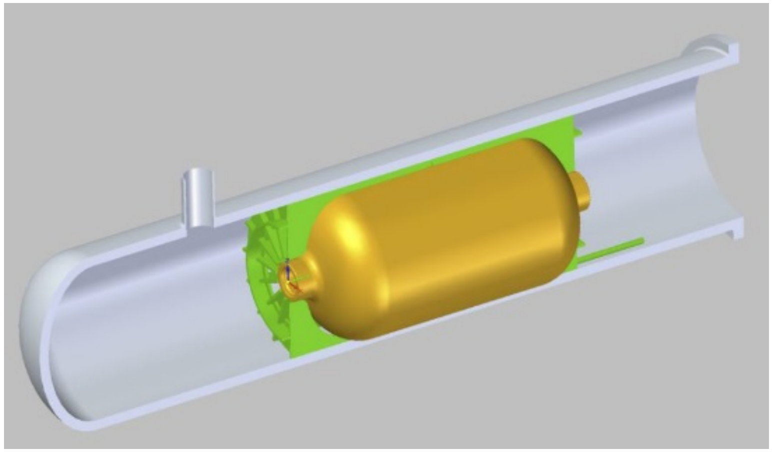
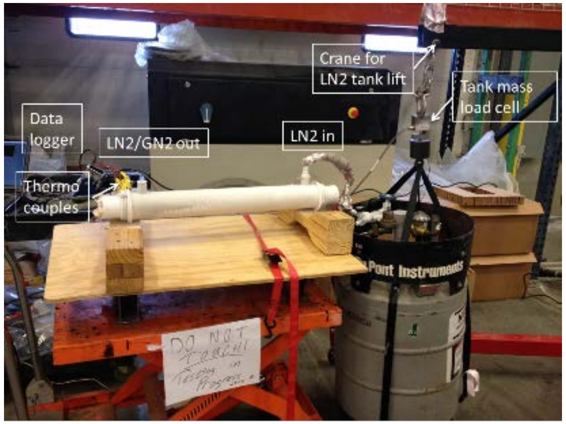
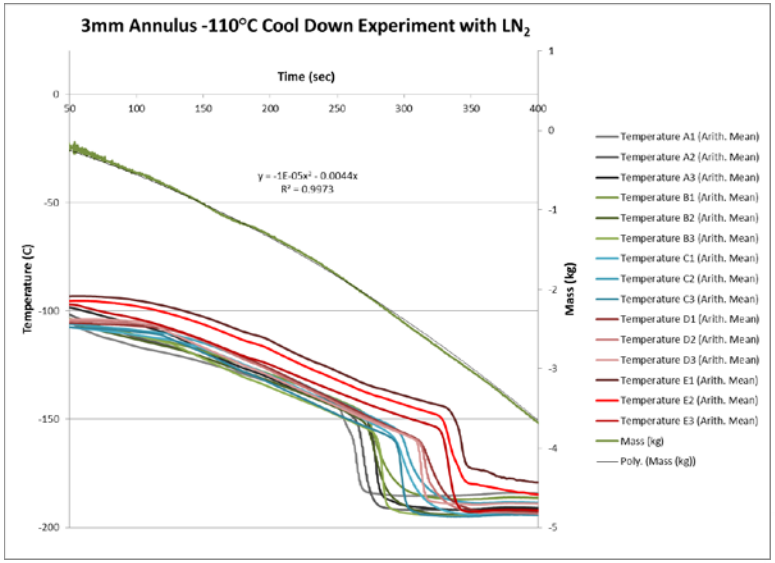
LN2 Tank Cooling Testing









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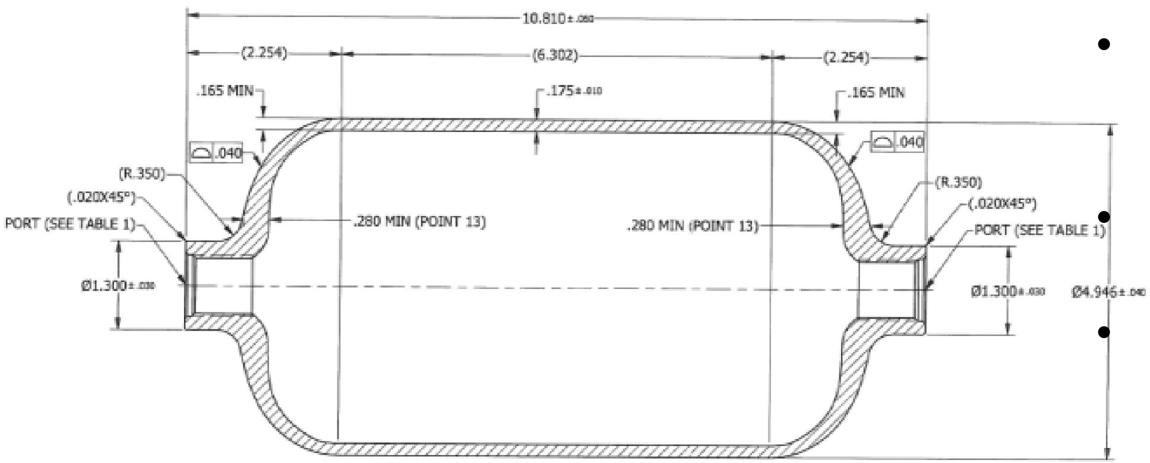
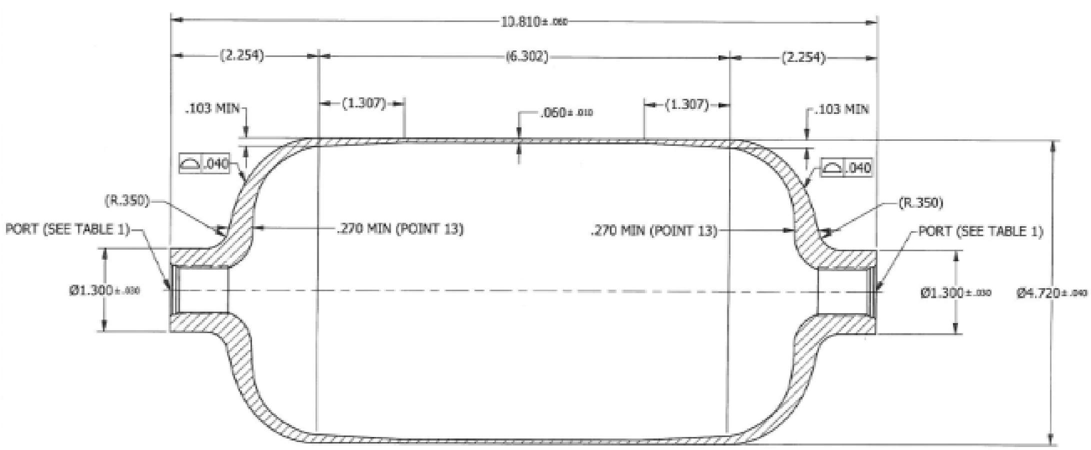
Phase 3 S*M*A*R*T Milestones - #3

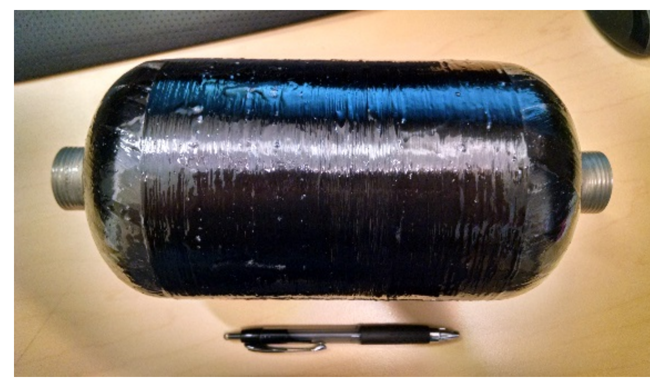
- Report on ability to design and manufacture alternate tank configurations, such as
  - monolithic Type 1,
  - Type 3 with suitable cryogenic liner, and
  - Type 4 with suitable cryogenic liner,
  - that can operate at 100 bar service pressure,
  - at temperatures of 80K – 160K, and
  - offer a further 10% reduction in weight compared with the Phase 3 baseline Type 1 tank, and
  - are consistent with safety requirements established by industry for hydrogen fuel containers.
  - Status – in work
    - Type 1 and Type 3 tanks have been manufactured and tested. Additional testing in 2Q 2015.
    - The Type 4 tank was designed in 1Q 2015. Fabrication and testing in 2Q 2015.

Alternate Tank Designs





- Monolithic Type 1 tank designed and fabricated for design comparisons and testing
- Type 3 liner based on Type 1 tank
- One unit has been wound and burst tested successfully



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Alternate tank designs

- Type 1 design will be tested
  - Ambient burst
  - Cryo cycling (minimum level)
  - Cryo burst
- Type 3 design will be tested
  - Ambient burst
  - Cryo cycling (minimum level)
  - Cryo burst
  - Effect of autofrettage pressure
- Type 4 design completed based on Type 1 and Type 3 design
  - Evaluating resin materials to use as a liner
  - Evaluating manufacturing method
  - Testing will include burst, cycling, and permeation

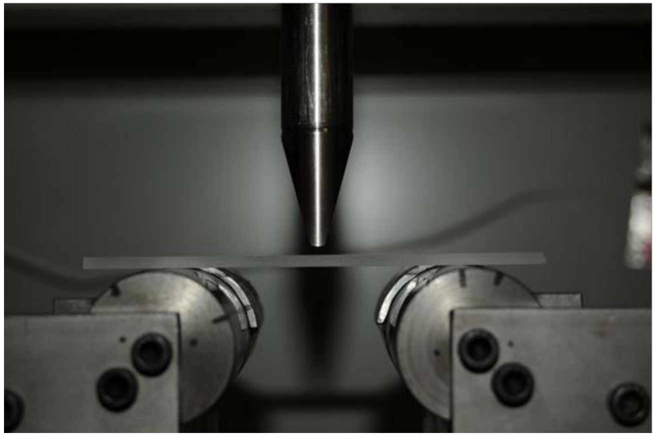
Vessel	Wt. (lb)	% 1	% n-1
1) T1 (1st 3 piece)	5.9	n/a	n/a
2) T1 (2nd 3-piece)	5.0	84	84
3) T1 (1-piece)	3.0	51	60
4) T3	2.23	38	74
5) T4	tbd	tbd	tbd

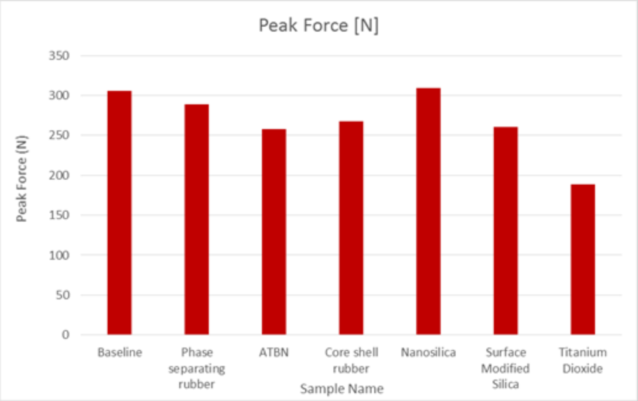
Type 4 subscale

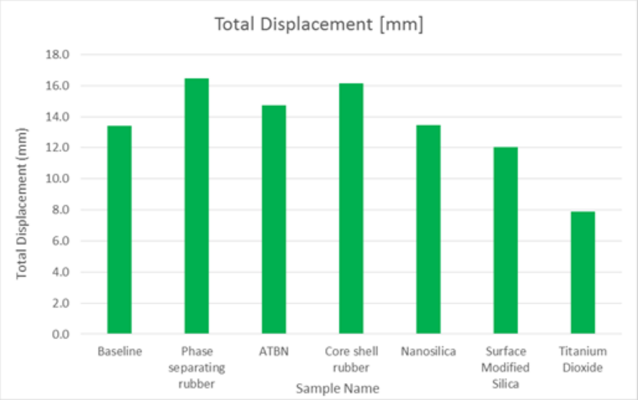
- Investigating alternatives to HDPE liner using current design/manufacturing approach
  - Liner is separate from composite
  - Coefficient of thermal expansion mismatch must be addressed
  - Brittle point of liner material must be addressed
- Investigating resin material liner using a removable mandrel
  - Liner is integral with composite
  - Permeation is reduced substantially by Arrhenius Rate Equation effects
  - Need to ensure no cracking of resin liner

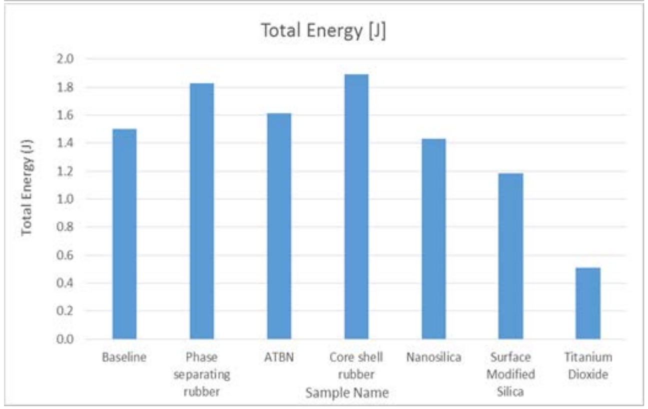
Resin impact testing

Material	Total Energy (J)	Peak Force (N)	Total Displacement (mm)
Baseline	1.50	305.59	13.42
ATBN	1.61	258.17	14.73
Core shell rubber	1.89	267.39	16.13
Nanosilica	1.43	309.54	13.45
Surface Modified Silica	1.19	260.80	12.05
Titanium Dioxide	0.51	188.89	7.91
Phase separating rubber	1.83	288.47	16.46









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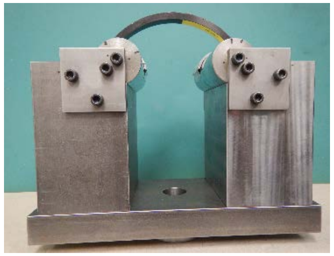
Development of composite impact test



- Improved impact properties of neat resin samples were observed during 3 point impact testing
  - Best performing resin formulation demonstrated 26% increase in total energy required to break samples.
- Impact testing of composite produced using toughened resin will determine whether these improved neat resin properties translate into improved impact properties of the composite.

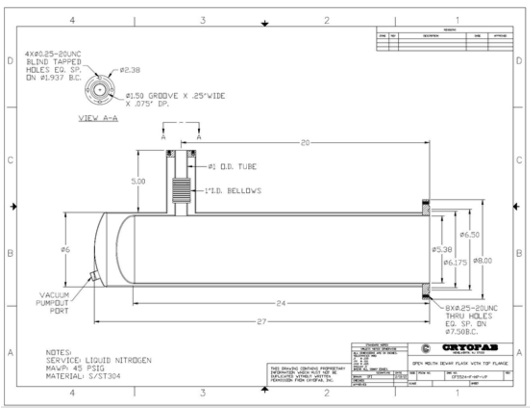
- 3 point impact
  - Same fixture used for 3 point impact testing of neat resin coupons
  - Rolling supports
  - Charpy impact tip

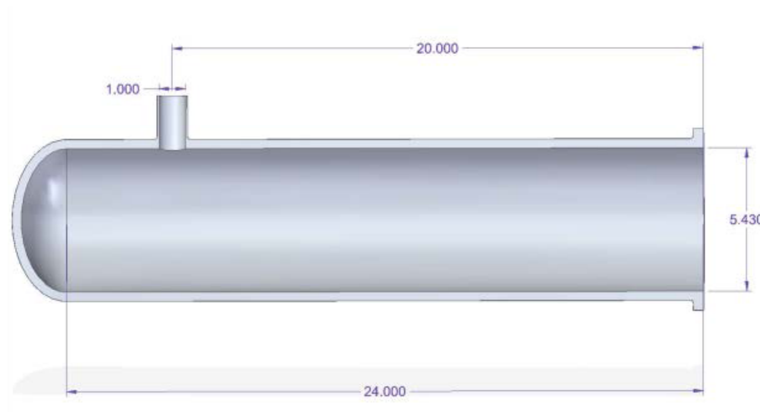
- Key test parameters being investigated:
  - Specimen length
  - Support span
  - Specimen supported concave up or concave down
  - Energy of impact – impact velocity and weight carried by impact carriage

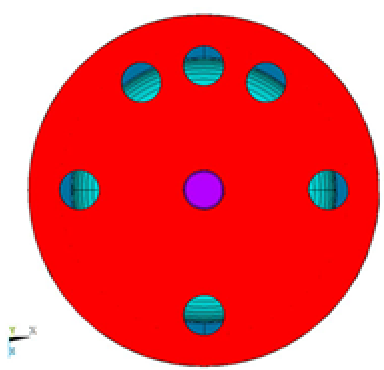
Phase 3 S*M*A*R*T Milestones - #4

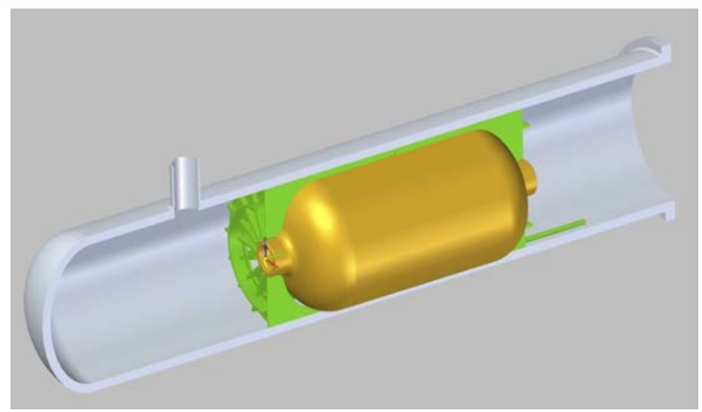
- With other HSECoE partners,
  - fabricate and demonstrate a thermal insulating tank with the LN2 tank cooling concept
  - and measure the cooling rate and transient heat loss for dormancy determination
  - meeting the technical target for refueling from 160K to 77K in 4.2 minutes using a surrogate adsorbent material.
  - Status – in work.
    - The vacuum insulated thermal shell has been built and delivered to Hexagon Lincoln.
    - A prototype tank and support structure has been installed. Thermal testing will be conducted in 2Q 2015
    - US Patent has been applied for

Insulating tank



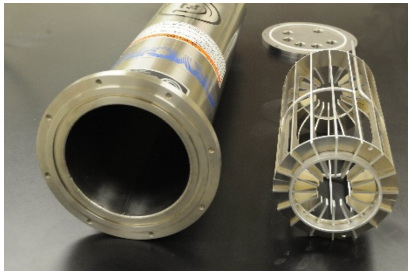


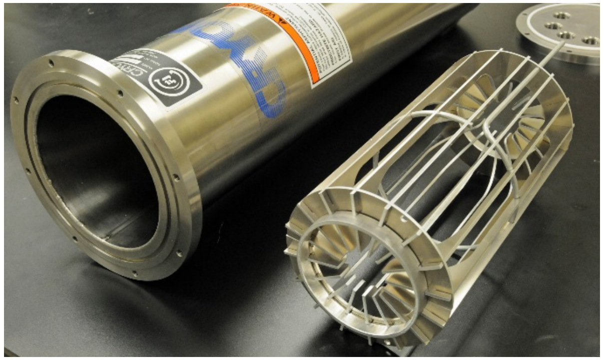


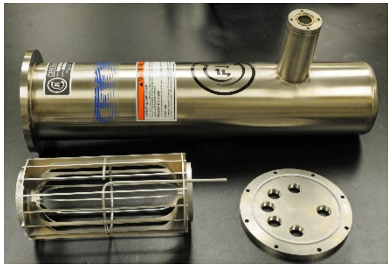


Insulating tank

- The insulating tank components have been delivered
- Testing conducted 31 March – 3 April
- Tests can be conducted on T1, T3, and T4 tanks







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Accomplishments

- Phase 1 improvements could be incorporated into Phases 2 & 3
  - 11% lower weight, 4% greater volume, 10% lower cost
- Phase 2 test vessels have been designed, manufactured, and tested
  - Analysis and burst testing confirms design and safety
  - Allows team members to demonstrate internal components
- Phase 3 test vessels have been manufactured and distributed
- Phase 3 S*M*A*R*T Milestones are nearing completion
- Patent being pursued for external vacuum insulating vessel, Hexagon Lincoln and PNNL inventors

Collaborations

- Monthly teleconferences with PNNL and team on pressure vessels and containment
- Monthly teleconferences with adsorbant team
- Monthly HSECoE Coordinating Council telecons
- Face to Face Meetings with HSECoE Team
  - June 16, 2014, Washington, DC
  - September 23-25, 2014, Lincoln, NE
- Tech Team Review Meeting
  - May 20-21, 2015, Southfield, MI

Future Work - Planned Tasks

- Completion of current activities
- Completion of final report by 30 September, 2015

Summary

- Phase 1 and 2 activities are complete, accomplishments summarized
- Phase 2 results supported decision making for Phase 3
- Completed Phase 3 delivery of test cylinders for use by partners for system testing
- Timely completion of Phase 3 SOPO Milestones is expected

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Technical Back-Up Slides

Qualification Tests

- Standards include CSA HGV2, SAE J2579
- Federal Regulations will be in 49 CFR, derived from UN Global Technical Regulation (GTR)
- Typical qualification tests:
  - Burst, FS = 2.25 for carbon, 3.5 for glass
  - Pressure cycling, 5500+ for automobiles, 15,000+ for buses
  - Environmental test, exposure to reactive fluids
  - *Flaw tolerance, pressure cycling with prescribed flaws/cuts
  - *Drop test, unpressurized, simulating handling damage
  - Fire test, localized and global fire
  - Accelerated stress rupture, looking for residual manufacturing stresses
  - *Penetration, non-shatterability when impacted
  - Permeation
  - Boss torque
  - Hydrogen gas cycling
  - Leak-before-break
  - *Additional tests?

* need to be re-evaluated for lower pressure adsorption applications

Design Verification Testing

- Subscale tanks for lab use would undergo limited testing:
  - Ambient burst
  - Cryogenic burst
  - Ambient cycling (until failure?)
  - Cryogenic cycling (200 – 500?)
  - Permeation (with new polymer liners)

Installing Adsorbant Materials

- Final approach will be dependent on:
  - Tank type and configuration
  - Size and placement of components
  - Configuration of adsorbant materials
- Options may include:
  - All Types: installation through enlarged port
  - Type 1: swage end after components installed, weld tank halves after components installed (friction stir welding?)
  - Type 2: swage end after components installed, weld end after components installed
  - Type 3: swage end of liner or weld liner halves after components installed, followed by winding and cure
  - Type 4: weld liner halves after components installed, followed by winding and cure