Development of Improved Composite Pressure Vessels for Hydrogen Storage

Norman L. Newhouse, Ph.D., P.E.

Hexagon Lincoln

18 June 2014

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*: $962,055

* as of 3/31/14

Barriers

- Barriers addressed
  - A. System Weight and Volume
  - B. System Cost
  - G. Materials of Construction
- Targets (2017)
  - Gravimetric capacity > 5.5%
  - Volumetric capacity > 0.040 kg H_2/L
  - Storage system cost < $12/kWh

Partners

- HSECoE 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 2017 Hydrogen Storage Goals for the storage system by identifying appropriate materials and design approaches for the composite container

	2017 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 2017
- 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

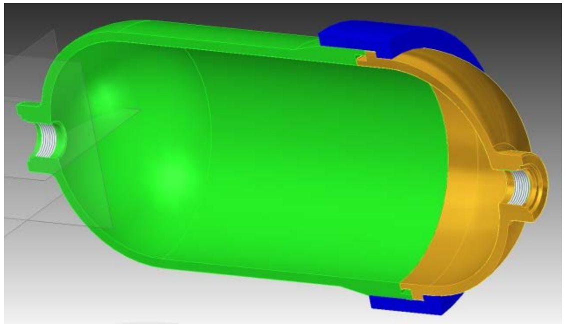
- Phase 1
  - Material evaluation for cost and weight reduction, internal volume increase
    - Projected cylinder improvements: 11% lower weight, 4% greater internal volume, 10% lower cost
  - Evaluate design and materials against operating requirements of storage systems selected by HSECoE Partners
    - 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

Phase 2 Results – First T1 Design

Designed to meet team needs for engineering demonstration, but less responsive to overall DOE targets

OAL = 10.867 inches
Collar OD = 6.165 inches
Cylinder OD = 4.848 inches
Wall thickness = 0.220 inches
Ports = 1-1/8 – 12
Volume = 2 liters
Service pressure = 100 bar
Design safety factor = 2.25 (min)
Burst pressure = 370 bar (actual)
Weight = 5.9 lb

Baseline for HexCell approach



HSECoE

HEXAGON LINCOLN

Progress – Phase 3

- SOPO and Milestones developed and agreed
- Manufactured and delivered 3-piece Type 1 tanks for Phase 3 testing
- Evaluating performance of vacuum shell elements
- Continuing tank development/optimization
  - Designing Type 1 and Type 3 tanks
  - Investigating Type 4 liner materials

- Expecting to meet all SOPO/Milestones by end of Phase 3

Phase 3 S*M*A*R*T Milestones: HL-1

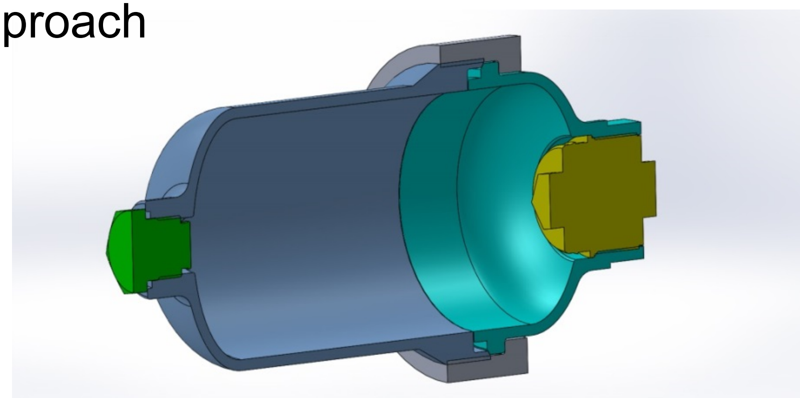
- Design and manufacture a baseline, separable Type 1 tank:
  - for phase 3 engineering demonstration
  - size (2L - 6L)
  - pressure (100 bar service pressure)
  - operating temperatures (80K – 160K)
  - interfaces specified by HSECoE team members
  - with a 10% reduction in weight per unit volume compared with the Type 1 tank tested in Phase 2.
- Due 12/31/13
- Completed, tanks have been distributed to HSECoE partners

Type I subscale tank – new design

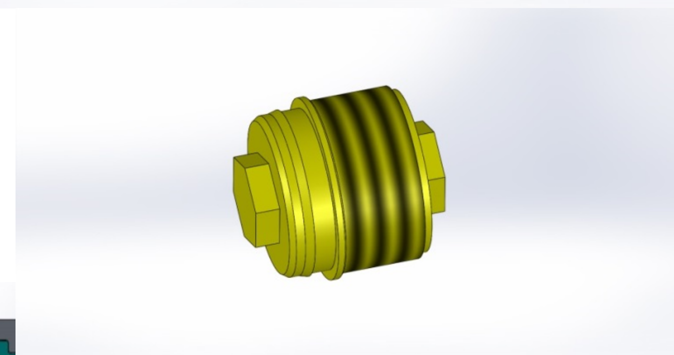
- New parameters - Per OSU's specifications, the new Type I tank for MATI application is desired to have the following:
  - Larger port (~ 1.75 – 2.5 inches)
  - A plug that can be inserted from the inside
  - The rest of the parameters will remain the same
    - Operating pressure: 100 bar
    - Operating temperature: as low as 77 K
    - Material: 6061-T6 Aluminum
    - Volume: 2 liters
- New Design
  - 2-1/8" – 12 UN port (larger pass-through)
  - Reduced wall thickness from 0.220" to 0.175" (lighter weight)
  - Designed new plug to be inserted from inside (ease of assembly)
    - 1" hex extrusions on both sides (this can be changed to whatever is more convenient)
  - Configuration uses existing cryo-seals (saved 6-7 week lead time)

New Phase 3 design

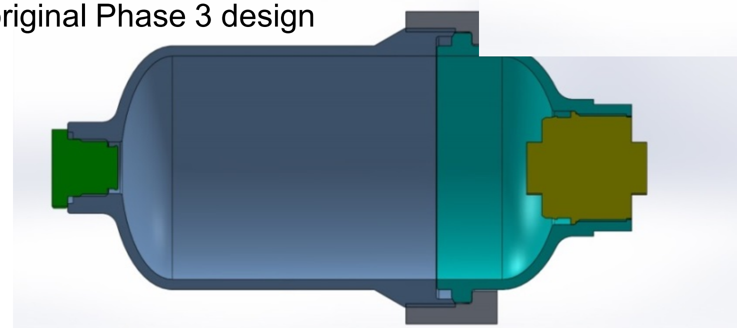
Designed to meet team needs for engineering demonstration – MATI approach
(could also be used for HexCell)



*OAL = 11.217 inches
Collar OD = 6.164 inches
*Cylinder OD = 4.758 inches
*Wall thickness = 0.175 inches
*Ports = 1-1/4 – 12; 2-1/8 – 12
Volume = 2 liters
Service pressure = 100 bar
Design safety factor = 2.25 (min)
*Burst pressure = 290 bar (actual, -22%)
*Weight = 5.0 lb (actual -15%, goal was -10%)



* Note: Identifies changes from original Phase 3 design

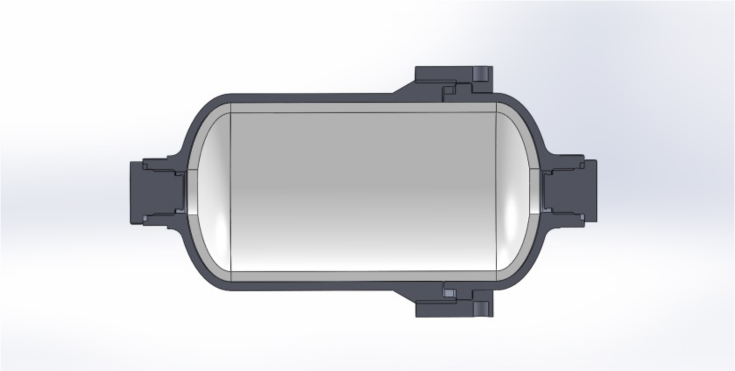


HSECoE

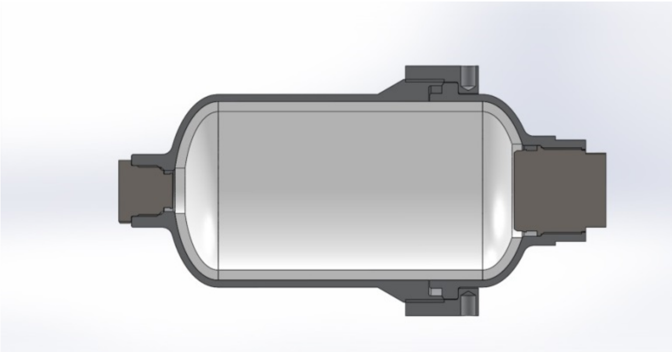
HEXAGON LINCOLN

Internal insulation provided

- PTFE liner
- Multi-piece construction
- Allows demonstration tank to be cooled by LN2 bath, and heat added to contents to release H2
- Required for HexCell, optional for MATI



Type 1 tank – HexCell design (with insulation)



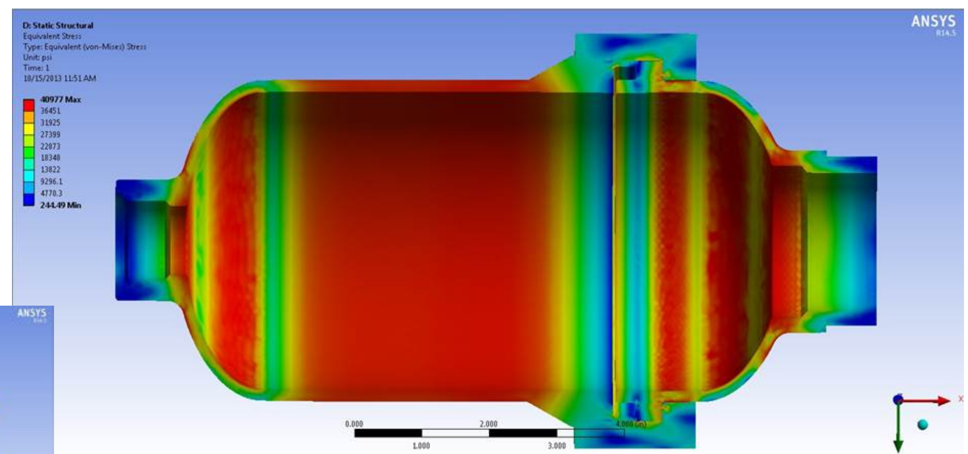
Type 1 tank – MATI design (with insulation)

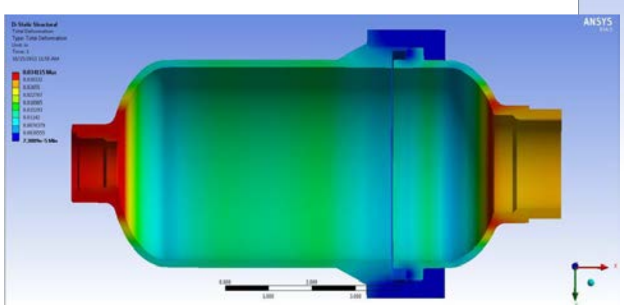
HSECoE

HEXAGON LINCOLN

FEA – stress and deformation

- Analyzed at 225 bar (2.25 x 100 bar)
- Maximum stresses in 38-40 ksi range
  - Below the typical room temperature strength of 6061-T6 aluminum
  - Strength will increase at cryogenic temperatures (approx. 25%)





Phase 3 S*M*A*R*T Milestones: HL-2

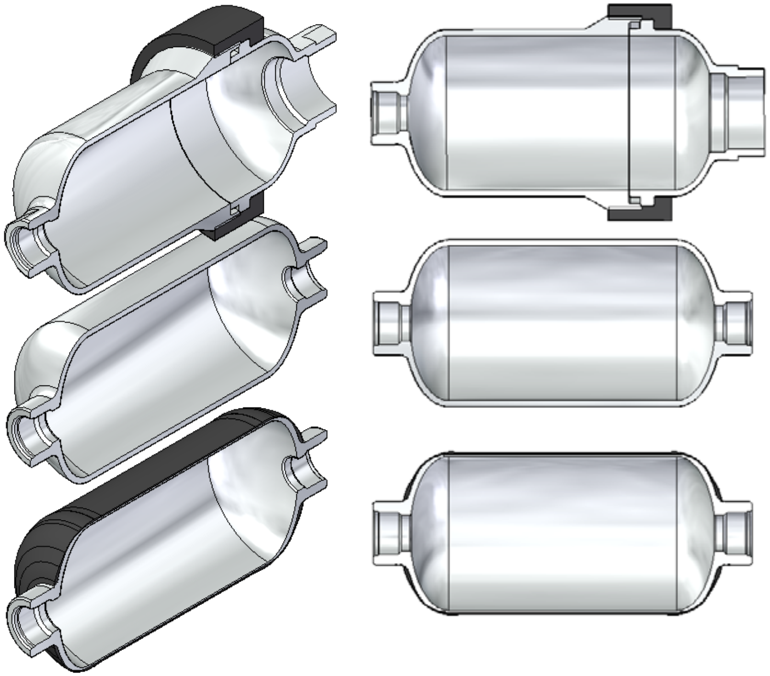
- With other HSECoE partners, report on the ability to design a full scale thermal isolation bottle concept tank
  - with the LN2 tank cooling
  - with a modeled cooling rate and transient heat loss for dormancy determination meeting the DOE technical targets
  - *Evaluate thermal-mechanical stresses during refueling, 1500 cycles*
  - *Identify any necessary design criteria to avoid pressure vessel failure under combined thermal-mechanical loading*
  - *Design a scale thermal isolation bottle using LN2 cooling*
  - *Meet DoE technical targets for refueling from 160K to 77K in 3.3 minutes*
  - *Meet any necessary fatigue design criteria*
- Due 9/30/2014
- In progress
  - Patent is proceeding
  - Looking at design options
  - Testing LN2 cooling of concentric shells

Phase 3 S*M*A*R*T Milestones: HL-3

- Report on ability to design and manufacture alternate tank configurations (better meeting DOE targets):
  - monolithic Type 1
  - Type 3 with suitable cryogenic liner
  - Type 4 with suitable cryogenic liner
  - operate at 100 bar service pressure
  - temperatures of 80K – 160K
  - offer a further 10% reduction in weight compared with the Phase 3 baseline Type 1 tank
  - consistent with safety requirements established by industry for hydrogen fuel containers (CSA HGV2, SAE J2579, FMVSS)
- Due 3/31/2015
- In progress

Type 1, Type 3 Subscales

- Initiated discussions with liner supplier
- Type 3 liner would be based on Type 1 tank design
- Projected weight savings from 3-piece Type 1 tank
  - Type 1 = 2.65 lb (-47%)
  - Type 3 = 1.88 lb (-62%)



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

Phase 3 S*M*A*R*T Milestones: HL-4

- With other HSECoE partners, fabricate and demonstrate a thermal insulating tank with the LN2 tank cooling concept
  - measure the cooling rate and transient heat loss for dormancy determination
  - meeting the DOE technical targets for refueling from 160K to 77K in 3.3 minutes using a surrogate adsorbent material.
- Due 6/30/2015
- Not started
  - Awaiting results: task on thermal insulating tank design
  - Awaiting results: task on monolithic Type1, Type 3, Type 4 subscales

HSECoE

HEXAGON LINCOLN

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
- Patent being pursued for external vacuum insulating vessel, Hexagon Lincoln and PNNL inventors

Responses to Previous year Reviewers' Comments

- Hexagon Lincoln has addressed several comments from last year's reviewers directly in this year's presentation.

- There are tasks and tests planned with different vessel types (Type 1, Type 3 and Type 4). What is the strategic approach behind these tasks.
  - The baseline 3-piece type 1 tank for Phase 3 is intended to serve the HSECoE team partners to assess their components. Additional work on Type 1, Type 3, and Type 4 tanks is to further address design and material optimization, particularly as related to cryo-adsorbant hydrogen storage, and ability to meet DOE targets.

- The requirements for the tests are not clear (e.g., references to SAE, ISO, etc.). The test descriptions should be attached in the backup.
  - CSA HGV2, SAE J2579, and 49 CFR requirements will be evaluated against the proposed design(s) during Phase 3, with an assessment of the appropriateness of current requirements, and if any test modifications or new tests are recommended. Cyclic fatigue tests will be conducted to higher levels, and possibly to failure, to help characterize materials. See Technical Back-Up Slides

- Hexagon Lincoln needs to address assembling, filling, and sealing the vessels, and to address material compatibility.
  - See Technical Back-Up Slides

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
  - May 14, 2013, Washington, DC
  - Oct 1-3, 2013, Corvallis, OR
- Tech Team Review Meeting
  - March 19-20, 2014, Southfield, MI

HSECoE

HEXAGON LINCOLN

Future Work - Planned Tasks

- *Design monolithic Type 1 tank*
  - Type 1 tank lower cost than Type 4
  - Alternate baseline if assembly issues addressed
- *Develop Type 4 cryogenic liner*
  - Opportunity for significantly lighter weight
  - Confirm cryogenic strength of carbon fiber
  - Confirm ability of liner to handle 80K operating condition
- *Demonstrate Type 3 cryogenic tank*
  - Confirm suitability of metallic liner
- *Demonstrate External vacuum shell*
  - With PNNL
  - Subscale test
- *Tank design/development/demonstrate will include:*
  - Identifying how to install components – install through larger boss opening vs. weldment vs. install during liner manufacturing
  - Room temperature burst and cycle testing in accordance with appropriate standards
  - Cold temperature burst and cycle testing in accordance with appropriate standards
  - Investigation of possible contaminants from liner materials

HSECoE

HEXAGON LINCOLN

Summary

- Phase 1 and 2 activities are complete
- Phase 2 results supported decision making for Phase 3
- Phase 3 SOPO and Milestones are established
- Phase 3 tasks are underway
- Timely completion of Milestones is expected

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