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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

Overview

Timeline

- Start 1 Feb 2009
- End 30 Jun 2014
- 65% complete

Budget

- Project funding $17,781,251
  - DOE Share $1,425,000
  - Cost Share $356,251
- FY12 = $215,000
- FY13 = $200,000

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 - TBD

Partners

- HSECoE **HSECoE**

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

Objectives - Relevance

- Meet DOE 2010 and 2017 Hydrogen Storage Goals for the storage system by identifying appropriate materials and design approaches for the composite container

	2010	**2017**
Gravimetric capacity	> 4.5%	> 5.5%
Volumetric capacity	> 0.028 kg H_2/L	> 0.040 kg H_2/L
Storage system cost	TBD	TBD

- Maintain durability, operability, and safety characteristics that already meet DOE guidelines for 2010 and 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

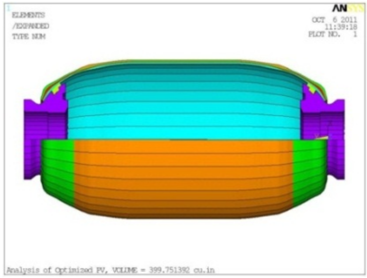
- Phase 1
  - Material evaluation for cost and weight reduction, internal volume increase
    - Projected cylinder improvements: 11% lower weight, 4% greater internal volume, 10% lower cost
  - Evaluate design and materials against operating requirements of storage systems selected by HSECoE Partners
    - Baseline design approach established
    - Liner material development is most significant issue
    - Maintain durability, operability, and safety
- Phase 2
  - Confirm operating conditions
  - Update baseline design and materials
  - Evaluate alternate designs
  - Evaluate alternate materials
  - Develop bench-top test vessel(s)

Progress – Phase 2 Test Vessel Criteria

- Consensus input from HSECoE Partners:

Dimension	Test Vessel 1	Test Vessel 2
Design Pressure	200 bar	100 bar
Maximum operating pressure	250 bar	125 bar
Minimum operating pressure	Vacuum, < 1e-5 torr	(same)
Internal liquid volume (dimensional priority)	~6 Liters	~2 Liters
Liner ID	16.6 cm (6.54 inches)	11.2 cm (4.41 inches)
Vessel OD/OAL	~2:1 aspect ratio	(same)
Temperature range	20ºK to 373ºK	80ºK to 373ºK
Vessel Type	Type 4	Type 1

Prior Results - Test vessel 1, Materials Testing

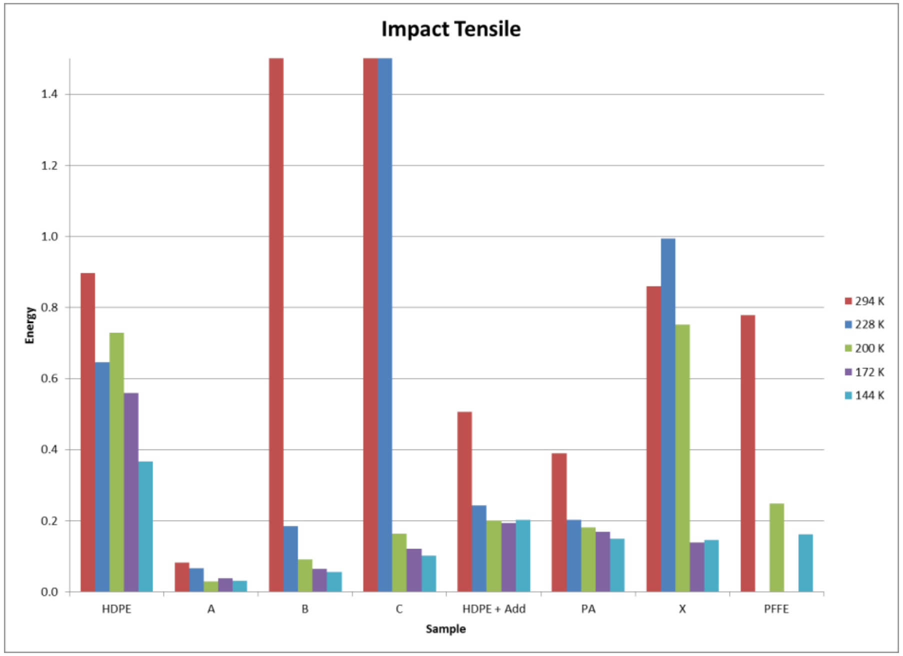


- Baseline dimensions
  - OD (Tank) = 183 mm (7.18 inches)
  - OAL = 372 mm (14.64 inches)
  - Volume = 5.68 liters
- Baseline construction
  - Fiber = T700
  - Resin = epoxy
  - Liner = HDPE
  - Bosses = 6061 Aluminum

- Existing vessel design tested (360 x 1680 mm)
  - Baseline materials (T700, Epoxy, HDPE)
  - Temperatures (min achieved) from 77°K (composite) to 108°K (liner)
  - Initial pressure 68 bar (1000 psi) at RT, ~ 34 bar at low temperature (stabilizes liner)
  - Two cylinders - two cycles each
  - No effect on room temperature burst properties.
    - 9253 psi & 9077 psi
    - Configuration nominal is 8978 psi, min required 8021 psi

Prior results - Liner material investigation

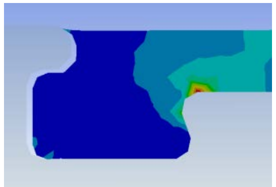
- Tensile Impacts of
  - HDPE (baseline)
  - Modified EVOH
  - HDPE with nano-additives
  - PA
  - PTFE



- Energy of impact provides relative values only
- Of materials tested, HDPE has best cold/cryo properties (tested to 144ºK)

Progress - Subscale Type 4 Cryo Testing

- Cryogenic testing has been conducted on subscale Type 4 tanks
  - Tank 1 leaked at 4129 psi
    - 62 bar (900 psi) hold
    - 13.8 bar/sec (200 psi/sec) pressurization
  - Tank 2 leaked at 3340 psi
    - 138 bar (2000 psi) hold
    - 13.8 bar/min (200 psi/min) pressurization
  - Pressure level greater than 2.25 x 60 bar
  - Leaking was from liner crack(s)
    - Crack appears to initiate at boss/liner interface
    - Region of high stress due to differential CTE
  - Laminate held up well
  - Considering method to re-seal liner and retest



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Progress – Test vessel 2

- Type 1 subscale vessel
- Three piece aluminum construction
  - Allows ease of assembly and replacement of components
  - Cryo service compatibility
  - Higher weight, but lower cost (~30% to 50% lower than type 4)
- Available for use by HSECoE partners in Phase 2
  - Ambient burst test to confirm safety

Progress – Test Vessel 2 Design

- 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)

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Progress - Subscale Type 1 Cryo Testing

- Type 1 subscale tank cycled 200 times to service pressure at 80K
  - Pressure cycling with liquid nitrogen
  - No thermal cycling, not expected to be an issue
- Burst pressure was 460 bar (6675 psi)
  - Burst pressure was 370 bar for ambient test
  - Strength of 6061-T6 increases with decreasing temperature
  - Similar failure mode, ambient vs. cryo
- Confirms safety in cryo use

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Progress - Full Scale Design Evaluations

- SMART milestones for report on full scale designs:
  - Evaluate Type 1 and Type 4 tanks
    - Designs compared on following slides
  - Design for 40°K to 160°K
    - Low temperature is not a problem for aluminum alloy Type 1
    - Liner issues for Type 4 with extreme temp (80K), need further development
      - Qualification tests passed at 219K (-54C)
      - Some testing successful between 80K and 219K
    - No issue expected for carbon fiber
  - Meet ASME pressure vessel code
    - ASME Code could be met when pressure was >210 bar, but overly conservative for 100 bar use
    - DOT/NHTSA has jurisdiction, FMVSS regulations would be met
  - Design for 60 bar service pressure
    - 60 bar and 100 bar service pressure considered in designs
  - Mass less than 10 kg and volume less than 120 L
    - Volume will depend on adsorbent efficiency
    - 60 L and 120 L designs compared
    - Weight could be met for 120 L design with Type 4 tank if optimized liner could be developed

Progress - Full Scale Design Comparisons

Tank	Mat'l	P (bar)	FS	Dia (mm)	L (mm)	Vol (liter)	Wt (kg)	PV/W
1	C	60	2.25	440	950	120	11.35	634
2	C	60	2.25	390	640	60	5.73	628
3	G	60	3.5	400	660	60	15.36	234
4	G	100	3.5	410	660	60	26.16	229
5	C	100	2.25	390	640	60	8.16	735
6	Al	60	2.25	390	640	60	16.36	220
7	Al	60	2.25	440	950	120	30.00	240

- Carbon tanks have highest performance (PV/W)
- Glass and aluminum tanks are similar performance
- Larger tanks will have slightly better performance
- Aluminum tank can be improved by choice of alloy and better control of strength

Progress - Optimizing

- Performance improvement by reducing Factor of Safety (FS) to 2.0
  - Stress rupture is still acceptable
  - Vacuum shell will provide additional damage tolerance

Tank	Mat'l	P (bar)	FS	Dia (mm)	L (mm)	Vol (liter)	Wt (kg)	PV/W
1	C	60	2.25	440	950	120	11.35	634
1A	C	60	2.0	439	950	120	10.58	681

- Performance improvement by using thinner liner, e.g. resin layer
  - Reduces cost and weight, increases volume
  - Permeation is reduced due to low temperature
  - Must avoid leakage and microcracking

Tank	Mat'l	P (bar)	FS	Dia (mm)	L (mm)	Vol (liter)	Wt (kg)	PV/W
1	C	60	2.25	440	950	120	11.35	634
1A	C	60	2.25	434	950	120	8.61	836

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
  - Team consensus on vessel requirements
  - Analysis and burst testing confirms design and safety
  - Allows team members to demonstrate internal components
- Cryogenic cycle and burst testing of Type 1 test tank to confirm suitability for Phase 2 and 3 system testing
- 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
  - May 14, 2012, Washington, DC
  - Oct 9-11, 2012, Mystic, CT
- Tech Team Review Meeting
  - March 20-21, 2012, Southfield, MI

Future Work - Planned Tasks

- ***Design separable Type 1 tank as Phase 3 baseline***
    - Reduces program risk, allows reassembly
    - Identify internal mounting features
- ***Design monolithic Type 1 tank***
    - Identify how to install components – larger boss opening vs. weldment
    - 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 80C operating condition
- ***Demonstrate Type 3 cryogenic tank***
- ***Demonstrate External vacuum shell***
    - With PNNL

Summary

- Type 1 and Type 4 lab subscale tanks designed, fabricated and provided to HSECoE partners
- Type 1 subscale tank successfully burst tested at ambient and cryo temperatures
- Type 4 subscale tank successfully burst tested at ambient temperature, but leaked at cryo temperature
- Designs evaluated to achieve SMART milestones, opportunities for improvement identified
- Phase III planned tasks identified