CENTER FOR TRANSPORTATION
AND THE ENVIRONMENT

Conformable Hydrogen Storage Coil Reservoir

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Project ID: ST126

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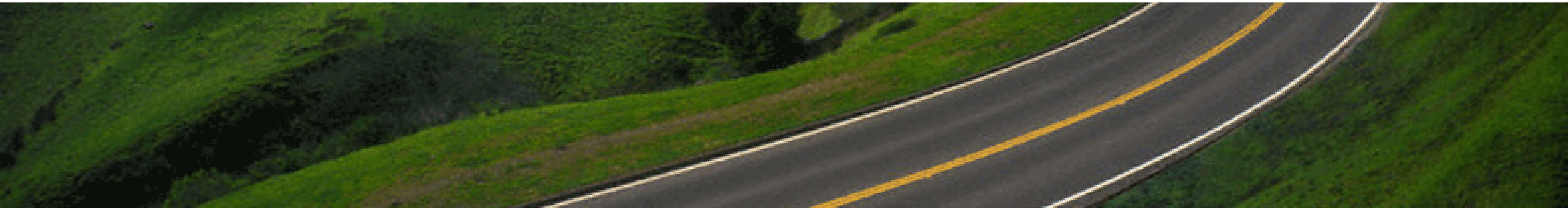


Overview

Timeline

Start: August 2015

End: August 2017

Budget

Total Project Budget: $1,250,161

Total Recipient Share: $265,500

Total Federal Share: $984,661

DOE Funds Spent: $327,408*

*As of 3/7/17

Barriers Addressed

- High cost, weight of 700 bar gaseous H_2 storage
- Rigid, cylindrical layout of conventional 700 bar tanks

Funded Partners

- High Energy Coil Reservoirs, LLC
- University of Texas – Center for Electromechanics
- Stan Sanders – Technical Expert

Relevance

Purpose: To develop game changing storage for compressed hydrogen gas that will provide a cost-effective and conformable storage solution for hydrogen vehicles

- Conformable, lightweight 700 bar gaseous hydrogen storage
- Storage system can be extended once proven at smaller sizes
- Continuous production processes

Initial two segment test vessels

Relevance

- Final vessel ~ 9% gravimetric capacity
  - Exceeds DOE Ultimate target
  - Conventional 5.6 kg 700 bar tank around 100 kg

$$\frac{5.6\ \text{kg}_{stored}}{33\ \text{kg}_{vessel} + 17\ \text{kg}_{BOS} + 10\ \text{kg}_{packaging}} \cong 9\%\ \text{Gravimetric Capacity}$$

- Cost target near DOE ultimate target ($266/kg H_2 stored)
  - ~$280/kg H_2 stored at low production volumes
  - Based on conceptual 5.6 kg system

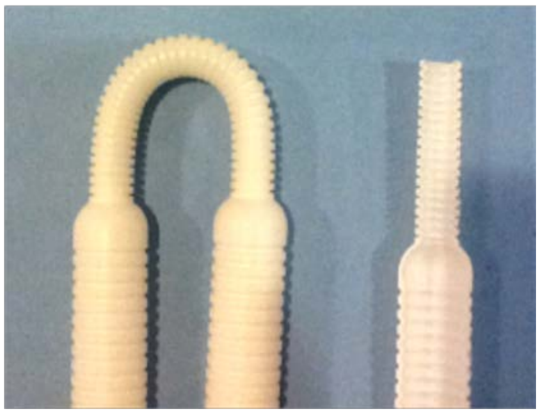
- Similar volumetric efficiency, increased flexibility for creative vessel layout and installation

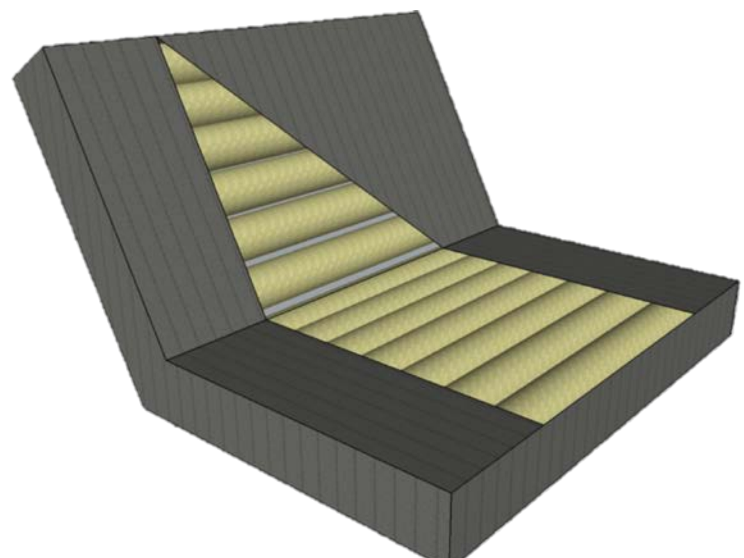
Approach - Teaming

- Center for Transportation and the Environment
  - Overall Project Management and Technical Oversight
- Stan Sanders
  - Technology Expert and IP Owner
  - Extensive experience in development and design of conventional and conformable vessels
- The University of Texas at Austin Center for Electromechanics
  - Hydrogen production and hydrogen test facility
  - Modeling, Resin Selection
- HECR
  - Commercialization investment partner

Approach: PV Design Overview

Pressure vessel is an extruded resin liner covered with Kevlar overbraid – both <u>continuous processes</u>





Approach: Solve Key Technical Risks

- Permeability Goal
  - Proposal goal of 0.05 g/(hr-kg stored)
  - OEM permeability requirement determined later to be 0.01 g/(hr-kg stored)

Approach: Solve Key Technical Risks

- <u>Burst Pressure</u>
  - Proposal goal of 3.1X 700 bar based on kevlar safety factor
  - Goal pressure of 2170 bar (31,473 psi)
  - Resin core does not contribute to mechanical strength

Approach: Key Steps

1. Resin Selection Matrix
2. Corrugation Tooling Development
3. Baseline Resin Testing/Tooling Validation
4. End fitting design/manufacture
5. Initial Pressure Vessel Manufacture
6. Safety Plan Development
7. Containment/Test Chamber Design and Build

- Initial Permeability Testing

- Burst Pressure Fiber Test
- Preliminary Burst Test
- Burst Pressure Vessel Test

- Secondary Resin Selection and Preliminary Testing
- Permeability Testing
- Pressure Cycle Testing

- Final Configuration Selection

Resin Selection Challenges

Permeability Challenges

- Challenge due to thin vessel wall of about 0.050”
- Extreme permeability barrier at odds with core production process, end fitting crimp process, and resilience during pressure cycling
  - High barrier resins tend to be brittle
- Dry pressure containment braiding adds no permeability barrier

Resin permeability data at high pressure or with hydrogen is difficult to find, or non-existent

Accomplishments – Resins Evaluated

Goal: 0.05 g/(hr-kg stored)

Over 100 resins evaluated via decision matrix

Resins Physically Evaluated

- Hytrel 5556 – Baseline resin, not suitable for permeability barrier
- Delrin 100ST – Brittle under compression, not tested extruded
- EVAL Resin A – Prototypes built, need more units for perm. testing
- EVAL Resin B – Could not complete extrusion process
- Hytrel 4275 – Hytrel w/o additives, not suitable

Good Candidate Resin Not Selected for Trials

- PVDC – "Saran" – Excellent barrier, processing characteristics originally not thought to be compatible with extrusion process

Resin / Polymer	Permeability (cm^3 (cm)/ atm sec cm^2)				Required thickness to meet 0.05 g/hr-kg H2 stored @ 700 bar	
	H_2	CO_2	He	N_2	*(cm)*	*(in)*
Hytrel 5556	na	1.80E-07	9.90E-08	1.40E-08	na	na
Acetal	1.50E-10	2.30E-09	na	na	0.0192	0.049 ★
EVALM100	1.62E-11	na	na	na	0.0021	0.005 ★
EVAL F101	1.30E-11	1.90E-12	3.70E-10	3.94E-14	0.0017	0.004 ★

Accomplishments and Progress

First Burst Testing:

- Revised braid design led to vessels that met 10,000 psi burst - allowed 4x safety factor for at least 2,500 psi testing on large format vessels
- Burst occurred as expected at outer radius of smaller tube diameter

Vessel burst above 10,000 psi

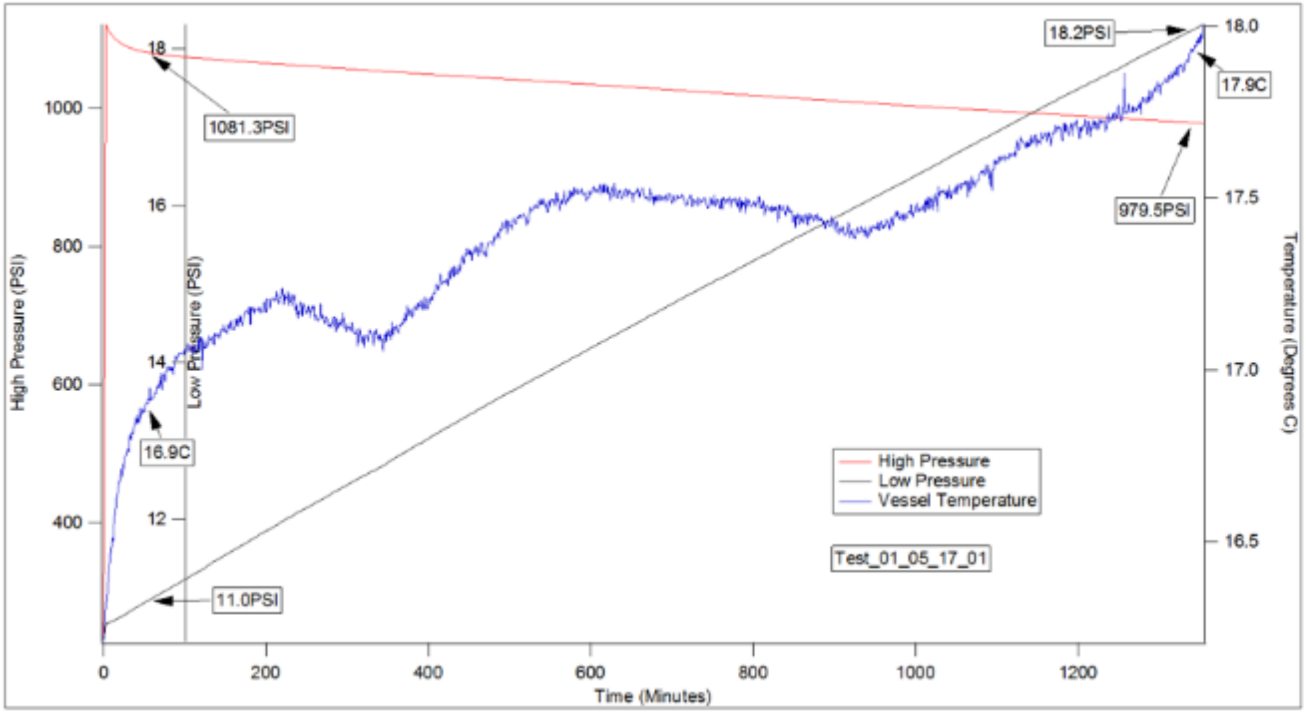
High Pressure Burst:

- Single test exceeded 33,000 psi burst
- End fitting crack ended test
- Plan to conduct additional tests in May 2017

Accomplishments and Progress

Leak Testing:

- Validated test cell hydrogen containment and measurement
- Confirmed baseline Hytrel permeability in line with expectations
- Initial resin was not intended as a barrier



Test	Leak Rate
Goal	<0.05 g/hr-kgH_2
1000 psi	0.6 g/hr-kgH_2
1800 psi	1.0 g/hr-kgH_2

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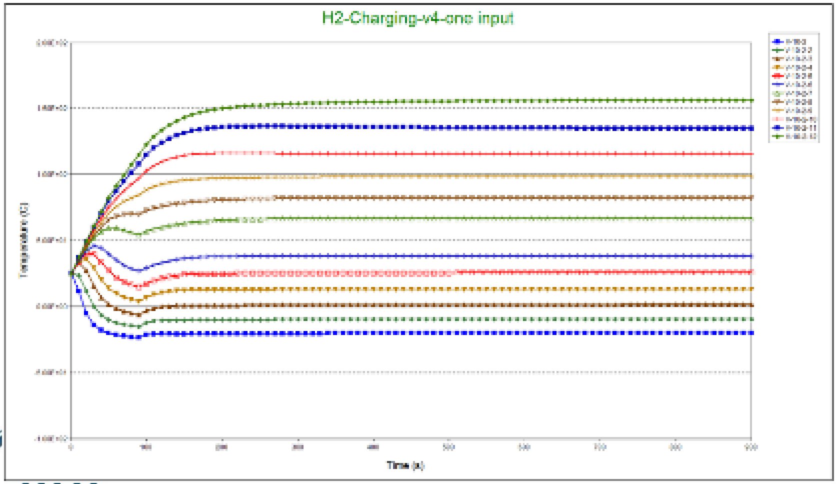
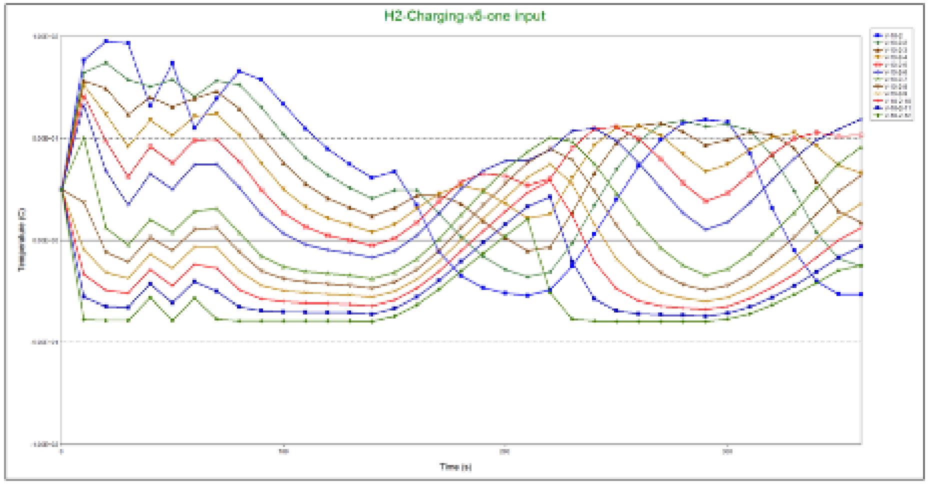
Accomplishments and Progress

Preliminary Thermodynamic Model:

- 140 vessel chain storing ~5 kg of hydrogen gas at 700 bar
- With -40C input, temperature for last vessel was simulated around ~150 ºC
- Temperature rise due to lack of flow through the vessel, eliminating opportunities for gas mixing and heat transfer
- Reversing flow entrance directions can keep temperature below 85 ºC
- Model not validated, but informs issue to be aware of in large vessel



Filling from single end



Reversing H_2 entrance during fill

Response to Previous Reviewer Comments

Why is permeability testing conducted at 400 bar for a 700 bar vessel?	**The current equipment on hand at UT-CEM is 350 bar rated, and 700 bar test equipment would be cost prohibitive under the grant. We expect good directional answers with 400 bar hydrogen, and hope to confirm results with a formal test at CSA.**
There should be additional OEM and industry engagement to develop a pressure vessel suitable for automotive use.	**Currently this project is seeking to address the highest risk challenges by showing an acceptable burst pressure and hydrogen permeability. We plan to engage OEMs more closely once credible results are in hand.**

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Collaborations: Project Possibilities

Kuraray Group

Manufacturer of EVAL resins. Kuraray provided prototype resins with enhanced flexibility and a high permeability barrier. Kuraray is interested to design a resin that meets the project requirements after initial testing under Phase 1.

CSA Group

We have a quote for a 3rd party 500 hour, 700 bar hydrogen permeability test at CSA's hydrogen test facility. With successful internal project testing, the project team would like to pursue a 3rd party test to provide confirmation of extrapolated results from our 400 bar permeability testing.

Remaining Barriers and Challenges

- Permeability requirement difficult to achieve in a thin wall flexible vessel – highest barrier resins are not typically flexible, or have processing challenges
- Preliminary pressure cycle life testing not complete yet
- Fully integrated design with selected resin and 2170 bar burst pressure not built yet
- Significant development and validation remaining to produce a market ready device
- Data suggests permeability rate may be less than linear, but not confirmed yet – permeability more than linear will require additional wall thickness

Proposed Future Work

Any proposed future work is subject to change based on funding levels

- Test 2 – 4 new resins for permeability
  - Build Cores, Quality Checks
  - Overbraid
  - Low Pressure Burst Test
  - Permeability Test
- Conduct repeatable high pressure burst test

- Go/No-Go Decision Point: Must achieve burst pressure of 2170 bar and hydrogen permeation below 0.05 g/hr/kg H_2 at 700 bar

- Explore feasibility with heavy duty vehicles at 350 bar; design changes for lower pressure may decrease permeation by factor of 4 from 700 bar design

Technology Transfer Activities

- Stan Sanders has experience commercializing conformable fuel tanks via partnerships and industry connections

Lightweight Industrial Oxygen Cylinder

Lightweight Firefighter SCBA Tank

Wearable Supplemental Oxygen Belt

Summary

- Project finalizing first phase work to develop a suitable resin and braiding combination to meet program requirements
- Successful outcome may make automotive and heavy duty hydrogen storage easier to package, cheaper, and lighter