Conformable Hydrogen Storage Coil Reservoir

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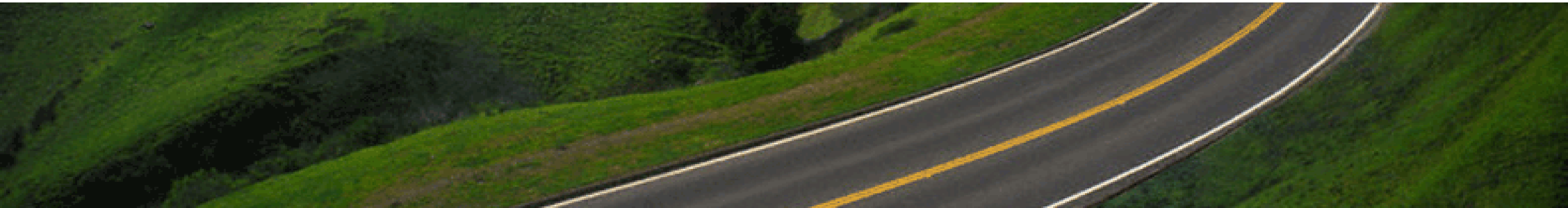


Overview

Timeline

Start: June 2015

End: January 2017

Barriers Addressed

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

Budget

Total Project Budget: $1,250,161

Total Recipient Share: $265,500

Total Federal Share: $984,661

**note numbers may change slightly during final negotiation with DOE*

Funded Partners

- High Energy Coil Reservoirs, LLC
- University of Texas – Center for Electromechanics

Relevance: Project Summary

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

- Conformable, lightweight 700 bar gaseous hydrogen storage system
- Development will occur over 18 months
- Initial proof of concept phase followed by 1kg H_2 demonstration system
- Storage system can be scaled up once proven at smaller sizes

Approach

Performance Target Summary:

- The results below are based on a 5.6 kg hydrogen storage vessel for light-duty vehicles at 700 bar with an internal volume of 140 L.
- Using a 4.5-cm outer diameter HPM vessel, the total vessel length is ~106 meters, which may be coiled and formed as necessary to fit multiple vehicle configurations.
- This project will develop a 1 kg vessel.

	DOE Projections for Type IV 700 bar storage at 500,000 units/yr	DOE 2020 Target	DOE Ultimate Target	Proposed HPM Vessel
Gravimetric capacity	1.5 kWh/kg (4.5 wt.% H_2)	1.8 kWh/kg (5.5 wt.% H_2)	2.5 kWh/kg (7.5 wt.% H_2)	3.7 kWh/kg (10.0 wt.% H_2)
Volumetric capacity	0.8 kWh/L (24 g H_2/L)	1.3 kWh/L (40 g H_2/L)	2.3 kWh/L (70 g H_2/L)	0.7 kWh/L (20 g H_2/L)
Cost	$17/kWh ($570/kg H_2 stored)	$10/kWh ($333/kg H_2 stored)	$8/kWh ($267/kg H_2 stored)	$8.40/kWh ($280/kg H_2 stored)

- Exceeds Ultimate Target Gravimetric Capacity
- Similar Volumetric Capacity to conventional 700 bar tanks, but conformable and more usable
- Approaches Ultimate Cost Target

Approach: Over-braiding Development

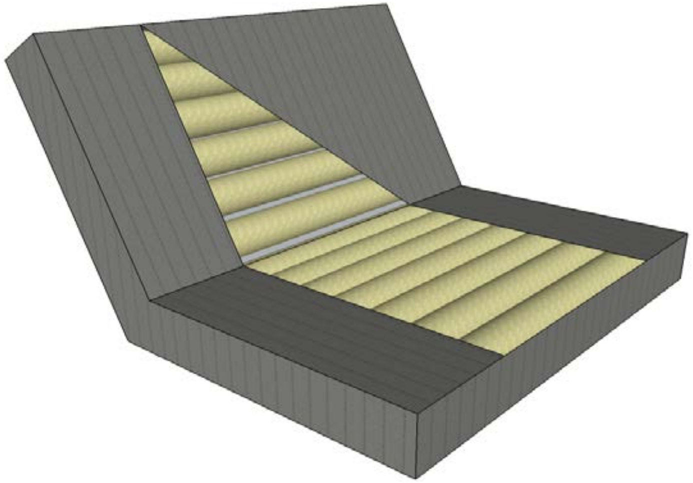
Over-braiding Development:

Over-braiding design is a function of:

- core size
- required burst/working pressure

Braiding design includes:

- required number of axial fibers
- longitudinal and cross fiber angles
- total braiding passes necessary to support pressure loading
- material is a Kevlar® yarn specified by HECR that is woven on the core with a continuous traction process



Conceptual Conformable Storage Layout

Approach: Design Specifications

Core Liner Resin Development:

Selection of a material to line the vessel will be determined by the extrusion workability characteristics of the resin as well as the permeability of the material to the hydrogen gas.

A resin will be selected that offers:
- superior resistance to hydrogen (low permeability)
- flexibility
- durability
- impact resistance
- thermoplastic (extrusion) performance

Possible liner configurations:
- single lumen of one resin
- multi-lumen
- multi-resin combination

		Leak Rate (g/hr/kgH2stored)				
		Acetal	PVDF	PCTFE	PET	HDPE
Thickness (in)	Thickness (cm)	2E-12	3.2E-11	3.4E-11	3.9E-11	2.95E-10
0.0039	0.01	0.078	1.248	1.326	1.521	11.508
0.0079	0.02	0.039	0.624	0.663	0.761	5.754
0.0197	0.05	0.016	0.250	0.265	0.304	2.302
0.0394	0.1	0.008	0.125	0.133	0.152	1.151
0.0591	0.15	0.005	0.083	0.088	0.101	0.767
0.0787	0.2	0.004	0.062	0.066	0.076	0.575
0.0984	0.25	0.003	0.050	0.053	0.061	0.460
Ideal Corrugator thickness range		Good candidates per leakage requirement below 0.05 g/hr/kg H2 stored				

- Current conformable design products have utilized elastomeric resins such as DuPont's Hytrel® thermoplastic polyester, and Zytrel® nylon elastomer.
- FEP, PTFE and ETFE fluoropolymers have also been used as hydrogen cylinder liners.
- Suitable alternatives with lower hydrogen permeability include PET, Acetal, and PVDF.

Approach: Resin Selection

Material Requirements:

- ***Material Requirement 1*** – *DOE cost requirements* (≤ \$12/kWh - \$400/kg H_2 stored). Per the above cost estimate, the HPM vessel has a calculated cost of about \$280/kg H_2 stored.

- ***Material Requirement 2*** – *gravimetric density* (1.8 kWh/kg - 5.5 wt.% H_2). The HPM hydrogen storage vessel offers significant weight savings compared to Type IV vessels, where the conceptual system is able to exceed DOE ultimate targets with a gravimetric capacity of 3.7 kWh/kg, which translates to a gravimetric storage capacity of 10.0 wt.% H_2.

- ***Material Requirement 3*** – *volumetric density (>0.7 kWh/L - 20g H_2/L).* The volumetric capacity is expected to be about 20 g/L, which is equivalent to existing Type IV storage vessels, except with the additional benefit of being conformable and adaptable to many vehicle platforms.

- ***Material Requirement 4*** – *hydrogen leakage (< 0.05 g/hr/kg H_2 stored at 700 bar).* Leak rate testing will be performed at ~400 bar from an existing 350 bar hydrogen fueling station, as such, an acceptable leak rate of 0.025 g/hr/kg H_2 stored at 350 bar will be considered equivalent to 0.05 g/hr/kg H_2 stored at 700 bar. Acetal resin is currently the leading candidate with a calculated leak rate of 0.008 g/hr/kg H_2 stored.

- ***Material Requirement 5*** *–operational temperature limit (-40°C ≤T≤ 85°C).* Established hydrogen fueling protocols allow the pressure vessel to reach 85°C during fueling operations. The pressure vessel must at a minimum tolerate this filling temperature.

Approach: Milestones

Milestone	Description	Estimated Completion Date
1.1	Simulate hydrogen fueling for a passenger vehicle hydrogen storage vessel using HPM technology.	7/13/15
1.2	Up to three resins identified for core liner with hydrogen permeability and compatibility that meets or exceeds high density polyethylene performance used in current Type IV composite tanks.	7/13/15
1.3	Specify and order extrusion and corrugation tooling. Capabilities include: 6-60 mm multi-layer output head, horizontal block with 8 ft bed, and ability to generate 6 ft HPM sections.	7/13/15
1.4	Test vessel(s) design complete for hydrogen storage at 700 bar. Approximate size of test vessel is 1 meter long with at least one flexible return section between vessel tubes.	7/14/15
1.5	Test vessel(s) fabricated. Approximately 1 meter long with one flexible joint and end fittings.	10/15/15

Approach: Milestones

Milestone	Description	Estimated Completion Date
1.6	Test vessel(s) survives pressure burst test exceeding 3.1X 700 bar.	11/12/15
1.7	Design and build test cell for hydrogen storage system demonstration.	10/29/15
1.8	Demonstrate hydrogen leakage of test vessel(s) at 350 bar is less than 0.025 g/hr/kg H_2 stored.	2/5/16
1.9	Down-select hydrogen storage vessel that meets or exceeds Type IV hydrogen storage cylinder performance.	2/26/16
Go/No-Go Decision Point	Present data to DOE confirming the 1 kg, 700 bar storage vessel meets the required 2170 bar burst pressure and hydrogen leakage rate under 0.05 g/hr/kg H_2.	3/1/16
2.1	Pressure vessel layout and design completed for a 700 bar, 1 kg hydrogen storage system.	2/29/16
2.2	Pressure vessel manufactured – liner corrugation, braiding, and end fittings.	4/15/16

Approach: Milestones

Milestone	Description	Estimated Completion Date
2.3	Pressure vessel survives burst pressure to 3.1X 700 bar	5/13/16
2.4	Hydrogen storage system design completed. Storage system includes 700 bar, 1 kg pressure vessel and balance of plant components needed to safely fuel and use compressed hydrogen gas for hydrogen vehicles	4/15/16
2.5	Pressure vessel container manufactured and tested at 700 bar hydrostatically	6/30/16
2.6	Perform preliminary cost model of hydrogen storage system for vehicle applications at 700 bar and develop example design for a 5.6 kg vehicle system.	6/28/16
2.7	1 kg, 700 bar hydrogen storage system assembled and inspected. Hydrogen storage system survives burst pressure to 3.1X 700 bar.	7/28/16

Approach: Milestones

Milestone	Description	Estimated Completion Date
3.1	Demonstrate cyclic hydrogen fueling at 350 bar.	10/27/16
3.2	Presentation of validated thermodynamic model along with supporting data.	10/12/16
4.1	Project Initiation	1/6/17
4.2	Perform Hazard Analysis and Develop hydrogen safety plan	10/12/16
4.3	Year 1 and 2 Project Management	1/6/17
4.4	Project Closeout	1/6/17

Accomplishments and Progress

Purpose:

- Produce a commercially available, highly scalable compressed air storage system to safely and effectively contain hydrogen at 700 bar.
- Significantly reduce both the cost and weight of gaseous hydrogen storage.
- Meet DOE's ultimate target for gravimetric storage and cost for 700 bar hydrogen storage.

Progress:

- This project was awarded on February 12, 2015 and is in the initiation and contracting phase.

Collaborations: Project Partners

- <u>High Energy Coil Reservoirs</u>

High Energy Coil Reservoirs (HECR) is a small independent research and development company formed to pursue development of high pressure gaseous fuel storage systems for vehicles.

- <u>University of Texas – Center for Electromechanics</u>

University of Texas – Center for Electromechanics (UT-CEM) is a research center world renowned for development and demonstration of advanced energy storage and power generation systems, and teams with companies to get the technology to market.

The team is exploring partnerships or vendors to conduct independent vessel permeability testing. In addition we plan to solicit feedback from DOE and vehicle OEMs during the project.

Remaining Barriers and Challenges

Risks	Mitigation
Prototype vessel design – hydrogen containment resin liner development	• Comprehensive search and evaluation of available resins • Detailed decision matrix to decide most promising candidates • Build and test several of most promising design alternatives
Prototype vessel design – reaching full required burst pressure	• Comprehensive overbraid design – HECR has previously tested vessels above required burst pressure • Higher strength overbraid fiber can be used if needed, but at higher cost

Although this project aims to provide a revolution in hydrogen storage, the development is expected to be a technology evolution for HECR. The baseline technology and manufacturing capability is already in commercial production. Once the development of the prototype vessel is complete and proven, overall project risk will be significantly reduced.

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Proposed Future Work

- Task 1: Vessel Design and Validation
  - 1.1 Vessel Thermodynamic Modeling
  - 1.2 Resin Identification
  - 1.3 Procure Corrugation Equipment
  - 1.4 Test Vessel Design
  - 1.5 Test Vessel Fabrication
  - 1.6 Test Vessel Pressure Testing
  - 1.7 Design and Build H_2 Test Cell
  - 1.8 Test Vessel H_2 Leakage Testing
  - 1.9 Test Vessel Thermodynamic Model Validation
  - 1.10 Down-select Final Pressure Vessel Design
- Go/No-Go Decision Point

A Go/No-Go decision point follows the initial vessel testing after achieving the required burst pressure of 2170 bar and proving the hydrogen permeation is extrapolated below 0.05 g/hr/kg H_2 at 700 bar. Following this initial testing, the team will design an 1 kg, 700 bar complete storage system.

Proposed Future Work

- Task 2: H_2 Storage System Design, Fabrication and Testing
  - 2.1 Pressure Vessel Layout and Design
  - 2.2 Pressure Vessel Fabrication
  - 2.3 Pressure Vessel Burst Testing
  - 2.4 H_2 Storage System Design
  - 2.5 H_2 Storage System Fabrication and Inspection
  - 2.6 Preliminary Cost Model
  - 2.7 H_2 Storage System Assembly and Inspection
- Task 3: H_2 Storage System Demonstration
  - 3.1 Cyclic Pressure Demonstration
  - 3.2 Update Thermodynamic Model
- Task 4: Project Management and Reporting
  - 4.1 Project Kickoff
  - 4.2 1st Year Quarterly Reporting and Project Management
  - 4.3 2nd Year Quarterly Reporting and Project Management
  - 4.4 Project Closeout

Technology Transfer Activities

- HECR has established pathways to commercialize conformable fuel tanks via partnerships and industry connections
- HECR is currently working on final testing for a commercially available conformable CNG storage vessel

Summary

- This project aims to reduce the cost, weight and difficult fit of conventional hydrogen tanks by developing a conformable 700 bar H_2 storage vessel
- Key development tasks include resin selection and over-braiding development
- Initial vessel will be a small proof of concept device to confirm permeability resistance and burst pressure
- Second phase device will be a complete storage system and store approximately 1kg H_2 at 700 bar