Insulated Pressure Vessels for Vehicular Hydrogen Storage

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Project ID # TV3

Overview

Timeline

- Start date: **October 2004**
- End date: **September 2006**
- Percent complete: **70%**

Barriers

- **B. Weight and volume**
- **H. Sufficient fuel storage for acceptable vehicle range**
- **L. Hydrogen boil-off**

Targets

- **2007 DOE volume target**
- **2010 DOE weight target**

Budget

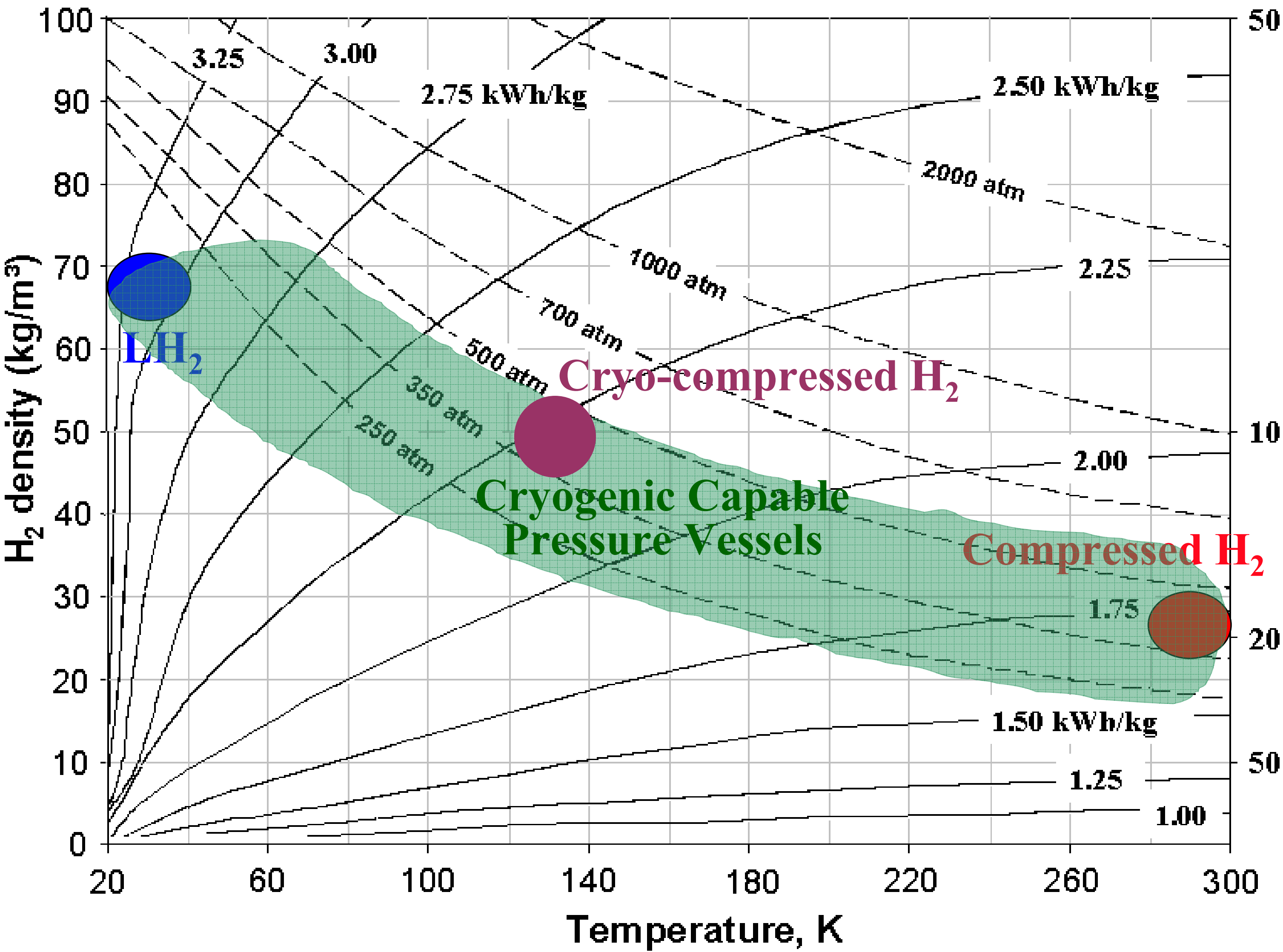
- Total project funding
  - DOE: **$515 k**
  - SCAQMD: **$350 k**
- Funding received in FY05:
  - **$225 k**
- Funding for FY06:
  - **$290 k**

Partners

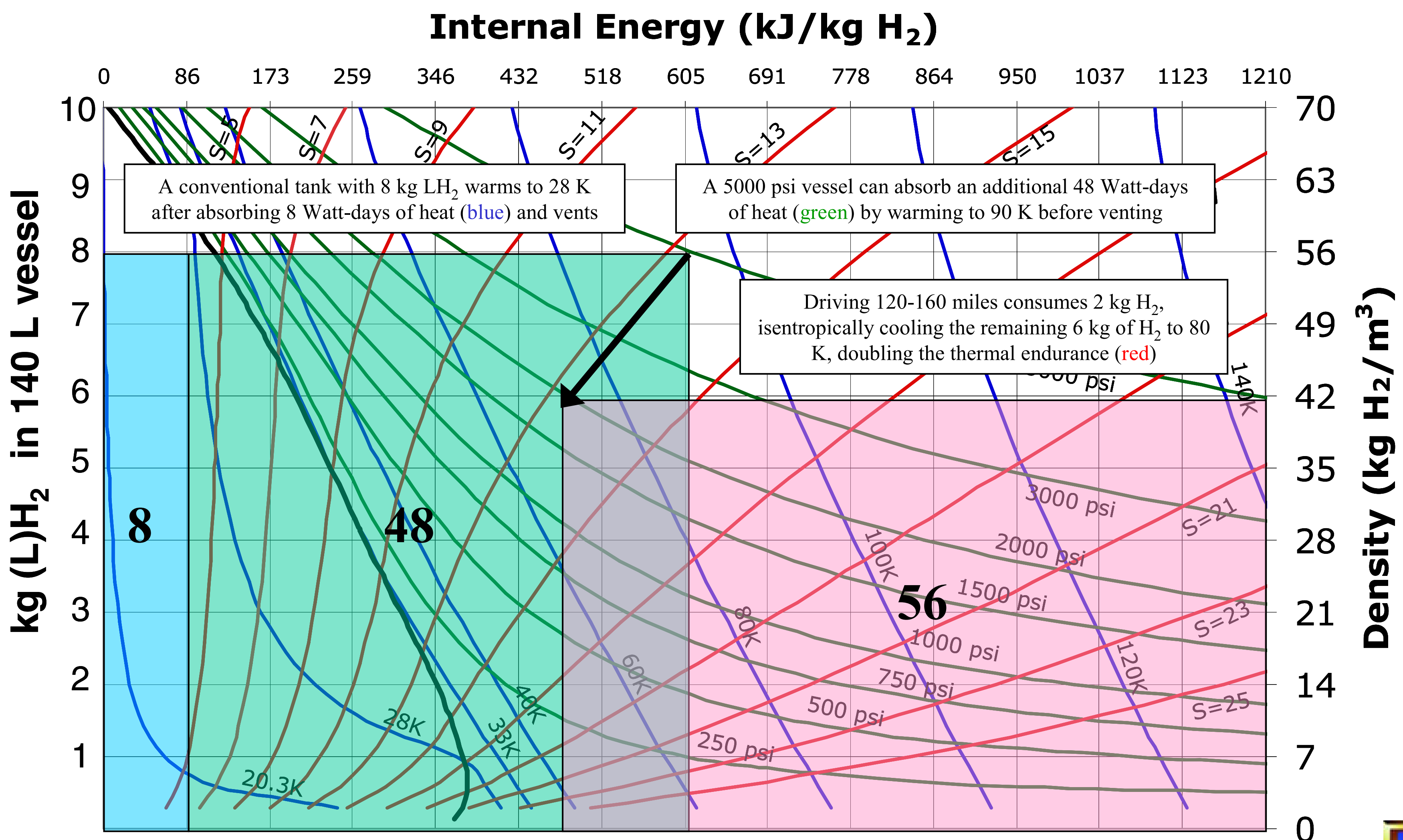
- Demonstrated cryotank technology with **SCI** and **SunLine,** funded by **SCAQMD**
- **Spencer composites,** CRADA **with Automotive Composites Consortium,** aerospace work funded by **DARPA**

Rationale: Our Cryogenic *Capable* Vessels can Store either Gaseous H_2 or LH_2, Capturing the Advantages of Both

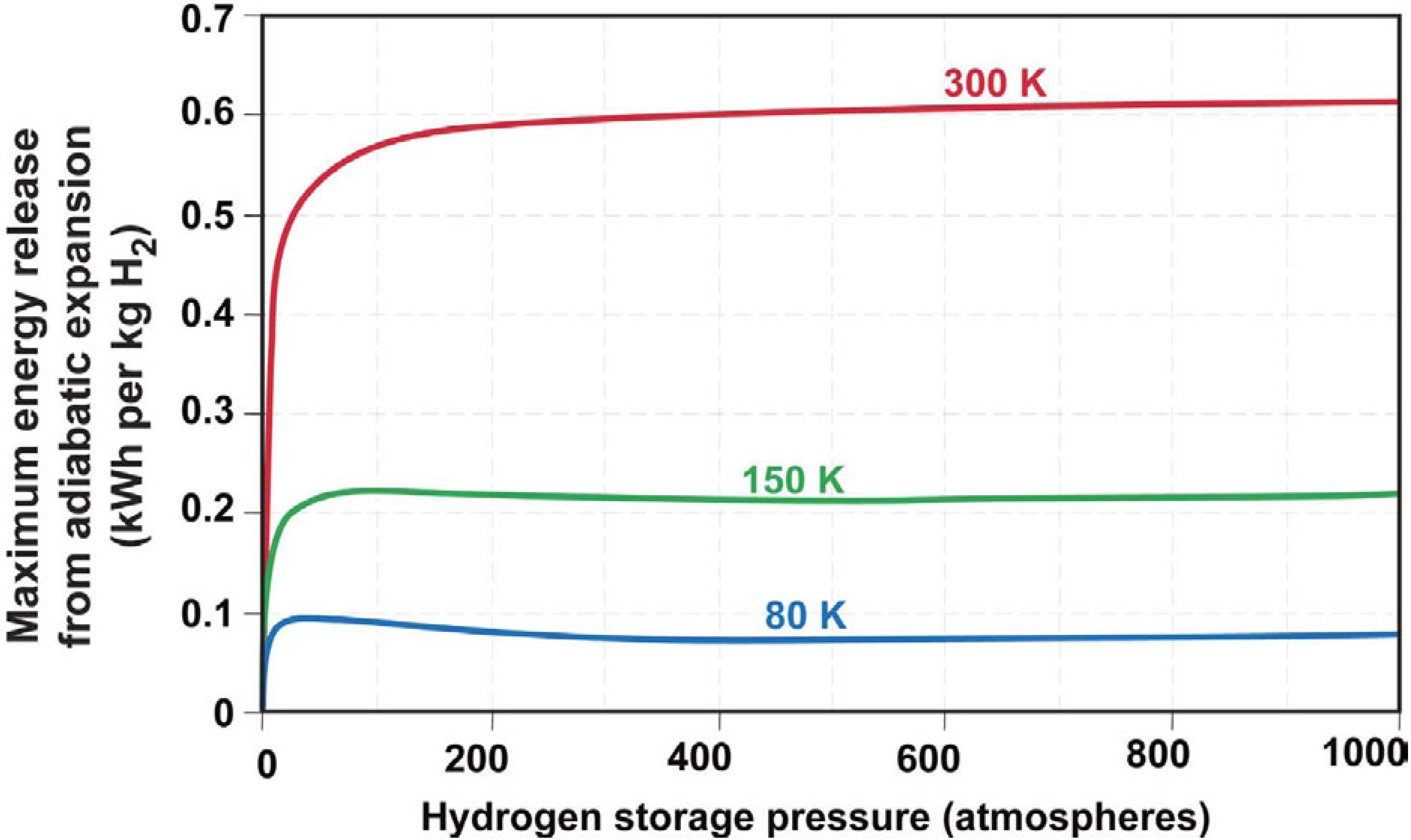
Cryogenic vessels operate across the entire H_2 phase diagram



A conventional tank with 8 kg LH_2 has 8 Watt-days of dormancy. An insulated 5000 psi vessel has 56 Watt-days of thermal endurance, which doubles as fuel (2 kg H_2) is consumed by driving



Cooling high pressure H_2 can increase safety removing energy from the gas radically reduces theoretical burst energy at cryogenic temperatures



Rationale: Why Insulate Pressure Vessels?

- Cryogenics lowers pressure vessel cost (2-3x less fiber for given capacity)
- Flexible refueling continuously matches storage method to drivers' current needs (cost, range, safety)
- Vessel temperature partially self-regulated (cools when driven – more so when fuller and/or warmer)
- Greatly extended dormancy (~5-10x vs. LH_2) *increasing* as fuel is used
- Cold H_2 has less stored PV energy
- Adaptable for solid state storage materials (e.g. carbon)

Objective: Demonstrate long range (200 to 500 mile) hydrogen hybrid vehicle with insulated pressure vessel

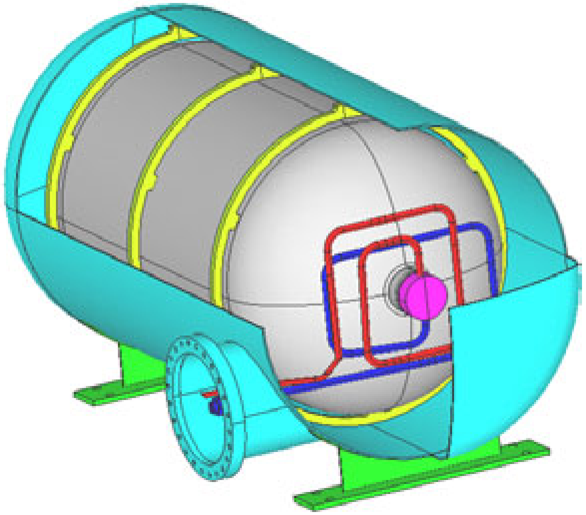
The vehicle

- Toyota Prius converted to H_2 fuel by Quantum.
- Originally equipped with 5000 psi 68 L pressure vessels (1.6 kg H_2)
- Est. fuel economy 50 miles/ kg H_2

LLNL Cryotank

- 151 L capacity
- stores 3.5 kg H_2 at 300 K, 5000 psi
- stores 6 kg H_2 at 150 K, 5000 psi
- stores 10.7 kg LH_2 at 20 K, 1 atm
- Meets DOE 2010 weight goal and DOE 2007 volume goal using LH_2 (297 Liter vacuum jacket volume)

Approach: we are designing, building, testing and demonstrating a compact insulated pressure vessel for long range hydrogen vehicles



design

construction

testing

demonstration

Accomplishments: We demonstrated refueling with both liquid and compressed hydrogen with our first generation insulated pressure vessel

- **Concept successfully demonstrated in SunLine pickup (SCAQMD funding)**
- **Wrote set of certification standards (funded by AQMD)**
- **Meets 2007 DOE weight target when full of LH_2**
- *Vertical* **orientation**

Our second generation insulated pressure vessel improves orientation, weight and volume

- *Horizontal* **orientation**
- **51% internal/external volume efficiency – lots of room for improvement**
- **48” long- Fits across compact pickup bed or inside trunk of midsize car**
- **Meets 2010 DOE weight goal and 2007 volume goal when full of LH_2**
- **Planned refueling and thermal management testing**
- **Planned demonstration of range and dormancy on H_2 Prius**

Thermal and mechanical integration and instrumentation steps

1. Attach instrumentation and heater to inner pressure vessel

2. Install mechanical support rings and multilayer insulation

3. Slide insulated vessel into outer vacuum vessel

4. Weld vacuum vessel and install flanges for high pressure lines

We are conducting extensive vessel testing to verify performance and guarantee safety

1. Vacuum test

2. Pressure test

3. Cryogenic cycling and dormancy test

4. Fueling test

Detailed listing of weights and volumes of vessels and components for first and second generation cryotanks

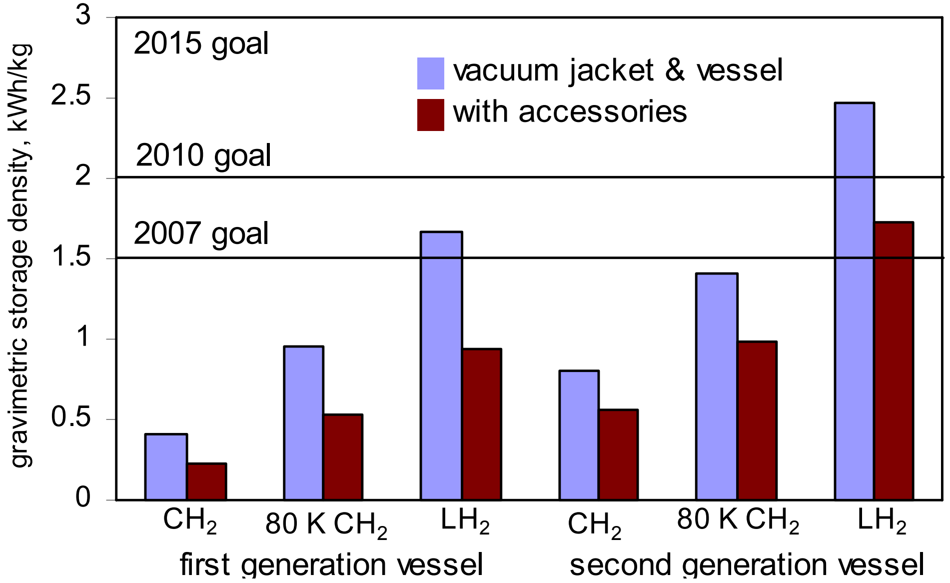
	first generation		second generation	
cryotank components	**Wt., kg**	**Vol., L**	**Wt., kg**	**Vol., L**
Hydrogen	9.5	135	10.7	151
Internal pressure vessel	65	33	68	34
Insulation and vacuum shell	117	212	65	112
Total, vessel & vac. shell	**191**	**380**	**144**	**297**
Computer	2.3	2.5	0.2	0.5
Computer Stand	2.3	0.5	0	0
Electronic boards	23	50	9	15
Level Sensor Box	0.9	2	0	0
Valve box	0	0	17	18
Pressure Transmitters	0.2	0.05	0.2	0.05
Pressure Gauges	2.7	0.5	2.7	0.5
Pressure Regulator	1.1	0.23	1.1	0.2
ASME Relief Valve	7	1.4	2.7	0
Circle Seal cryogenic valves	19.5	3.9	0	0
Nupro Relief Valves	0.5	0.09	0.2	0.05
Vent and fill valve	0.3	0.05	1.8	0
Rupture Disc	0.2	0.05	0.2	0.05
LH_2 Fill Hose	10.7	10	0	0
Tank Frame	9.1	1.3	7	0.6
Heat Exchanger	6.8	5	3.2	0
Explosion proof (EP) Cond.	5	5	0	0
Non EP Conduit	5	5	1.4	1.4
EP Enclosure	11.4	14	0	0
Tubing	13.6	5	6.8	2.5
Aluminum Plate	9.1	3	0	0
Wire	13.6	2.7	4.5	0.9
Grounding Lugs	1.4	0.3	0.1	0.03
Misc. Nuts and Bolts	2.3	0.5	1.1	0.2
Miscellaneous Fittings	1.8	0.4	1.8	0.4
Total for accessories	**150**	**113**	**61**	**40**
Total	**341**	**493**	**205**	**337**

First generation

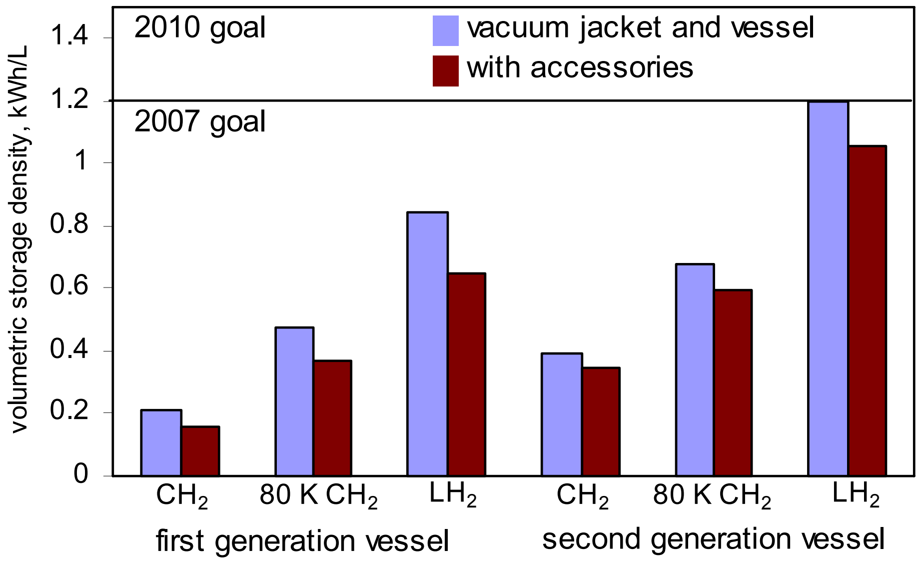
Second generation

Our second generation insulated pressure vessels filled with LH_2 can meet the 2007 volume and 2010 weight DOE targets (neglecting accessories)

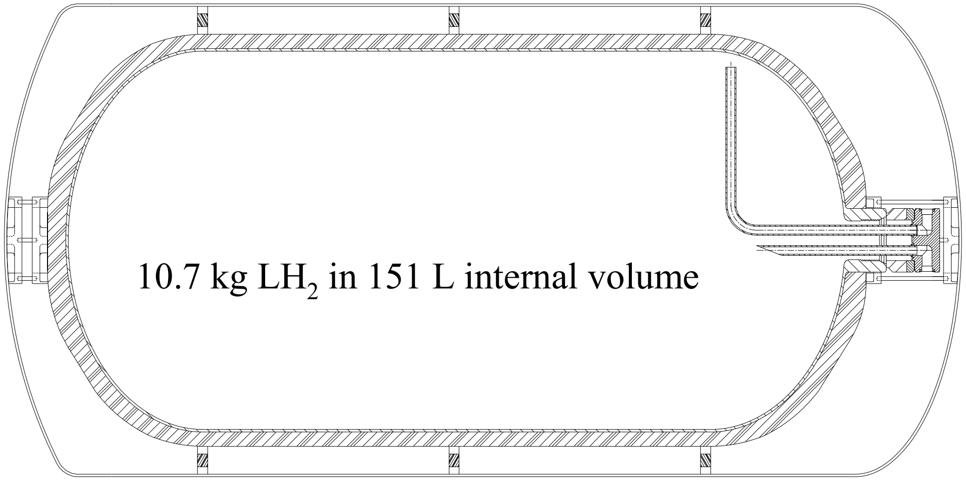
Weight targets



Volume targets

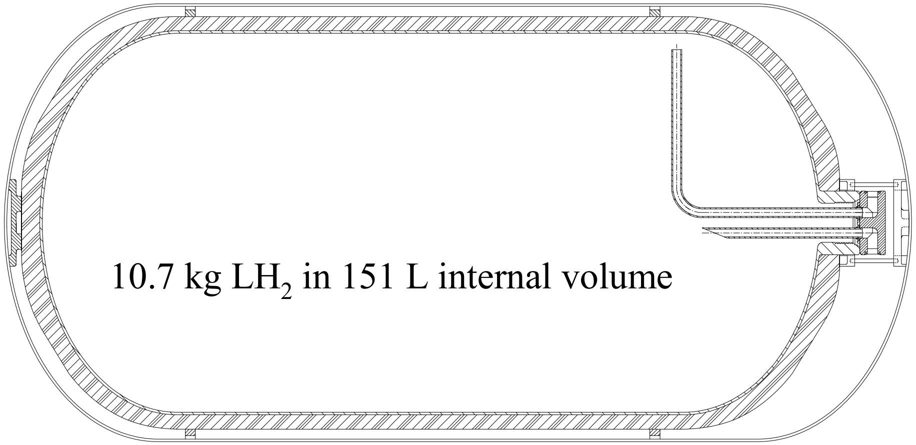


Future work: we will develop improved insulated pressure vessels that can meet the DOE 2010 volume goal using LH_2



Current vessel

- 35 mm insulation thickness
- Volumetric efficiency: 51%
- 297 L, 1.2 kWh/L
- meets 2007 DOE volume goal with 1 atm LH_2



Custom fabricated vessel

- 12 mm insulation thickness
- Volumetric efficiency: 64%
- eliminated Al-Steel transition piece
- Embedded support rings
- 238 L, 1.5 kWh/L
- meets 2010 volume goal

Summary: we are developing an insulated pressure vessel that meets the DOE targets and achieves up to 500 mile driving range in a H_2 hybrid

- Our flexibly fueled insulated pressure vessels provide benefits with respect to compressed and liquid H_2 vessels
  - More compact than CH_2 tanks
  - Lower evaporative losses and storage energy than LH_2 tanks
- We designed, built, and tested a horizontal cryogenic vessel which meets the 2010 DOE weight and 2007 DOE volume goals on LH_2
  - Substantially more compact than previous generation vessel
  - Will be installed in a long range hydrogen hybrid vehicle to verify thermal endurance and range.
- We designed an advanced insulated pressure vessel concept to meet the DOE 2010 volume goal

Supplemental slides

Responses to reviewers' comments:

- *It is not clear that insulated pressure vessels have advantages with respect to traditional LH_2 tanks.* **Insulated pressure vessels offer energy savings through flexible refueling and greatly extended dormancy (~10x), virtually eliminating evaporative losses**
- *It is difficult to see how the 2015 or even the 2010 targets can be met.* **Our current design meets the 2010 weight goal. We can meet the 2010 volume goal by increasing the volumetric efficiency. Achieving the 2015 targets will need a combination of pressurized LH_2, higher performance pressure vessels and/or conformability**
- *Mass and volume numbers are impressive but do not seem to include the full system.* **We have listed the weight and volume of our vessels, vacuum jacket, and all accessories.**
- **PI might benefit to collaborate with tank builders for future work. We are working more closely with Structural Composites Industries on developing custom fabricated vessels to improve the volume performance of our future cryogenic capable tanks.**

Publications and presentations

Patents

- **Lightweight Cryogenic-Compatible Pressure Vessels for Vehicular Fuel Storage,** Salvador M. Aceves, Gene Berry, Andrew H. Weisberg, US Patent 6,708,502 B1, March 23, 2004. World Patent WO 2004/029503 A2, April 8 2004.
- **Storage of H2 by Absorption and/or Mixture within a Fluid,** Gene Berry and Salvador Aceves, World Patent WO 2005/015076 A1, February 24, 2005.

Publications in Books and Technical Journals

- **Hydrogen Storage and Transportation,** Gene Berry, Joel Martinez-Frias, Francisco Espinoza-Loza, Salvador Aceves, Invited chapter, Encyclopedia of Energy, Volume 3, pp. 267-281, Elsevier Academic Press, New York, 2004.
- **Hydrogen Production,** Gene Berry, Invited chapter, Encyclopedia of Energy, Volume 3, pp. 282-294, Elsevier Academic Press, New York, 2004.
- **The Case for Hydrogen in a Carbon Constrained World,** Gene D. Berry and Salvador M. Aceves, Invited discussion paper, ASME Journal of Energy Resources Technology, 2005.
- **Vehicular Storage of Hydrogen in Insulated Pressure Vessels,** Salvador M. Aceves, Gene D. Berry, Joel Martinez-Frias, Francisco Espinosa-Loza, Accepted for publication, International Journal of Hydrogen Energy, 2006.
- **Liner Materials for Composite Tanks**, Andrew Weisberg, Invited paper for “Materials for the Hydrogen Economy,” CRC Press, 2005.

Publications in Refereed Proceedings

- **Development and Demonstration of Insulated Pressure Vessels for Vehicular Hydrogen Storage,** Salvador M. Aceves, Gene D. Berry, Proceedings of the 15th World Hydrogen Energy Conference, Yokohama, Japan, June 27-July 2, 2004.
- **Advanced Concepts for Vehicular Containment of Compressed and Cryogenic Hydrogen,** Salvador M. Aceves, Gene D. Berry, Andrew Weisberg, Francisco Espinosa-Loza, Scott Perfect, Proceedings of the 16th World Hydrogen Energy Conference, Lyon, France, 2006

Technical Report

- **Hydrogen Absorption in Fluids: An Unexplored Solution for Onboard Hydrogen Storage,** Gene D. Berry, Lawrence Livermore National Laboratory Report UCRL-TR-209650, Livermore, CA, February 2005.
- **Proposed Standards for Hydrogen and Liquefied Natural Gas Insulated Pressure Vessels,** Report to the South Coast Air Quality Management District August 2004

Presentations

- **Advanced Hydrogen Containers,** Andrew Weisberg, Invited presentation, American Physical Society, March 2005.
- **Cryogenic Hydrogen Storage**, Salvador Aceves, Invited Presentation, Materials for the Hydrogen Economy, September 2005

Critical Assumptions and Issues

- ***Need to demonstrate high insulation performance***
- ***Need to demonstrate incorporation in the vehicle***
- ***Need to demonstrate long vehicle range***