# IV.E.1 Advanced Concepts for Containment of Hydrogen and Hydrogen Storage Materials

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## Objectives

- Design, fabricate and test conformable vessels with high volumetric efficiency and with potential for high pressure or hybrid storage options.
- Develop innovative concepts that may be able to meet the DOE 2010 hydrogen storage targets.

## Technical Barriers

This project addresses the following technical barriers from the Hydrogen Storage section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) System Weight and Volume
(D) Durability/Operability
(E) Charging/Discharging rates
(H) Balance of Plant (BOP) Components
(J) Thermal management
(L) High-pressure Conformability
(O) Hydrogen Boil-Off

## Technical Targets

**TABLE 1.** Lawrence Livermore Cryo-Compressed Vessels Progress Toward Meeting DOE On-Board Hydrogen Storage Targets

| Storage Parameter | Units | 2007 Target | 2010 Target | 2005 1st Prototype | 2007 2nd Prototype |
|---|---|---|---|---|---|
| Specific Energy | kWh/kg | 1.5 | 2 | 0.92 | 1.5 |
| Energy Density | kWh/L | 1.2 | 1.5 | 0.64 | 1.1 |
| Storage System Cost | $/kWh | 6 | 4 | - | ~7-15* |

*Preliminary estimates by TIAX and industry developers

## Accomplishments

- Developed new concepts for high performance hydrogen storage containers.
- Worked with industry on developing cycle life and vacuum stability requirements for cryo-compressed vessels.

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## Introduction

One of the fundamental hurdles limiting the broad applicability of hydrogen vehicles is storing enough hydrogen on-board for a reasonable range (over 300 miles for the U.S. market). Several approaches are being pursued, including physical storage (liquid or compressed hydrogen), chemical storage, hydrogen absorption in metal hydrides, or hydrogen adsorption in high surface area adsorbents. All these approaches present fundamental limitations in weight and volume densities. Some forms of storage (hydrides and carbon structures) also require thermal management (heating during desorption and cooling during absorption or adsorption). Regardless of which form of hydrogen storage is ultimately selected by the vehicle manufacturers, there is a great need to develop high performance low cost containers for hydrogen or hydrogen storage materials. For best performance, these containers should be compact, conformable, meet the pressure and temperature requirements for the different forms of hydrogen storage, and provide efficient means for thermal management. The capabilities being developed at LLNL will have potential to support the development and evaluation of a number of storage options including high pressure, cryogenic, and hybrid material systems.

## Approach

A few years ago we developed the concept of flexibly fueled cryo-compressed vessels and we are working on demonstrating their high storage density and thermal endurance. Cryo-compressed vessels can be fueled with ambient temperature compressed hydrogen for lower energy consumption or with liquid hydrogen for long range. When filled with liquid hydrogen, cryo-compressed vessels contain two to three times more fuel than compressed hydrogen tanks at room temperature, and have ~10 times higher thermal endurance than conventional liquid hydrogen ($LH_2$) tanks, eliminating evaporative losses in routine use. Our vessels are also applicable to hydrogen storage materials that may benefit from their low temperature and high-pressure capability.

## Results

In 2007, our second-generation cryo-compressed vessel was demonstrated in a hydrogen-fueled Toyota Prius (Figure 1). Our cryo-compressed vessel demonstrated high gravimetric and volumetric performance, meeting the DOE 2007 weight goal and approaching the DOE 2007 volume goal. The vehicle also delivered the longest driving distance ever for a hydrogen vehicle, with 650 miles (under atypical conditions due to the constrained driving conditions of the test). We estimate a 500-mile range under urban or highway driving conditions. Although the tank used the entire trunk space, an acceptable driving range is anticipated with an improved underbody design. The vehicle demonstration work was funded by the Technology Validation program element.

We see many further improvements to the cryo-compressed technology that will increase its volumetric and gravimetric efficiency even more. The goal is meeting the very challenging DOE 2010 weight and volume goals including all system accessories.

Our approach for improved cryo-compressed vessel performance focuses on developing an advanced composite material modeling capability that can guide us toward better vessel designs of either conformable or cylindrical shapes. Current methodologies for composite material analysis do not take into account the detailed structure of the composite (fiber and resin) and instead consider averaged properties, either over the whole thickness of the composite or across the different layers of the fiber. We see much potential in developing detailed composite models that follow a more fundamental approach and directly model the fiber and the resin, initially at the lamina level and ultimately at the individual strand level (Figure 2). This approach, implemented into high performance LLNL computers, will improve composite material characterization by increasing the accuracy of the results and leading to a first-principles based approach that does not require the use of empirical models such as currently used for failure analysis.

Finally, we are also working with industry on addressing the remaining technical hurdles that keep cryo-compressed vessels from commercialization. These issues are cryogenic cycle life and outgassing (stability of the vacuum in the thermal insulation). We are planning experiments that will characterize these issues and clear the way for cryo-compressed vessel use in the commercial sector.

**FIGURE 1.** Cryo-Compressed Vessel Installed Onboard the Prius Hydrogen-Fueled Hybrid Vehicle

## Conclusions and Future Directions

- We have installed a cryo-compressed vessel into our prototype hydrogen vehicle, a Toyota Prius hybrid vehicle converted to hydrogen. The vessel meets the DOE 2007 weight target and it is within 10% of the DOE 2007 volume target. The Prius was driven 650 miles on a single tank of liquid hydrogen.

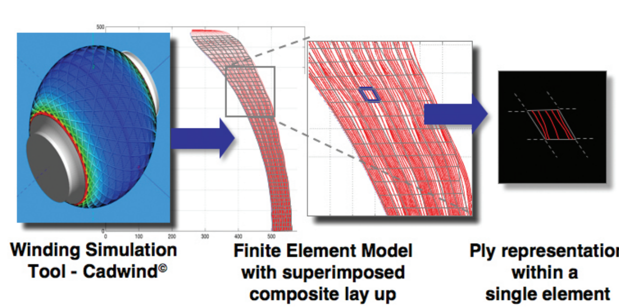


**FIGURE 2.** Modeling Procedure for Detailed Analysis of Composite Materials Capable of Resolving the Composite at the Lamina Level or at the Strand Level

- We are enhancing our advanced analysis capabilities for composite materials that may allow us to improve the performance of cryogenic pressure vessels.
- We are working with industry in developing test standards for cryogenic cycling and vacuum stability requirements.

## Special Recognitions & Awards/Patents Issued

1. Storage of H2 by Absorption and/or Mixture within a Fluid, Gene Berry and Salvador Aceves, US Patent 7,191,602, March 20, 2007.

## FY 2007 Publications/Presentations


1. Advanced Concepts for Vehicular Containment of Compressed and Cryogenic Hydrogen, Salvador M. Aceves, Gene D. Berry, Andrew H. Weisberg, Francisco Espinosa-Loza, Scott A. Perfect, Proceedings of the 16th World Hydrogen Energy Conference, Lyon, France, June 10–15, 2006.

2. Vehicular Storage of Hydrogen in Insulated Pressure Vessels, Salvador M. Aceves, Gene D. Berry, Joel Martinez-Frias, Francisco Espinosa-Loza, International Journal of Hydrogen Energy, Volume 31, pp. 2274-2283, 2006.

3. Cryogenic Hydrogen Storage, Salvador Aceves, Invited Presentation, Materials Science and Technology 2007 Conference and Exhibition, September 2007.

4. Setting a World Driving Record with Hydrogen, Salvador Aceves, Science and Technology Review, June 2007, http://www.llnl.gov/str/June07/Aceves.html.