IV.E.1 Low Cost, High Efficiency, High Pressure Hydrogen Storage

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Project Objectives

- Develop methods of achieving the DOE 2007 hydrogen storage system targets using 10,000 psi compressed hydrogen storage tanks.
- Explore, develop and demonstrate composite design and optimization techniques to lower tank cost.
- Investigate embedded sensors to monitor composite health.
- Evaluate cooling the hydrogen to increase the storage density ("CoolFuel" approach).
- Demonstrate tanks that incorporate the new technologies and are applicable to real world automotive application.

Technical Barriers

This project addresses the following technical barriers from the Storage section (3.3.4.2) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(A) System Weight and Volume
(B) System Cost
(C) Storage Efficiency
(D) Durability/Operability
(E) Charging/Discharging Rates
(J) Thermal Management
(M) Lack of Tank Performance Data and Understanding of Failure Mechanisms

Technical Targets

Current Status on Achieving Storage Targets

Storage Parameter	Units	2007 Targets	2010 Targets	Current 10,000 psi System Status
Specific Energy	kWh/kg	1.5	2.0	1.3*
Energy Density	kWh/L	1.2	1.5	0.8
Storage System Cost	$/kWh	6	4	10

*Note: Previous reports have stated a number as high as 1.6 kWh/kg. The 1.3 kWh/kg value was achieved through sub-scale testing. Currently Quantum does believe that 1.6 kWh/kg will be achieved through testing of full-scale tanks.

Accomplishments

- Located a vendor, assessed fiber placement capabilities and determined viability of fiber placement to reduce tank cost from $16/kWh to $11/kWh. (NOTE: The $11/kWh does assume high manufacturing volumes; i.e. at least 500,000 units annually.)
- Fabricated one tank using localized re-enforcement techniques; tank produced a lower than expected burst pressure (6,000 psi versus an expected burst pressure of 11,750 psi), however, significant gains were made in understanding the technology. A second tank is currently underway to further evaluate the technology. It was determined that Quantum does not possess the required software to fully design a 10,000 psi pressure vessel using localized re-enforcement techniques.
- Successfully identified one point in the relationship between damage and cyclic failure in 5,000 psi pressure vessels. The changes in strain on the surface of the tank as it approached failure were captured via strain gages. This information allows for more focused testing in future experiments and represents a large step toward our goal.
- The thermal model for our pressure vessel has provided more detail to the previously calculated predictions for the thermal requirements and benefits of the CoolFuel system. The benefits are increased gaseous hydrogen density that provides approximately 25 extra minutes of driving with the requirement that it must be used at least within

1.5 days of fueling before gas discharge is necessary to prevent an over-pressure condition.

- It was also shown in the thermal model that in-tank mixing is required to cool the gas uniformly in the tank after filling. It is not currently possible to fill a tank such that the desired CoolFuel temperature is achieved at the end of the fill and thus additional in-tank cooling is required. This additional cooling will be ineffective unless mixing is possible and mixing places additional requirements on the tank that are not currently feasible.

Introduction

The world's premier automotive original equipment manufacturers (OEMs) developing fuel cell vehicles have demonstrated significant interest in cost-effective and efficient high-pressure hydrogen storage systems. The current Quantum TriShield™ tank technology is close to meeting the percent weight, energy density, and specific energy goals of 6% hydrogen by weight. However, the current product line utilizes premium "aerospace-grade" carbon fiber reinforcement to meet the challenging structural requirement of supporting over 23,500 psi burst pressure as specified in current regulations. It is unreasonable to expect a significant raw material cost reduction to achieve the 2010 cost goal of $6 per kWh, even if economies of scale are taken into account.

Approach

The primary focus is to meet the cost goal of the DOE hydrogen storage technical targets with no/minimal loss in energy capacity. Quantum's current 10,000-psi TriShield™ tank technology is close to meeting many of DOE's targets, but the cost is still a major issue. Since the carbon fiber cost is a large portion of the overall cost (40-70%), the approach is to reduce the amount of carbon fiber needed to build the storage system while maintaining equivalent levels of performance and safety. This will be accomplished by improving the fiber translation using non-conventional filament winding processes and integrating sensors to actively monitor tank health. Reducing the amount of fiber used may also reduce the overall weight of the system. In addition, a third track to this project involves reducing the temperature of the stored hydrogen in order to increase its density.

Results

The first 10,000 psi hydrogen storage tanks developed by Quantum with DOE funding utilized high grade aerospace fiber to attain high performance. This achievement came at a very high cost due to the premium carbon fiber used. Subsequent 10,000 psi designs were able to employ mid-grade aerospace fibers, but the costs were still too high for commercial applications. The effort in Track 1 resulted in a 10,000 psi design using commercial grade carbon fiber while maintaining the level of performance on other technical goals. Using subscale tanks, the specific energy for the baseline system design (mid-grade aerospace carbon fiber) is about 0.66 kWh/kg, which equates to approximately 1.3 kWh/kg (see explanation above of 1.6 kWh/kg versus 1.3 kWh/kg) at full-scale. Quantum designed, fabricated, and tested over twenty tanks using various fiber types and resin systems to try to meet or exceed this baseline value. Through the composite design and wind pattern optimization process, one subscale design using commercial grade fiber was able to achieve 0.68 kWh/kg. However, this process alone will not produce a storage system that meets the 1.5 kWh/kg goal for 2007.

Quantum began looking for a way to continue the development and optimization of the composite structure using a technique called localized re-enforcement. This technique was thought to allow the composite to be better utilized for its strength capabilities. By better utilizing the strength of the composite, some of the composite would no longer be needed, and would allow weight as well as cost to be removed from the pressure vessel. This investigation is still on going, and Quantum is working with an outside vendor to assist with design, analysis, and fabrication of a tank.

Another approach Quantum is investigating is lowering the safety factor of the tank design while increasing the safety level of the storage system through the integration of active strain sensors. Measuring increased localized strain resulting from structural damage to the pressure vessel may provide for the ability to reduce the design safety factor, thus reducing the amount of required carbon fiber. The types of strain sensors used were reduced to two and then to one during the course of the project. Fiber optic-based strain gages proved to be too fragile, expensive and technically difficult to acquire readings and thus were excluded from testing until their fundamental issues can be addressed. Testing has continued with analog, or resistance, strain gages since they are inexpensive, easy to work with and yield clean data.

Another major issue that was addressed during this period was the ability to relate damage to cyclic failure. Our previous efforts were hampered by the fact that it was unknown how much damage was required to produce a failure in a given number of cycles. During this period a test was performed that yielded a very important data point for this aspect of the project. A 35 MPa (5,000 psi) pressure vessel was damaged by being dropped mid-cylinder onto a 1.25-inch diameter steel rod and pressure cycled at an amplitude of 45.5 MPa

(6,600 psi) for over 20,000 cycles, which is well past the life of the tank. The strain sensors measured no increase in strain during those first 20,000 cycles. The pressure amplitude was then increased to approximately 55.2 MPa (8,000 psi) and the tank failed at the damage location after approximately 800 cycles at that pressure (Figure 1). The strain gages measured changes in strain during those 800 cycles. Those gages measuring axial strain were sensitive to the distance away from the damage, whereas those gages measuring radial strain were not noticeably sensitive to distance away from the damage.

A vital consideration for the third track of this project was discovered and considered through the use of the thermal model previously created and corroborated with test data. As the pressure vessel is filled the temperature of the gaseous hydrogen in the vessel increases approximately 60 Kelvin, depending in part on the starting temperature of the gas. This fact means the hydrogen will be at a greater temperature than that needed for CoolFuel since the state of the art of composite pressure vessel design is not capable of handling temperatures low enough to accommodate an intake temperature of 140 Kelvin. Thus, it was considered that the gas could be chilled to the required 200 Kelvin after the fill was complete. A problem lies with the fact that hydrogen gas does not conduct heat very well and in the thermal models, shows that a temperature gradient exists at steady-state cooling if mixing is not used. There is currently no method of mixing hydrogen gas inside a composite pressure vessel and this aspect of the design presents a challenge that would require a method of mixing to be developed (Figure 2).

In addition to the issues of temperature uniformity are the problems experienced in balancing the benefits provided by higher gas density due to colder

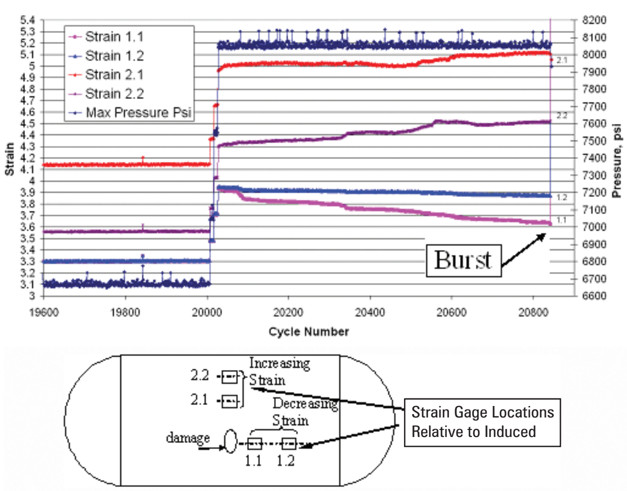

FIGURE 1. Strain Measurement of Damaged Vessel during Pressure Cycling

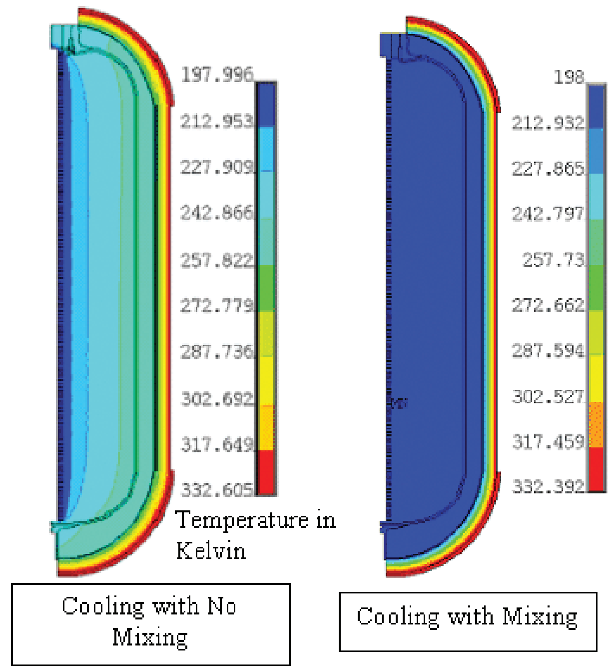

FIGURE 2. Hydrogen In-Cylinder Temperature With and Without Mixing

temperatures and the heat rejection required to attain those lower temperatures. The benefits can be quantified in terms of how much extra energy is provided to the end-user and these benefits must out-weigh the costs of supplying that extra energy. Approximately 3 million Joules per kilogram is required to bring the hydrogen gas from room temperature to the 200 Kelvin required for CoolFuel. If the gas is provided via liquid hydrogen supply then the required energy would be lessened depending on the delivery temperature. Once these issues are resolved, the added benefits of CoolFuel provide approximately 45 minutes of normal driving time or 1.5 days of dormancy before venting must occur to prevent an overpressure condition.

Conclusions and Future Directions

- The work will continue on the localized re-enforcement of the domes on a 10,000 psi pressure vessel. Quantum is currently working with a vendor to further develop the process. Another attempt will be made to reach the specific energy of 1.3 kWh/kg, while simultaneously reducing cost. Once this process is proven, it will be necessary to determine if any additional benefits can be realized using localized re-enforcement to lower the cost of the composite structure.
- The work performed on detecting a damage-induced failure condition via the use of strain sensors has produced promising results and provides a benchmark with which more productive future tests can be conducted. The first step is to reproduce

these results using a single pressure amplitude. This will be followed by tests that will add data points to the damage/failure relationship and that will provide more surface measurements over the surface of the vessel.

- The work performed for the CoolFuel concept has uncovered another obstacle that will make its implementation difficult. The future of this portion of the project will focus on assessing the viability of the approach and how benefits provided by the system can outweigh the costs. This portion of the work will be coordinated with Lawrence Livermore National Laboratory researchers pursuing a similar approach with their "cryo-compressed" tank technology.