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High-Pressure Conformable Hydrogen Storage for Fuel Cell Vehicles

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Abstract

Thiokol Propulsion is currently developing conformable tanks for gaseous hydrogen storage at 5,000 psig. These tanks have a water volume of 68 liters and have external dimensions of approximately 12.8 in. x 21.2 in. x 27.9 in. At an operating pressure of 5,000 psig, this volume will allow storage of 3.4 lb. of hydrogen, providing 23% more capacity than two cylinders in the same volume envelope. The tanks are fabricated using carbon fiber TCR® prepreg, plastic liners, and aluminum polar bosses. During the past five years, a significant technology development effort has been completed that has resulted in a baseline tank design that has passed many of the tests outlined in the NGV2-1998[1] standard for natural gas modified for 5,000 psig hydrogen storage. This paper will summarize the design process as well as provide a complete synopsis of tank testing.

Introduction

Fuel cell-powered vehicles have the potential to provide a solution to air quality problems as well as to reduce U.S. dependence on foreign fuel sources. A fuel cell combines hydrogen with air to produce electricity to power a vehicle, with water vapor as the primary by-product. A key issue for fuel cell operation is the availability of hydrogen on-board the vehicle. Hydrogen can be provided either as a compressed gas, as a cryogenic liquid, or as an adsorbed element using metal hydride storage. Alternatively, an on-board reformer can be used to generate hydrogen from gasoline, diesel, natural gas, or methanol. Of these alternatives, compressed hydrogen is considered the best near-term solution for hydrogen storage on a motor vehicle due to the relative simplicity of gaseous hydrogen, rapid refueling capability, excellent dormancy characteristics, low infrastructure impact, and low development risk.[2]

Despite these advantages, on-board high-pressure hydrogen storage must overcome several technical challenges in order to be viable in the long term. The energy density of hydrogen is significantly less than that of competing fuels as shown in Figure 1. Even with the high efficiencies projected for fuel cell vehicles, up to three times the current fuel efficiencies for internal combustion engines, a large volume of gaseous hydrogen storage will be required for acceptable vehicle range.

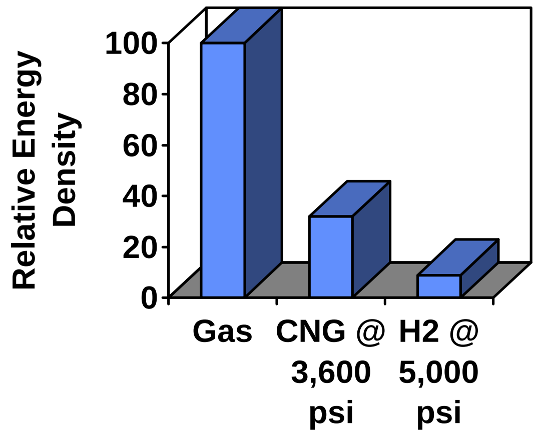

Figure 1. Comparison of fuel energy densities

With increased fuel requirements, the size of the fuel storage system becomes an issue. Liquid fuels such as gasoline and diesel can be stored in tanks that closely conform to the available space on the vehicle without reducing cargo capacity. For a gaseous fuel, the added requirement of pressurized storage constrains the geometry of the fuel tank. Because cylindrical tanks provide near-optimum pressure vessel structural efficiency, vehicles currently utilizing gaseous fuel systems employ one or more compressed storage cylinders. However, the cylindrical geometry of these tanks often does not lend itself to efficient use of the normally rectangular fuel storage volumes available on a vehicle as shown in Figure 2. In a rectangular envelope with an aspect ratio (width/height) equal to an integer, cylinders occupy less than 75% of the available storage volume. For non-integer aspect ratios, this figure can be as low as 50%.

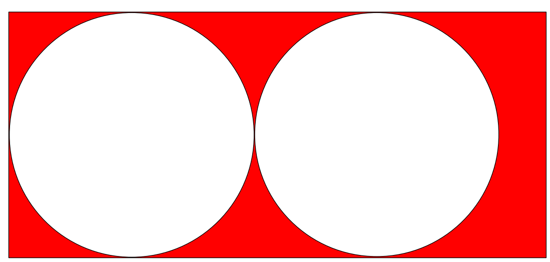

Figure 2. Cylindrical tanks in a rectangular envelope

The twin issues of energy density and packaging efficiency combine to exact a significant range penalty for gaseous-fueled vehicles. A lower energy density fuel dictates that a larger volume of fuel will be required for the same range as a conventionally fueled vehicle. However, the requirements of pressurized storage dictate that a smaller volume of fuel can be stored in the same envelope used for a conventional gasoline tank. This situation typically results in the location of additional gaseous fuel storage cylinders in the vehicle cargo area. This results in an increased vehicle range at the expense of vehicle payload.

The problem of maximizing on-board gaseous fuel storage is being addressed through the development of a conformable pressurized tank. Based on the physical principle that cylinders efficiently contain internal pressure via membrane response, the fundamental concept for the conformable tank consists of adjoining cell segments with internal web reinforcements. The general approach is shown in the cross-section in Figure 3. The result is a multi-cell pressure vessel. The number of internal cells is optimized for volume and pressure capacity and depends in large part on the aspect ratio of the envelope.

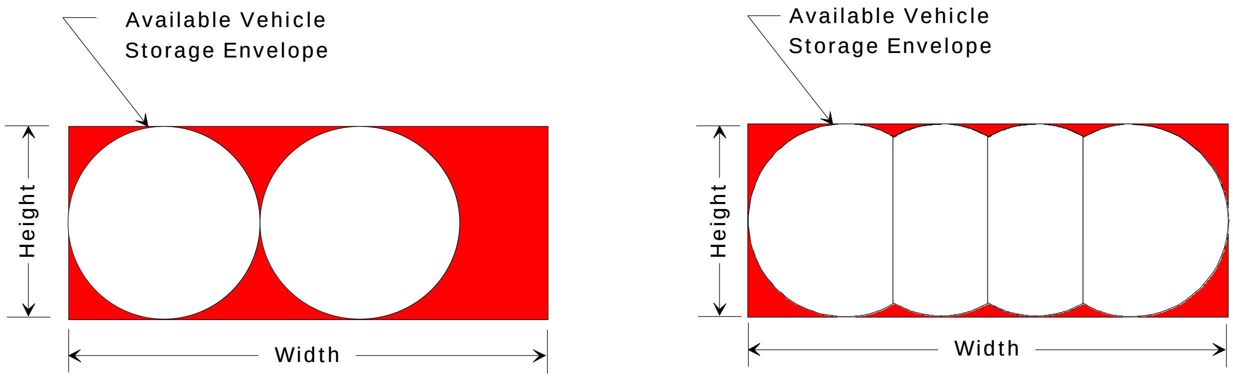

Figure 3. Cylinders vs. a conformable tank in a rectangular envelope

The expected benefits in volumetric efficiency of the conformable tank concept compared to multiple cylinders in a rectangular envelope are shown in Figure 4. Regardless of aspect ratio, the internal volume of the multiple cylinders never exceeds 70% of the envelope volume; except for aspect ratios close to 1.0, the conformable tank provides significantly increased storage volume.

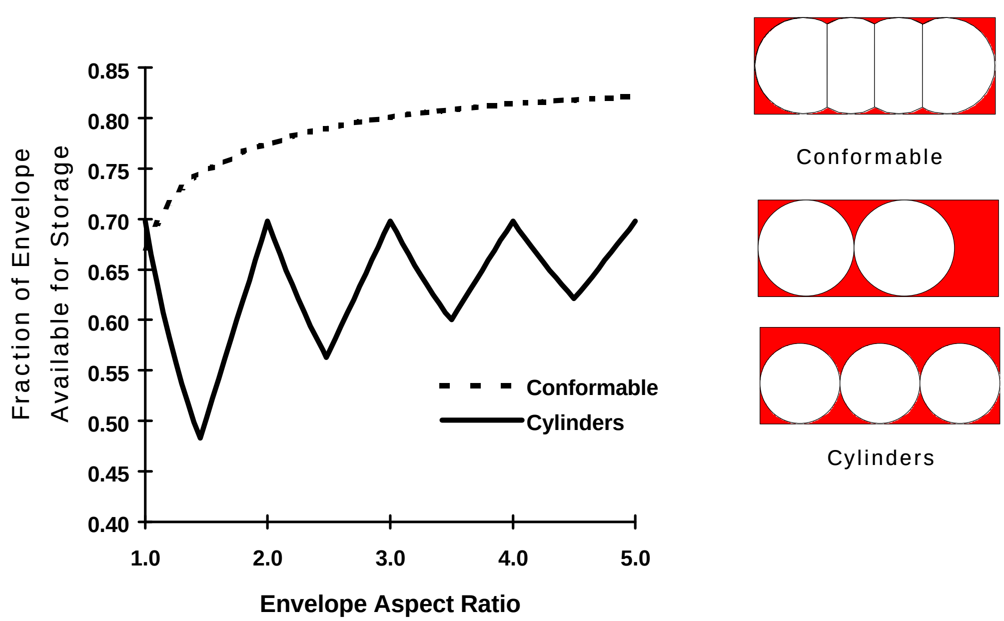

Figure 4. Comparison of storage efficiencies as a function of storage envelop

Discussion

To sustain the service pressures required for conformable hydrogen storage, material and process trade studies dictated the use of a carbon fiber composite tank design that employed a plastic liner and aluminum polar bosses. Use of the carbon composite material also allows the tank design to meet structural, cost, weight, and volume constraints. The plastic liner must prevent permeation of the stored gas through the structural composite while also serving as the mandrel for filament winding. From both weight and cost considerations, a plastic liner manufactured using a rotational molding process was selected for use in the baseline tank design. Rotational molding provides the dual benefits of low-cost tooling requirements for prototype development as well as the capability for molding non-symmetrical shapes.

The initial tank designs strove to exploit the advantages inherent in the use of carbon composite materials. The tailorability of filament-wound composites offers the opportunity to optimize tank wall thickness by applying less material in the lower-stressed axial direction, and by applying more material in the higher-stressed hoop direction. Finite element analysis combined with Thiokol's experience in winding composite rocket motor cases allowed for the completion of the initial conformable composite tank designs. The individual cells comprising the tank were wound with a combination of hoop and helical composite layers. These cells were then joined together to form a complete tank using winding tooling that allowed a final hoop overwrap to be wound over all of the cells. Careful control of the transition radius between the curved outer wall and the flat internal web allowed elimination of most of the bending and peel stresses at the joint between the cells. The geometry of the tank cross-section is shown in Figure 5. A U.S. Patent[3] has been obtained for the design and fabrication approach.

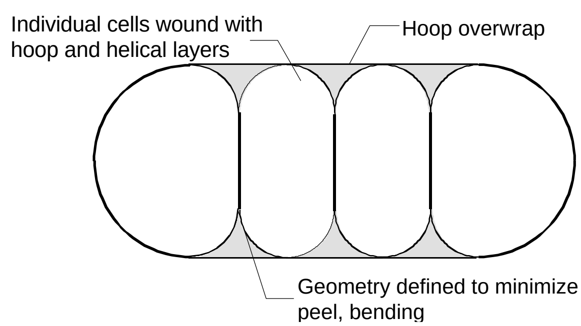

Figure 5. Conformable tank configuration

In efforts prior to FY1999, the structural capabilities of the resulting composite conformable tank design, were demonstrated using a sub-scale, two-cell prototype tank design. The prototype, pictured in Figure 6, occupies a storage envelope of 10.5 in. x 15.5 in. x 19 in. and has a capacity of 7.5 gallons. Mandrels for winding the individual cells were fabricated from sand mixed with a water soluble binder. The sand was cast and cured in a metal mold, and a thin layer of elastomeric material was applied to the surface of the mandrel for containing the pressurizing fluid. Following winding of the carbon/epoxy hoop overwrap and oven cure of the tank, the sand was washed out of the interior. Winding of an individual cell is shown in Figure 7. The finished prototype tank had a weight of 23 lb., including 15 lb. of composite. Prototypes were fabricated using Toray's M30S carbon fiber with Thiokol's TCR® prepreg resin system. Considerable trial and error was required to develop filament winding procedures for the non-axisymmetric conformable geometry.

The target burst pressure for the prototype tank was 11,250 psig, corresponding to a safety factor of 2.25 for a 5,000 psig service pressure tank. This was consistent with qualification requirements for CNG fuel tanks[1]. A burst pressure of 10,950 psig was achieved, verifying the capability of the composite conformable tank concept to meet the strength requirements for a hydrogen fuel tank. This design served as a baseline for the development of a full-scale hydrogen conformable storage tank that would have a service pressure of 5,000 psig and a service life of 20 years.

Figure 6. Prototype two cell conformable tank

Figure 7. Filament winding a conformable cell

Conformable hydrogen storage tank design activities completed in FY1999 included full-scale tank design, structural capability demonstration, and liner material evaluation and selection. Successful completion of FY1999 activities demonstrated the primary functional requirement for a full-scale high-pressure conformable hydrogen tank: the capability for safely withstanding the service pressure of 5,000 psi. However, additional requirements must be satisfied in order to demonstrate safe and reliable operation of the tank within the motor vehicle environment. Over a lifetime of service, the tank will experience cyclic loading due to repeated fills, extremes of temperature, exposure to corrosive fluids, potential damage both during handling and vehicle operation, and possible creep and stress rupture due to sustained high pressure loading.

The ANSI/AGA NGV2-1998 standard provides a comprehensive set of design and qualification test requirements for compressed natural gas (CNG) vehicle fuel tanks to ensure safe operation over the tank lifetime. In the absence of a comprehensive standard for hydrogen vehicle fuel tanks, and because of their similarity with CNG tanks, Thiokol will use NGV2-1998 qualification requirements modified for tank operation at 5,000 psig as the basis for safety and durability testing and evaluation under the present program.

The primary approach employed in FY2000 efforts is to subject a total of 6 tanks produced using the technology developed in FY1999 to qualification testing based on

NGV2-1998 modified for 5,000 psig tank operation in order to identify and address critical safety and durability issues. Accordingly, a total of 6 two cell conformable tanks were fabricated and delivered to Powertech Laboratories in Surrey, British Columbia, Canada for testing during the month of March 00. The tests conducted are defined in the NGV2-1998 standard and included temperature cycling, accelerated stress rupture, drop, environmental, penetration, and permeation. Test criteria for the complete NGV2-1998 standard and results obtained on the 6 tanks are summarized in Table 1 below;

Table 1: Conformable Hydrogen Tank Test Criteria and Results

Test	Criteria for Successful Test*	Result
Burst	Safety Factor 2.25 * 5,000 psig = 11,250 psig	Pass
Ambient Cycle	15,000 cycles without failure: 45,000 cycles without rupture to 1.25 safety factor * 5,000 psig = 6,250 psig	Pass
Environmental Cycling	Subject to fluid exposure, pendulum impact, gravel impact, high low, ambient temperature cycling, burst above 9,000 psig	Pass
Flaw Tolerance	Machined flaws followed by cycling (15,000 cycles to 6,250 psig)	Not Tested**
Drop	A total of 6 drops from a height of 6 feet followed by ambient cycling of 15,000 cycles to 6,250 psig	Pass
Penetration	Bullet penetration of tank pressurized to 5,000 psig with hydrogen. Tank must not fragment	Pass
Permeation	Specified leak rate for hydrogen	1.2 scc/l/hr
Bonfire	Must safely vent	Not tested
Hydrogen Gas Cycling	1,000 cycles with hydrogen to 5,000 psig, followed by leak test and destructive inspection	Not tested
Accelerated Stress Rupture	Tank pressurized to 6,250 psig and held at pressure for 1,000 hours at 149 F. At conclusion, tank must burst above 8,438 psig	Pass

* Requirements for a tank with 5,000 psig service pressure and a 20 year service life. Burst test results were conducted at Thiokol on additional conformable tanks that were not a part of the lot of 6 tanks sent to Powertech.

****** Tank expected to pass this test based on positive results for a compressed natural gas tank of similar design operating at 3,600 psig.

Conclusions

Thiokol has successfully designed and demonstrated a two cell conformable tank capable of storing hydrogen at 5,000 psig that will meet most of the design criteria of the NGV2-1998 standard. Additional testing will be required to certify the design to the NGV2-1998 standard. Additional challenges for this effort include increasing the tank operating pressure to 10,000 psig and incorporation of lower cost manufacturing components and techniques.

Future Work

Thiokol has currently completed all of its existing contract efforts for the DoE. An additional proposal has been submitted for a follow-on effort. Future tasks will either be completed on the follow-on contract or using Thiokol discretionary funding. Additional future efforts are defined below;

1.) Complete the remaining tests on the full-scale tank outlined in the NGV2-1998 standard.
2.) Extend the conformable tank design to operate at 10,000 psig.
3.) Incorporate component and manufacturing cost improvements into the existing tank design.

Acknowledgments

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2. B. D. James, G. N. Baum, F. D. Lomax, Jr., C. E. Thomas, I. F. Kuhn, Jr., “Comparison of Onboard Hydrogen Storage for Fuel Cell Vehicles,” Task 4.2 Final Report under Subcontract 47-2-R31148, prepared for Ford Motor Co. under DOE Prime Contract DE-AC02-94CE50389, Directed Technologies, Inc., 1996.

3. “Composite Conformable Pressure Vessel,” U.S. Patent No. 5,566,630, Nov. 26, 1996.