Hydrogen Composite Tank Program

Principal Investigator: Dr. Neel Sirosh, Director of Fuel Storage
QUANTUM Technologies WorldWide, Inc.
17872 Cartwright Road, Irvine, CA 92614
Phone: (949) 399-4698; e-mail: nsirosh@qtww.com

Introduction

There is a strong demand in the automotive market for cost-effective and efficient high-pressure hydrogen storage systems. World's premier automotive OEMs developing fuel cell vehicles have demonstrated significant interest in compressed hydrogen storage systems developed and validated by QUANTUM Technologies, under DOE contract DE-AC36-00GO10494. The currently validated QUANTUM "TriShield" tank technology (see Fig. 1) meets the percent weight, energy density, and specific energy goals of 6% hydrogen by weight, 1,050 W-h/L, and 2,000 W-h/kg, targets of the DOE and significant cost reductions are possible with further optimization.

Fig. 1 TriShield™ Type IV Tank

The 5,000 and 10,000 psi tanks developed by QUANTUM Technologies have been validated to meet the requirements of DOT FMVSS304, NGV2-2000 (both modified for 10,000 psi hydrogen) and draft E.I.H.P standard. Typical safety tests completed, in order to ensure safety and reliability in an automotive service environment included: Burst Tests (2.35 safety margin), Fatigue, Extreme Temperature, Hydrogen Cycling, Bonfire, Severe Drop Impact Test, Flaw Tolerance, Acid Environment, Gunfire Penetration, Accelerated Stress, Permeation and Material Tests.

Over the next decade beyond, a significant market is expected to develop for fuel cell powered products. These products will be designed to provide clean, quiet, vibration-free electric power on demand for a variety of applications in the transportation and industrial vehicle, stationary power and portable power markets. In the automotive market, each of DaimlerChrysler, Ford, General Motors, Honda, Hyundai, Nissan, and Toyota has recently announced its intention to introduce fuel cell vehicles sometime between 2003 and 2005, with mass production of fuel cell vehicles anticipated to begin in the latter part of the decade.

Project Goals and Objectives

The objective of the DOE Hydrogen Composite Tank Program was to design, develop, validate, fabricate, and manufacture hydrogen fuel tanks and in-tank regulators (Fig. 2) along with vehicle integration brackets and isolators and have them delivered to Virginia Tech University and Texas Tech University in support of the Future Truck competition.

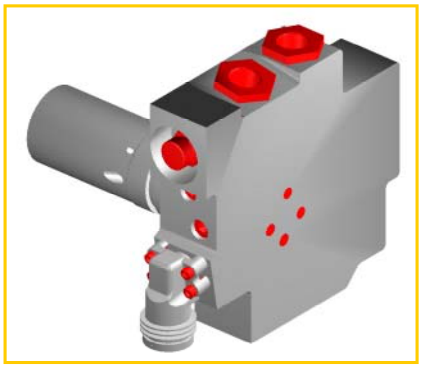

Fig. 2 "In-Tank" Pressure Regulator

This project is part of the DOE program to demonstrate the feasibility of the use of compressed hydrogen as an automotive fuel. However, the lack of convenient and cost-effective hydrogen storage, particularly for an on-board vehicular system, is a major impediment to its widespread use. Improvements in the energy densities of hydrogen storage systems, reductions in cost, and increased compatibility with available and forecasted systems are required before viable hydrogen energy use will be realized. Possible approaches to hydrogen storage include: compression, liquefaction, chemical storage, metal hydrides, and adsorption. Although each storage method has desirable attributes, no approach currently satisfies all the efficiency, size, weight, cost, and safety requirements for transportation or utility use. Research continues in these areas, with progress being made in all approaches.

Specific goals of the project were to:

- Develop and demonstrate 7.5 wt % and 8.5 wt% Type IV composite hydrogen storage tanks of specified sizes
- Validate 7.5 wt% and 8.5 wt% Type IV composite hydrogen storage tanks
- Develop and validate 5,000 psi in-tank-regulators
- Build, assemble, test and supply tanks with in-tank-regulators for DOE Future Truck and Nevada hydrogen bus programs
- Demonstrate 10,000 psi hydrogen storage tanks

Milestones

Key milestones in the development and commercialization of QUANTUM's high-pressure storage technologies include:

1999 Breakthrough in new, ultra lightweight, low-cost storage addressing barriers related to permeability and effects of hydrogen embrittlement.

2000 As part of a DOE-sponsored development program with Lawrence Livermore National Laboratory and Thiokol, achieved a "World Record" hydrogen storage mass efficiency of 11.3 weight percentage on a prototype 350 bar (5,000 psi) tank

- This achievement received an innovation award from the DOE Hydrogen Technical Advisory Panel (HTAP)
- Awarded patent for in-tank regulator for fuel cell and natural gas vehicles.
- Commenced shipping high efficiency TriShield™ hydrogen storage tanks (5,000 psi and 3,600 psi) for a number of vehicles and stationary applications (Fig. 3).

Fig. 3: 5,000 psi (350 bar) TriShield Tanks

- QUANTUM's 350 bar tank in a Hyundai Santa Fe FCEV is the first to fill to 350 bar with hydrogen.
- Demonstrated proof-of-concept 10,000 psi (700 bar) tank and began validation testing.
- In November 2001, achieved European Integrated Hydrogen Project (EIHP) specifications for 5,000 psi hydrogen storage tank, the first all-composite tank to achieve this.
- Achieved CSA certification for industry's first 5,000 psi (350 bar) in-tank regulation system under NGV 3.1 standards.
- Designed and developed industry's first hydrogen 10,000 psi (700 bar) in-tank regulation system.
- Developed industry's first solenoid valve designed exclusively for hydrogen use
- Shipped tanks for DOE Future Truck and Nevada bus programs

2001 Received industry's first regulatory certification of 10,000 psi hydrogen storage tanks (EIHP-based tests)

- Shipped 10,000 psi tanks systems for OEM applications
- Obtained Japanese (KHK) certification for 5,000 psi hydrogen storage tanks

- Developed, validated and shipped tanks for Future Truck 2002 (Ford)

Status of Progress

Developed at QUANTUM's Advanced Technology Center in Irvine, California, the QUANTUM TriShield™ all-composite hydrogen storage cylinder removes the barriers to more rapid commercialization of hydrogen-powered fuel cell vehicles. QUANTUM has introduced this rugged, low cost, ultra-lightweight, storage efficient hydrogen storage tank to improve the range and safety of hydrogen powered fuel cell vehicles.

The QUANTUM advanced composite tank technology incorporates a "TriShield™" design philosophy (see Fig. 4). The QUANTUM Type IV TriShield™ cylinder, as illustrated below, is comprised of a seamless, one piece, permeation resistant, cross-linked ultra-high molecular weight polymer liner that is overwrapped with multiple layers of carbon fiber/epoxy laminate and a proprietary external protective layer for impact resistance. TriShield™ hydrogen tanks feature a single-boss opening to minimize leak paths.

TriShield™ hydrogen tank is designed to accommodate QUANTUM's patented in-tank regulator, (see Fig. 2) which confines high gas pressures within the tank and, thus, eliminates high-pressure fuel lines downstream of the fuel storage subsystem. By combining a check valve to assist tank filling, fuel filtering, fuel tank pressure and temperature monitoring, pressure relief device and tank lock-off in the regulation module the system cost can be significantly reduced.

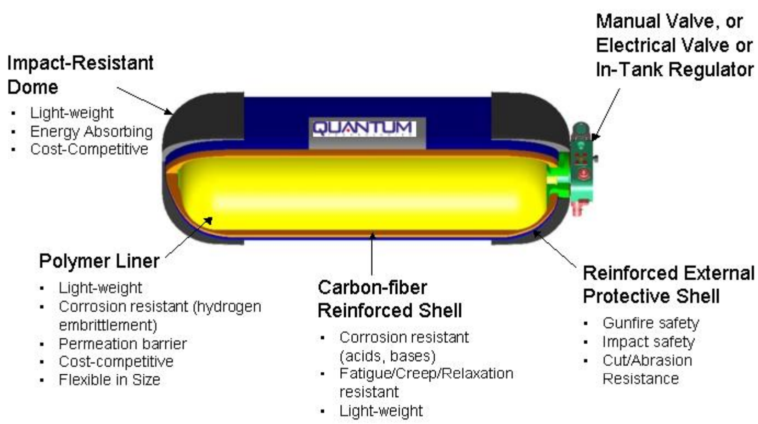

Fig. 4: TriShield™ Tank Construction

Gaseous fuels, especially hydrogen, inherently have a much lower energy density than liquid fuels, such as gasoline. Compression to high pressure is required to increase the mass of hydrogen stored, and resulting vehicle range, within a given space on-board a vehicle. Compressed natural gas, for example, is typically stored at 3,000 psi (200 bar) or 3,600 psi (250 bar). Hydrogen needs to be compressed to even higher pressures because of its even lower energy density. To date, hydrogen tanks designed for fuel cell vehicles have been developed to store hydrogen at pressures of up to 10,000 psi (700 bar) to maximize vehicle range. Hydrogen cylinders are actually designed to handle pressures considerably higher than the rated service pressure – to meet a minimum safety factor of 2.35 burst strength and to accommodate an increase in gas temperature during fast filling.

Standards developed by ANSI/AGA, NGV2-1998 and NGV2-2000 have become the key for industry acceptance of high-pressure storage cylinders, although FMVSS 304 is the minimum standard required by the U.S. Department of Transportation (DOT). Since no international standards or specifications have yet been approved for hydrogen cylinders, they are currently following compressed natural gas (CNG) tank classifications, which fall into these categories:

- Type I - all metal cylinder
- Type II – load-bearing metal liner hoop wrapped with continuous filament
- Type III – non-load-bearing metal liner axial and hoop wrapped with continuous filament
- Type IV - non-load-bearing non-metal liner wrapped with continuous filament

The International Standards Organization (ISO) is developing fuel cell vehicle and hydrogen storage standards within technical committees TC22/SC21 and TC197. The European Integrated Hydrogen Project (EIHP) has also formulated state-of-the-art hydrogen system standards. The standards, both those based on CNG and those being developed for hydrogen, specify a number of tests to ensure safety, reliability, and durability of the compressed hydrogen fuel storage system. The various types of validation tests are listed in Figure 5.

Hydrostatic Burst
Ambient Cycle
Gunfire Penetration (*see picture*)
Flaw Tolerance
Drop Test
Hydrogen Cycle
Tensile Properties
Boss End Material
Extreme Temperature Cycle
Acid Environment
Bonfire (*see picture*)
Accelerated Stress
Permeation
Softening Temperature
Resin Shear
Boss Torque Resistance

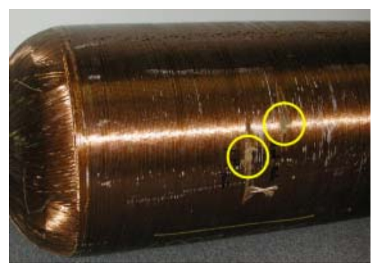

Fig. 5 Validation Tests

Future Work

The storage, transport, and delivery of hydrogen are critical elements for a practical hydrogen energy system. The goal to develop efficient and cost-effective hydrogen storage systems is driven primarily by the mobile applications for hydrogen, where size and weight of a storage device are major constraints. Other applications will also benefit from the technological advances made for on-board hydrogen storage systems. Since the energy density of hydrogen gas is significantly less than that of conventional fuels, larger tanks are required for equivalent range. Furthermore, the geometry of traditional high-pressure cylinders generally does not conform to the available space on the vehicle, thereby raising tank packaging issues. Tank cost and weight also significantly influence the amount of fuel that can be carried.

QUANTUM is working with ATK Thiokol Propulsion, its strategic alliance partner, in addressing these issues through the development of high-pressure conformable tanks for on-board hydrogen storage. The lightest-weight approach uses high-strength, filament-wound carbon fiber composite for structural efficiency, with polymer liners as permeation barriers. The quasi-conformable storage concept uses multiple cells, with the number and shape of the cells tailored to maximize internal volume within a rectangular envelope while maintaining membrane loading for structural efficiency. Each cell is filament-wound with a combination of hoop and helical layers, followed by a hoop overwrap over the assemblage of cells. Depending on the shape of the envelope, up to 50 percent more storage may be possible with a conformable tank than with cylinders.

Hydrogen poses challenges, both real and perceived, as a transportation fuel. The most challenging application is the light-duty vehicle or, more specifically, the automobile. Automobiles impose the greatest constraints with respect to available space on-board the vehicle and consumer expectations for vehicle range. In the near-term, fuel cell vehicles will likely first be introduced for fleet applications in 2003-05. Fleet applications will likely have centralized refueling available, so a vehicle range of 100 – 150 miles (160 - 241 km) would be acceptable. In terms of mass of hydrogen, this range could be achieved with about 3 kg of hydrogen supplying a fuel cell vehicle. Mature compressed and liquid hydrogen storage technologies of reasonable size and weight could achieve this short-term goal, as shown in the following table. Metal hydrides, although providing more compact storage, would impose a significant weight penalty.

Technology	Storage System Volume	Storage System Weight
5,000 psi Compressed H_2 Tanks	145 L	45 kg
10,000 psi Compressed H_2 Tanks	100 L	50 kg
Metal Hydrides	55 L	215 kg
Liquid H_2	90 L	40 kg

Short-term Goal: 3 kg H_2 (215 km)

In the long-term, average consumers will expect fuel cell vehicles to be transparent compared to the gasoline-powered vehicles they drive today with respect to cost, convenience and operation. In fact, it is likely that fuel cell vehicles will have to offer a significant value proposition to encourage consumers to adopt a new technology rather than continue with something that is tried and true. Vehicle range will be an important factor to consumers, especially as a hydrogen refueling infrastructure begins to develop. Fuel cell vehicle range of over 400 miles (644 km) will be needed, or roughly 7 kg of hydrogen stored on-board. Advanced storage materials, including alanate hydrides and carbon nano-structures, will have to emerge from the current conceptual stage to reduce hydrogen storage system size and weight, as shown in the following table. However, both of these solid-state storage media are years from commercialization. QUANTUM's 10,000 psi TriShield™ could potentially meet this long-term goal without significantly impacting either the passenger or storage compartments.

Technology	Storage System Volume	Storage System Weight
5,000 psi Compressed H_2 Tanks	320 L	90 kg
10,000 psi Compressed H_2 Tanks	220 L	100 kg
Alanate Hydrides	200 L	222 kg
Carbon Nanotubes	~ 130 L	~ 120 kg

Long-term Goal: 7 kg H_2 (700 km)

Commercialization

The markets for QUANTUM's advanced TriShield™ high-pressure storage technology appear to be growing. Quoting one major OEM, the hydrogen storage efficiency achievements by QUANTUM's TriShield™ tanks "has made us re-think our fuel cell fuel strategy." Major automotive OEMs and bus OEMs are expected to be the major markets for this technology. In addition, QUANTUM sees growing interest in stationary and, especially, hydrogen refueling infrastructure applications for its advanced TriShield™ storage tanks.

Since 1995, QUANTUM has invested significantly in research and development of technology and products that support the use of fuel cell systems. The commercialization of our technology products has established QUANTUM as a leader in fuel storage, fuel metering, and electronic controls for hydrogen systems. QUANTUM continues to pursue further advances in storage technology, materials, regulators, metering, sensors, controllers, and refueling infrastructure that will enable fuel cell vehicles to become as transparent to the consumer and end user as today's gasoline engine-powered automobiles.

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