Flexibly Fueled Storage Tank Brings Hydrogen-Powered Cars Closer to Reality

As a Department of Energy national laboratory, Livermore has long been involved in research and development of alternative energy technologies for transportation, including hydrogen fuel. Hydrogen-fueled passenger cars can have significant advantages over today's or tomorrow's gasoline cars. They can eliminate automotive air pollution, reduce our nation's oil dependence, and reduce or eliminate greenhouse gas emissions from transportation, if the hydrogen fuel is produced from nonfossil energy resources.

But as a recent article on the front page of the *Wall Street Journal* (March 7, 2003) makes clear, hydrogen cars may be a long way off. Numerous obstacles must be overcome before passenger cars using hydrogen become a viable alternative to gasoline-powered vehicles. Not the least of these is the development of extremely fuel-efficient passenger cars. Be they fuel-cell vehicles or hybrid vehicles burning hydrogen in an internal combustion engine, these cars must get the equivalent of 60 to 100 miles per gallon (25 to 42 kilometers per liter) and be capable of storing 5 kilograms of hydrogen onboard to achieve a driving range of 300 to 500 miles (480 to 800 kilometers). The world's major automobile manufacturers are addressing this challenge in a variety of hydrogen vehicle development programs.

Meeting the Storage Challenge

Other obstacles to hydrogen cars fall into three large categories: hydrogen production, refueling infrastructure, and hydrogen storage onboard the vehicles. Researchers in Livermore's Energy and Environment Directorate have been addressing these problems for almost a decade. (See *S&TR*, July 1995, pp. 26–27; May 1997, pp. 12–14; December 1999, pp. 4–13.) Recently, a team in Energy and Environment's Energy Technology and Security Program has turned its attention to the challenges of storing hydrogen fuel onboard automobiles. Led by engineer Salvador Aceves, associate program leader for transportation, the group has designed and tested a safe and compact system for on-vehicle storage of hydrogen fuel. The tank, which shows great promise, was featured on the cover of the February 2002 issue of *Mechanical Engineering* and will soon be installed on test vehicles.

The beauty of the Livermore tank, says Aceves, is that it can safely and simultaneously accommodate three forms of hydrogen fuel—conventional high-pressure hydrogen gas, cryogenic compressed gaseous hydrogen, and liquid hydrogen. And it does so while minimizing the storage challenges and maximizing the energy efficiency potential of each.

Three Fuel Forms, One Tank

Similar to compressed natural gas vehicles, prototype hydrogen vehicles use compressed hydrogen, stored onboard at about room temperature and under moderate pressure (25 to 35 megapascals). Unfortunately, these moderate pressures lead to large fuel tanks and/or limited driving range because the energy density of simple hydrogen molecules (H_2) is lower than the energy density of conventional fossil fuels such as gasoline (C_8H_{18}) or natural gas (CH_4), both of which are more complex molecules. One kilogram of hydrogen gas at 25 megapascals occupies nearly 60 liters (16 gallons), but its energy (33.3 kilowatt-hours) is equivalent to just 1 gallon of gasoline. Compressed hydrogen is a simpler, less costly, and more energy-efficient method of storage than other methods and is well suited for the range of the majority of urban drivers in the U.S.: 150 to 200 miles.

Since all gases occupy less volume at colder temperatures, compressed hydrogen can be stored more compactly when cryogenically cooled. At temperatures of 80 kelvins (–193°C), near the boiling point of liquid nitrogen, 60 liters of hydrogen gas at 25 megapascals contains the energy equivalent to more than 3.3 gallons of gasoline, enabling cars using cryogenic hydrogen to greatly extend their driving range.

Liquid hydrogen is even more compact than cryogenic hydrogen, but because hydrogen's boiling point (20 kelvins) is lower than that of any substance except helium, liquefying hydrogen is complicated and not energy efficient. Typically, 11 to 12 kilowatt-hours of electricity are needed to produce 1 kilogram of liquid hydrogen, which contains only 33.3 kilowatt-hours of fuel energy. This high energy penalty is a key factor in the high production cost of liquid hydrogen.

Liquid hydrogen has its advantages, however. It is relatively easy and safe to store and transport in compact, lightweight, low-pressure containers. According to project engineer Gene Berry, a hydrogen car designed to get the equivalent of 60 miles per gallon of gasoline uses 100 liters of liquid hydrogen to travel 420 miles, compared to 240 miles on high-pressure (70 megapascals) compressed hydrogen and 140 miles on moderate-pressure (35 megapascals) compressed hydrogen. Liquid hydrogen is thus ideal for long highway trips. Its advantages help explain why it has become the favorite of BMW's 20-year hydrogen vehicle development program.

The rub is that liquid hydrogen is extremely sensitive to heat, expanding significantly when warmed only a few degrees. When a hydrogen-fueled car is not being driven, heat exchange between the storage tank and the outside environment warms the fuel, causing it to evaporate. As the hydrogen fuel expands, the pressure in the tank increases. The hydrogen must therefore be vented to the atmosphere to prevent the dangerous buildup of excessive pressure.

Cryogenic hydrogen fuel in a standard liquid hydrogen tank typically warms up enough in 3 to 4 days after refueling to require venting. The tank team used computer analysis to determine that when liquid hydrogen is stored in a conventional low-pressure (0.5-megapascal) tank in a car that gets the equivalent of 80 miles per gallon, it would begin to vent and lose fuel if driven (on average) less than about 15 miles daily. Evaporation losses increase sharply if the car is driven less. In a parked car, an entire tank of liquid hydrogen fuel will completely evaporate in just 3 weeks. Eliminating this evaporation is a primary goal of Livermore's tank design.

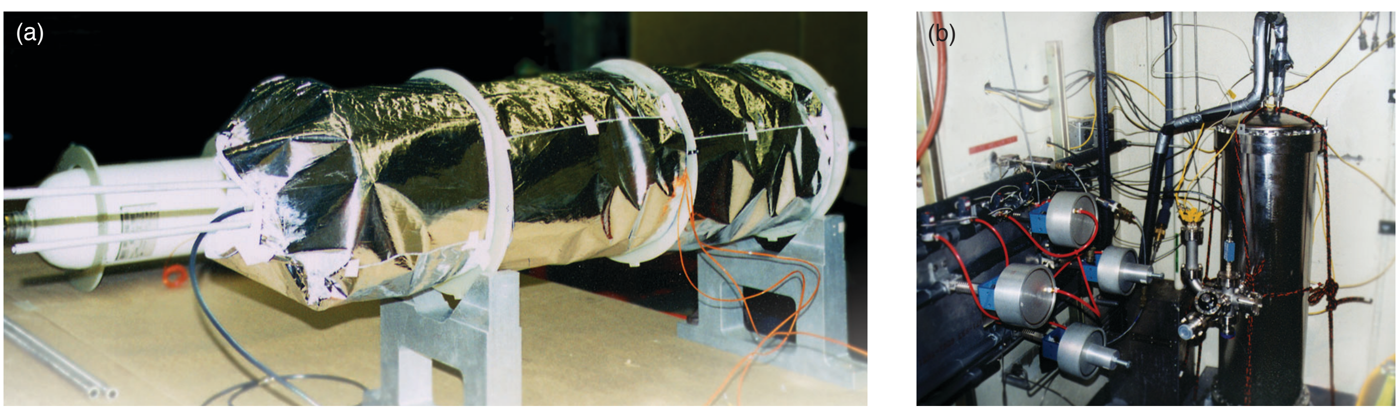
Insulation in a Vacuum to the Rescue

To date, conventional cryogenic hydrogen storage vessels could accommodate only low-pressure liquid hydrogen. By insulating conventional high-pressure vessels, the Laboratory's team designed a tank that successfully combines cryogenics and high pressure to allow three forms of hydrogen to be stored in one tank. Aceves and his team determined that commercially available aluminum-lined pressure vessels coated with composites (Aramid or carbon fiber) identical to those popular for natural gas storage offered the low weight and affordability desired for automotive fuel storage. The researchers coated a standard pressure vessel with 80 layers of highly reflective, metallized Mylar and then enclosed and sealed the insulated inner vessel in a stainless-steel outer tank. A vacuum is then created between the inner and outer tank. "Heat transfer, which is the culprit for evaporation loss, operates through convection, conduction, and radiation," says Aceves. "The vacuum created between the two tanks eliminates the convection and conduction that would otherwise have occurred with a standard tank. The multiple layers of reflective material considerably reduce heat transfer by radiation."

The researchers built openings in the outer jacket for thermocouples, strain gauges, and a capacitive level sensor to measure pressure, temperature, and the fuel level within the test tank. They equipped the tank with safety devices to prevent catastrophic failure in case hydrogen leaked into the vacuum area. Relief valves open if the pressure limits are exceeded, and if the relief valves fail, rupture disks prevent explosive pressure release.

Putting the Tanks to the Test

To determine if the Livermore-designed tank meets rigorous U.S. Department of Transportation and Society of Automotive Engineers safety standards, the researchers constructed tanks to one-fifth scale and subjected them to



The Livermore hydrogen fuel storage tank has two basic parts: (a) a composite-coated interior pressure vessel wrapped with 80 layers of Mylar insulation and (b) an exterior stainless-steel pressure vessel. The vacuum induced between the two vessels minimizes the heat transfer that causes cryogenic hydrogen to evaporate.

Livermore's insulated cryogenic hydrogen tank has undergone 27 different tests to demonstrate its safety and reliability. (a) The tank after being shot with a .30-caliber armor-piercing bullet. The bullet punctured the tank without fragmenting it. (b) The Livermore tank during the bonfire test and (c) following the test. The tank was charred but retained its structural integrity, a key safety consideration.

27 tests of materials, construction, and performance. Many tests involved thousands of repetitions, or cycles. For example, to determine whether the tanks can withstand severe and repeated pressure changes at extremes of internal temperature, the tanks were pressurized from zero to full-service pressure (25 megapascals) and then returned to zero. The cycle was repeated 5,000 times, about 5 times the number of cycles that a typical tank will experience over a 150,000-mile vehicle lifetime. The cycles were first done with an internal tank temperature of 140°F and external ambient air temperatures at 95-percent humidity and then repeated with an internal tank temperature of –60°F and external high-humidity ambient temperatures. The tanks were also subjected to 20 thermal cycles, with tank temperatures ranging from 200°F to –60°F at full-service pressure.

Some of the more dramatic tests included dropping tanks 3 meters onto a hard surface, firing a .30-caliber armor-piercing bullet at a tank from 15 meters, and placing pressurized tanks in bonfires. The tanks survived or suffered acceptable damage. The tank was pierced by the bullet but did not fragment, and it was charred by the fire but retained its structural integrity and did not explode.

The tank design passed all of these tests and met all of the standards. In some instances, the tanks exceeded the testing criteria—and the team's expectations—especially for cryogenic storage. "When the tests showed that the cryogenic tanks were at least as strong as conventional tanks, people sat up and took notice." says Berry. "Suddenly, the Livermore concept was considered a viable option for storing hydrogen on cars of the future."

Now Comes the Real Test

The next step for the Livermore researchers is installing their insulated cryogenic pressure vessels on vehicles for field testing. They are now working on a second-generation tank, which will hold 9 kilograms of liquid hydrogen, energy equivalent to 9 gallons of gasoline. They are working with two partners in getting their tanks on the road: Structural Composites Industries, a leading manufacturer of pressure vessels based in Pomona, California, and Sunline Transit of Thousand Palms, California. Sunline, a mass transit agency serving the Palm Springs area, has agreed to install two second-generation Livermore tanks on pickup trucks. One truck will carry hydrogen, and the other will carry natural gas.

If the second-generation tank is successful, the Livermore team will give the design what many consider the real test: subjecting these tanks to continual, daily use. In these days of high gasoline prices and increasing concerns about air pollution and global warming, on-road testing of the Livermore hydrogen fuel tank is one small step of a long journey.

—Laurie Powers

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