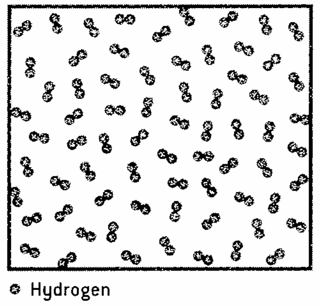
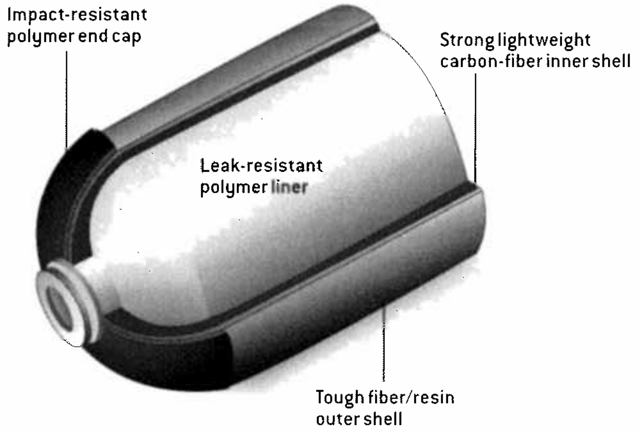
COMPRESSED HYDROGEN

Lightweight but strong, high-pressure cylinders that resemble diving tanks store the compressed gas at 5,000 and 10,000 pounds per square inch.

STORAGE DENSITY





Pros	Cons	Status
Low weight	High volume; requires high-pressure compression and refueling	Available

oline tank will be even more difficult, given that much of its allotted space will be taken up by the tanks, valves, tubing, regulators, sensors, insulation and anything else that is required to hold the six kilograms of hydrogen. Finally, a useful system must release hydrogen at rates fast enough for the fuel-cell and electric motor combination to provide the power and acceleration that drivers expect.

Containing Hydrogen

AT PRESENT, most of the several hundred prototype fuel-cell vehicles store hydrogen gas in high-pressure cylinders, similar to scuba tanks. Advanced filament-wound, carbon-fiber composite technology has yielded strong, lightweight tanks that can safely contain hydrogen at pressures of 5,000 psi (350 times atmospheric pressure) to 10,000 psi (700 times atmospheric pressure) [*see box above*]. Simply raising the pressure does not proportionally increase the hydrogen density, however. Even at 10,000 psi, the best achievable energy density with current high-pressure tanks (39 grams per liter) is about 15 percent of the energy content of gasoline in the same given volume. Today's high-pressure tanks can contain only about 3.5 to 4.5 percent of hydrogen by weight. Ford recently introduced a prototype "crossover SUV" called Edge that is powered by a combination plug-in hybrid/fuel-cell system that stores 4.5 kilograms of hydrogen fuel in a 5,000-psi tank to achieve a total maximum range of 200 miles.

High-pressure tanks would be acceptable in certain transportation applications, such as transit buses and other large vehicles that have the physical size necessary to accommodate storage for sufficient hydrogen, but it would be difficult to manage in cars. Also, the current cost of such tanks is 10 or more times higher than what is competitive for autos.

Liquefying stored hydrogen can improve its energy density, packing the most hydrogen into a given volume of any existing option. Like any gas, hydrogen that is cooled sufficiently condenses into a liquid, which at atmospheric pressure occurs around –253 degrees Celsius. Liquid hydrogen exhibits a density of 71 grams per liter, or about 30 percent of the energy density of gasoline. The hydrogen weight densities achievable by these systems depend on the containment and insulation equipment they use [*see box on opposite page*].

Liquefied hydrogen has important drawbacks, though. First, its very low boiling point necessitates cryogenic equipment and special precautions for safe handling. In addition, because it operates at low temperature, the containers have to be insulated extremely well. Finally, liquefying hydrogen takes more energy than compressing the gas to high pressures. This requirement drives up the cost of the fuel and reduces the overall energy efficiency of the cryocooling process.

Nevertheless, one carmaker is pushing this technology onto the road. BMW plans to introduce a vehicle this year called Hydrogen 7, which will incorporate an internal-combustion engine capable of running on either gasoline (for 300 miles) or on liquid hydrogen for 125 miles. Hydrogen 7 will be sold on a limited basis to selected customers in the U.S. and other countries with local access to hydrogen refueling stations.

Chemical Compaction

SEARCHING FOR promising ways to raise energy density, scientists may be able to take advantage of the chemistry of hydrogen itself. In their pure gas and liquid phases, hydrogen molecules contain two bound atoms each. But when hydrogen atoms are chemically bound to certain other elements, they can be packed even closer together than in liquid hydrogen. The principal aim of hydrogen storage research now is finding the materials that can pull off this trick.

Some researchers are focusing on a class of substances called reversible metal hydrides, which were discovered by accident in 1969 at the Philips Eindhoven Labs in the Netherlands. Investigators found that a samarium-cobalt alloy exposed to pressurized hydrogen gas would absorb hydrogen, somewhat like a sponge soaks up water. When the pressure was then removed, the hydrogen within the alloy reemerged; in other words, the process was reversible.

Intensive research followed this discovery. In the U.S., scientists James Reilly of Brookhaven National Laboratory and Gary Sandrock of Inco Research and Development Center in Suffern, N.Y., pioneered the development of hydride alloys with finely tuned hydrogen absorption properties. This early work formed the basis for today's widely used nickel–metal hydride batteries. The density of hydrogen in these alloys can be very high: 150 percent more than liquid hydrogen, because the hydrogen atoms are constrained between the metal atoms in their crystal lattices [*see top box on next page*].

Many properties of metal hydrides are well suited to automobiles. Densities surpassing that of liquid hydrogen can be achieved at relatively low pressures, in the range of 10 to 100 times atmospheric pressure. Metal hydrides are also inherently stable, so they require no extra energy to maintain storage, although heat is required to release the stored gas. But their Achilles' heel is mass. They weigh too much for practical onboard storage. Metal hydride researchers have so far attained a maximum hydrogen capacity of 2 percent of the total material weight (2 weight percent). This level translates into a 1,000-pound hydrogen storage system (for a 300-mile driving range), which is clearly too heavy for today's 3,000-pound car.

Metal hydride studies currently concentrate on materials with inherently high hydrogen content, which researchers then modify to meet the hydrogen storage system requirements of operating temperatures in the neighborhood of 100 degrees C, pressures from 10 to 100 atmospheres and delivery rates sufficient to support rapid vehicle acceleration. In many cases, materials that contain useful proportions of hydrogen are a bit too stable in that they require substantially higher temperatures to release the hydrogen. Magnesium, for example, forms magnesium hydride with 7.6 weight percent hydrogen but must be heated to above 300 degrees C for release to occur. If a practical system is to rely on waste heat from a fuel-cell stack (about 80 degrees C) to serve as the "switch" to liberate hydrogen from a metal hydride, then the trigger temperature must be lower.

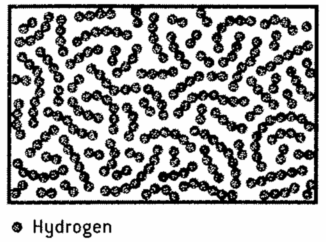
Destabilized Hydrides

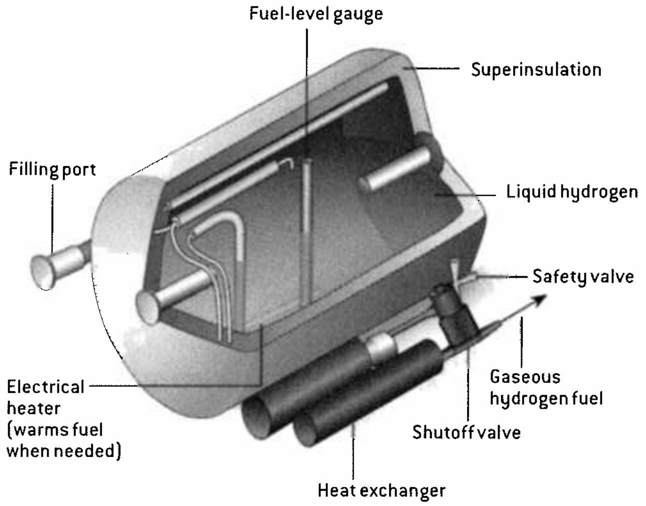
CHEMISTS John J. Vajo and Gregory L. Olson of HRL Laboratories in Malibu, Calif., as well as researchers elsewhere are exploring a clever approach to overcoming the temperature problem. Their "destabilized hydrides" combine several substances to alter the reaction pathway so that the resulting compounds release the gas at lower temperatures.

LIQUID HYDROGEN

Cooled to –253 degrees Celsius, hydrogen condenses and liquefies. Considerable amounts of insulation and ancillary equipment are required to maintain this low temperature.

STORAGE DENSITY





Pros	Cons	Status
Low weight and volume	Continual loss because of boil-off; energy penalty to liquefy hydrogen	Available

Destabilized hydrides are part of a class of hydrogen-containing materials called complex hydrides. Chemists long thought that many of these compounds were not optimal for refueling a vehicle, because they were irreversible—once the hydrogen was freed by decomposition of the compounds, the materials would require reprocessing to return them to a hydrogenated state. Chemists Borislav Bogdanovic and Manfred Schwickardi of the Max Planck Institute of Coal Research in Mülheim, Germany, however, stunned the hydride research community in 1996 when they demonstrated that the complex hydride sodium alanate becomes reversible when a small amount of titanium is added. This work triggered a flurry of activity during the past decade. HRL's lithium borohydride destabilized with magnesium hydride, for example, holds around 9 percent of hydrogen by weight reversibly and features a 200 degree C operating temperature. This improvement is notable, but its operating temperature is still too high and its hydrogen release rate too slow for automotive applications. Nevertheless, the work is promising.

Although current metal hydrides have limitations, many automakers see them as the most viable low-pressure approach in the near- to mid-term. Toyota and Honda engineers, for

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MELISSA THOMAS; QUANTUM TECHNOLOGIES (*cylinder*)
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