Hydrogen as a Fuel and Its Storage for Mobility and Transport

Louis Schlapbach, Guest Editor

Abstract

This brief article describes the content of this issue of *MRS Bulletin* on Hydrogen Storage. Hydrogen is a powerful, clean, synthetic fuel with the inconvenient property of being an ideal gas under ambient conditions. In order to use hydrogen efficiently as a fuel, compacting it for mobile storage is a key issue. As an introduction to the following seven contributions on different storage techniques and their potential, we start with a description of the technical and socioeconomic aspects of the mobility and transport issues involved and present an overview of volumetric and gravimetric storage densities for hydrogen.

Keywords: *fuel cells, energy density, hydrogen storage, liquid hydrogen, metal hydrides.*

Introduction

In industrialized countries, one-third to one-half of the energy generated annually is used to power buildings and another third is used to move people and goods. As energy is rather inexpensive to produce, the applied energy technologies are often in the low-technology, low-efficiency range. The need to move people and goods continues to increase with increasing globalization, but the sustainability and safety of the energy supply to meet these needs are questionable. In terms of mass and distance, transport by air consumes the most energy, followed by road travel, then rail.

Vehicles can be linked to a power line with a continuous supply of energy (electric trains) or they can carry their energy or produce it on board (trucks, cars, bicyclists, airplanes, submarines). Combustion and electricity are the main methods of supplying energy for mobility and transport. Will this change in the future?

Many other high-energy-density, reversible, and controllable chemical reactions may be considered when shortages in the energy supply or environmental issues force us to look for alternatives. Thermally or electrochemically driven processes forming oxides, halides, nitrides, carbides, or hydrides with elements and compounds of Periods 1, 2, and 3 should be evaluated.

But we dream of another solution: hydrogen as a synthetic fuel.

Why Hydrogen?

Hydrogen[1–3] is the most abundant element in the universe (75 at.%). On Earth, we find it in small quantities in air and, of course, in unlimited amounts but chemically bound in H_2O. It is a nontoxic and highly volatile gas. In the area of energy technology, we find hydrogen (1) in gaseous, liquid, or solid hydrocarbons; (2) in nuclear fission and fusion processes; and (3) as synthetic fuel produced by the dissociation of H_2O or hydrocarbons using primary energy (coal and other fossil fuels, electricity or heat from nuclear or renewable energy, photons).

Hydrogen is the simplest element in the periodic table, with just one electron. As a gas, it exists in the form of molecular H_2, which liquefies at 21 K and solidifies at 14 K. Solid hydrogen is a molecular insulator. Under high pressure, it should transform into an atomic solid, the simplest metal, and possibly a room-temperature superconductor.

The oxidation of hydrogen, that is, its combustion with air to form water, is a very attractive exothermic chemical reaction, with two main advantages over other processes:

- It is a clean combustion of a nontoxic fuel: no CO_2 is produced, and when lean hydrogen–air mixtures are used, NO_x formation is prevented.
- The delivered energy per mass of hydrogen is very high, due to its electron per nucleon ratio, which is the best of all elements, and the high energy gain per electron.

Why are we not using these advantages of hydrogen for our energy needs today? Because the problems of production and particularly of storage have not yet been solved.

The traditional town gas, made from burning coal and water, contains about 50 vol% hydrogen, so the use of hydrogen as a fuel source is familiar and should not raise undue concerns. Electrolysis would be the appropriate production method for hydrogen, where electric energy is available. Thermochemical cycles have been abandoned, and photochemical production is not a mature technology.

The storage of hydrogen is a crucial issue for mobility and transport applications. Gravimetric and volumetric hydrogen-storage densities are summarized in Figure 1. Safe and comfortable modern cars consume 5–6 kg of fuel per 100 km in a combustion engine; in the future, a hybrid fuel cell/electric motor could reduce the fuel consumption to around 3 kg per 100 km. Taking into account that the energy per mass of hydrogen is 2.5–3 times higher than that of conventional liquid hydrocarbons, we need to store about 8 kg of hydrogen to drive 400 km in the combustion mode (or 4 kg of hydrogen in the fuel-cell mode). Since 1 kg of hydrogen has a volume of 11 m^3 at room temperature and atmospheric pressure, a tank with considerable storage space would be needed.

This issue of *MRS Bulletin* is dedicated to various techniques for compact storage of hydrogen gas—classical ones like high pressure or liquefaction as well as sorption on high-surface-area solids or bulk sorption, and newer chemical processes that still suffer from the lack of reversibility. None of the presented solutions is economically competitive yet with today's inexpensive liquid hydrocarbons. However, as we are looking for non-CO_2-producing solutions, we should compare the hydrogen solution with other alternatives.

Following this introduction, Irani describes conventional steel high-pressure

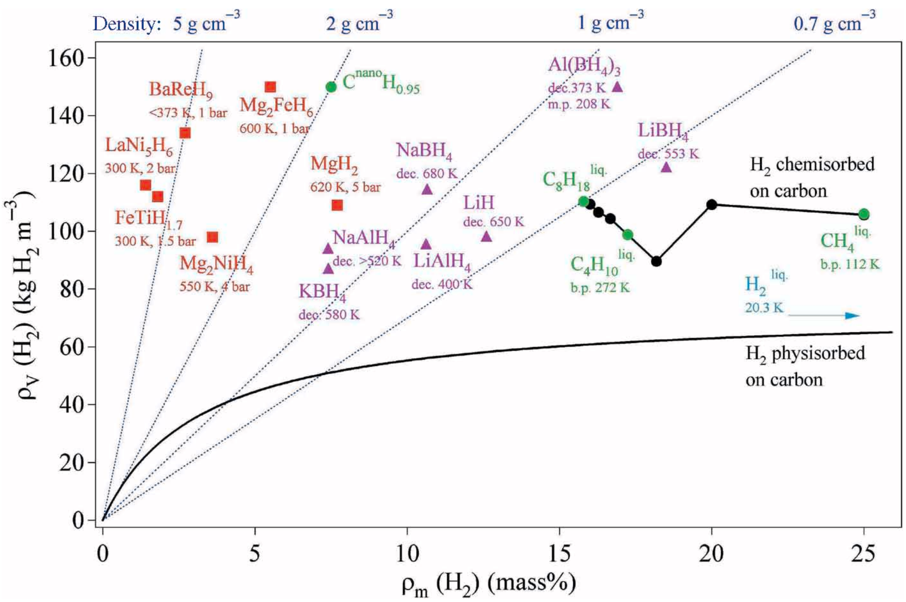

Figure 1. Stored hydrogen by volume and by mass. The graph shows volumetric hydrogen density ρ_v versus gravimetric hydrogen density ρ_m for various materials to store hydrogen by bulk absorption, surface adsorption, or compound formation; dec. is the decomposition temperature, m.p. is melting point, and b.p. is boiling point. The container is not taken into account.

tanks and modern composite and fiber-reinforced aluminum tanks for hydrogen storage. It is noteworthy that Japan recently changed legislation concerning high-pressure gas tanks and now allows them on the roads. A problem with high-pressure tanks is, of course, that they deliver hydrogen at varying pressure instead of the constant pressure needed for transportation typical for applications.

Techniques and advantages of liquid hydrogen and its storage in superinsulated vessels is the topic of the contribution from Wolf. The most extensive tests of this technique so far have been performed using a fleet of city taxicabs in Stuttgart, Germany. The rather high energy loss that results from the liquefaction process is, of course, a concern.

More focused on materials science are the next three articles concerning the reversible process of solution of hydrogen in metallic alloys and metal hydride formation. Bowman and Fultz describe hydride formation through gas-phase absorption. Joubert et al. discuss electrochemical hydride formation for storage of electricity (the Toyota Prius hybrid vehicle uses this technology). The third article in this group, by Akiba and Okada, describes hydrogen bulk sorption by a new class of metallic alloys showing the highest sorption capacity in the lower-temperature range.

The initial excitement of potential hydrogen storage in carbon nanostructures is over.[4] A critical description of findings in hydrogen sorption by carbonaceous species and ways to prepare these species on the laboratory scale and in larger amounts is covered in the article by Züttel and Orimo, along with an illustration of efforts to extend the storage range using, for example, carbon magnesium composites.

Finally, as sometimes happens in scientific and technological progress, we look back at existing materials systems to apply them to new technologies, in this case, borates of light metals, alanates (complex aluminum compounds), and others, which have been known for more than 50 years for their high hydrogen content. Until 1996, they were considered far too stable to reach reversibility in an everyday energy process; then it was shown that the individual roles of thermodynamics and kinetics had not been interpreted correctly: catalysts were developed that brought reversibility close to the levels required. Bogdanović and Sandrock describe this new approach in their article.

What characterizes a good hydrogen-storage unit for mobility and transport applications? Safety, reversibility in a temperature range of the order of 0–100°C, and high hydrogen concentration to provide an empty storage mass in a reasonable proportion to the total mass of the vehicle are required.

The U.S. Department of Energy (DOE) has set a goal that the fuel component should be 6.5 mass% of a total hydrogen-storage system (containment plus fuel). If energy efficiency is a rationale, then a different definition would have to be applied. For cars, the aim is to move a person with some amount of luggage (e.g., 100 kg mass) in a safe and comfortable way and reasonably rapidly from point A to point B. Modern 1000-kg automobiles are capable of doing this. One could set a limit of maximum energy consumption for that transfer (e.g., 1–2 kg of hydrogen per 100 km) and then define that the fuel component of the storage system must reach 5–10%, for example. As long as DOE-supported projects define a "mid-sized car" as a 2500-kg vehicle, the 6.5% target makes no sense and is certainly not innovative.

While progress is being made, an ideal technology for hydrogen storage is not yet available; without it, hydrogen will not become a major fuel for mobility and transport.

For more detailed reviews of this subject, we refer readers to References 5–7.

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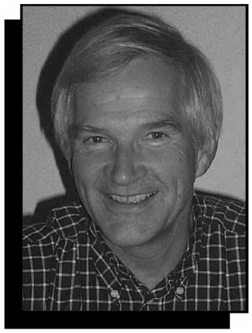
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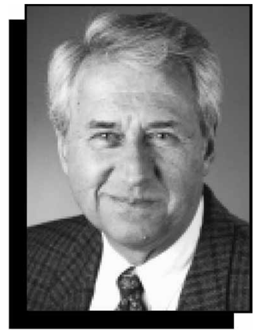
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Robert C. Bowman Jr.


Brent Fultz


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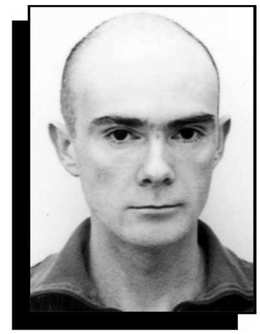
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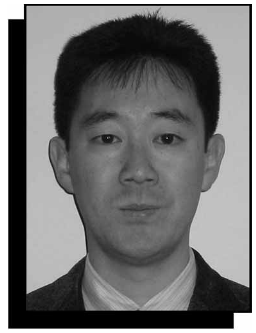
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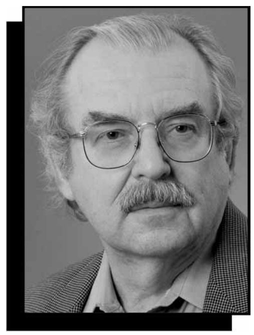
Annick Percheron-Guégan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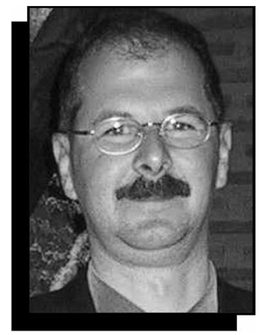
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