Buckyballs

Congratulations on achieving your 10th anniversary. I have enjoyed every educational issue and greatly appreciate the high-quality color graphics and cutting-edge articles. Your February/March issue was especially appealing because of the brilliant editorial selections and complementary articles on spectroscopy, hydrogen storage, and carbon nanotubes.

One shortcoming I find in the Figure 1 illustration accompanying "Simplifying carbon nanotube identification" (p. 24) is the reference to "a sheet of graphite," which is distinctly different in its material and geometric structure from C_{60} bucky- (nano-) tubes.

Even with flexible nodal joints, regular hexagons will curve only slightly as they become nonplanar. However, it is highly questionable whether the curvilinear diameter and chiral wrapping angles of the cylindrical portion of the nanotubes as illustrated can be achieved without the introduction of curved struts and possibly irregular hexagons. Furthermore, as with hemispherical geodesic domes, buckyballs, and soccer balls, without the introduction of strategically placed pentagons along with the straight-strut hexagons illustrated, it would be virtually impossible to achieve half-spherical fullerene structures as tube end caps as shown in the contorted illustrations.

As we interdisciplinarians exchange architectural and structural knowledge with other scientists, it would be helpful to communicate with scalar graphics beyond rather abstract 3D spectrofluorimetric computer plots. It behooves us to have a better grasp of the first science—mathematics, and the first math—geometry. In that manner, we can avoid such distortions as wrapping tetrahedrally textured metal skins over a reinforced concrete dome as at Disney's Epcot Center, which is totally nongeodesic. American Institute of Architects Gold Medallist Buckminster Fuller noted that "the two largest domes in the world were both in Rome and were each 150 feet in diameter. They were St. Peter's, built around 1500 AD, and the Pantheon, built around 1 AD. Each weighs approximately 30,000 tons. By contrast, my own 150-foot geodesic dome in Hawaii weighs only 30 tons—one thousandth the weight of its masonry counterpart."

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Hydrogen rules?

In response to letters about "Bottling the Hydrogen Genie" (April/May, p. 6), the authors refer to "well-to-wheel" studies comparing fuel cells to conventional internal combustion engines. But fuel cells will not compete with conventional internal combustion engines; they will compete with gasoline-powered hybrid engines. Since current hybrids have at least twice the fuel efficiency of conventionally powered cars, the advantage of fuel cells becomes vanishingly small. And hybrid technology continues to improve, while hydrogen fuel-cell technology does not yet exist in a viable form.

Eventually, the world will run out of inexpensive gasoline. There are many alterna-

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tives, of which hydrogen is only one. I have not seen any analysis showing that hydrogen-powered fuel cells are the best replacement for gasoline. In fact, given the many technical and thermodynamic hurdles, one wonders whether the automotive industry's interest in fuel cells is influenced by its desire not to have to make a switch.

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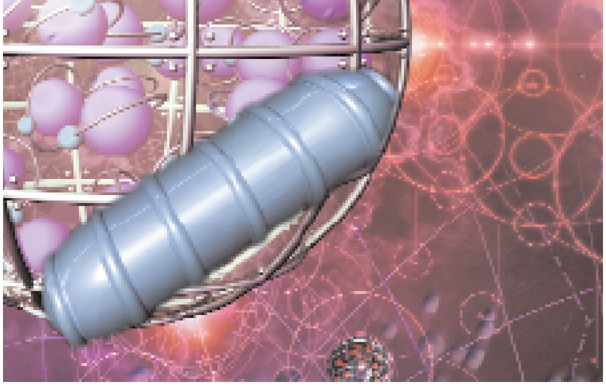
Hydrogen energy enthusiasm is again high, yet almost nothing has changed from its last peak, nearly 30 years ago. Storage and distribution technologies remain huge stumbling blocks for this otherwise interesting energy carrier. Pure liquid hydrogen is far too cold for small-scale use, and hydrogen gas requires very high pressure to compress useful amounts. Unfortunately, approaches to these twin obstacles of storage and distribution are in a deep rut even during an age when "thinking outside the box" is the mantra.


Anthony Robinson

As the lead researcher and author of the 1976 National Science Foundation report (and later book) *The Hydrogen Energy Economy: A Realistic Appraisal of Prospects and Impacts*, I stumbled across the intriguing fact that some liquids are highly dissolvable in others, even at low temperatures. Immediately, I thought how wonderful it would be if ample hydrogen could be easily dissolved in and recovered from liquid nitrogen, an easily handled cryogen, or even liquid methane, a warmer, but potentially more dangerous, cryogen.

But that proved a baseless dream, and I could uncover no hints of other prospective hosts except metal hydrides. Regrettably, the most commonly used metal hydrides are too heavy and costly in the bulk needed for widespread automotive fuel use. The lighter alkali metal hydrides seem far too nasty for popular consumption. The only truly new possibility is carbon nanostructures, but much more needs to be learned.

Nevertheless, I remain hopeful that a wide-ranging, Edisonian-style, trial-and-error search for relatively benign substances that could absorb and release hydrogen might bear fruit. Edisonian-style research is long out of vogue, but maybe the time has come for major government funding for a broad search guided only by a set of flexible fuel-handling goals, instead of funding just for research that deepens ruts already known to be impractical.

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Singer, Bringhurst, Meyer, Pinkerton, Wicke (April/May, pp. 4–7), and others have characterized the obstacles to achieving the hydrogen economy as threefold. I see them as at least fivefold.

1. Energy source. The point was made that hydrogen is not an energy source but rather an energy carrier. And that is where it all starts—we need a new energy source. There was an article in the *Seattle Times* (January 24, 2004) about mining H_3 on the moon and returning it to Earth to use in H_3/H_3 fusion reactors to make prodigious amounts of electricity with no nuclear waste. Presumably, the (waste?) heat energy or the resulting electric energy could be used to produce useful amounts of hydrogen. Others have suggested fusion of H_3/boron-11 as a nuclear-waste-free energy source. I envision a solar still on the moon producing oxygen, hydrogen, and helium-3 by heating moon soil and rock. The oxygen that isn't used directly for life support could be used in fuel cells with the hydrogen to make electricity for local use, and the resulting water would be useful. The biggest hurdle is probably the invention and development of fusion reactors to make use of these potential energy sources. Kulcinski and Santarius at the University of Wisconsin seem to be at the forefront of these speculations (http://fti.neep.wisc.edu/neep533/FALL2001/neep533.html). Unfortunately, enormous invention, development, and infrastructure steps are necessary before these energy sources become a reality.

2. Hydrogen production. I have seen no clear-cut solution to the production of large quantities of hydrogen. But if hydrogen is to be produced, it seems that the place to do it is near a new energy source.

3. Hydrogen storage. A lot has been written about the use of pressure tanks for storage of hydrogen on our future vehicles. Pressure tanks strike me as being a heavy and inefficient idea. If you did have a high-pressure tank in your vehicle, the hydrogen would have to be expanded to atmospheric pressure to make use of it in proton-exchange-membrane fuel cells. The hydrogen will get very cold when expanded, so it would likely do a great job of air conditioning your sports utility vehicle in the summer in the South. However, when I was growing up in North Dakota, there were a few days when it was –54 °F. I don't see anyone suggesting how to deice a hydrogen tank in any kind of efficient vehicle under those kinds of conditions. (As a matter of fact, we had to be careful about the expansion of propane from a tank supplying a standby electric generator for a small shopping center in North Central Washington!) So maybe we need to rethink whether it is really hydrogen that we want to use to fuel our vehicles.

4. Infrastructure. Transporting hydrogen to your local "gas" station, as well as storing it and fueling your vehicle there, has to be different than for gasoline. Similar operations are now being done on a limited scale with propane. Hydrogen is probably safer than propane in that it is lighter than air and should not pool at ground level where ignition sources abound and where ignition would be most problematic. But large-scale, do-it-yourself vehicle-fueling with hydrogen strikes me as not being the best choice we could make. Another choice would be something like the sodium borohydride solution developed by Millennium Cell (www.millenniumcell.com). Sodium borohydride appears to be environmentally friendly, a safe-to-handle liquid, and an efficient hydrogen/energy carrier. The company's hydrogen-on-demand system releases a useful quantity of hydrogen in the presence of its proprietary catalyst, along with heat (which can be used or vented) and sodium metaborate, which could be recycled to re-create sodium borohydride.

5. Cost. Vehicle fuel-cell drivetrains are said to be too costly now, but, considering the global market potential and the amount of development work being carried out, it seems certain their cost will fall. Much of the technology in place in hybrid cars is applicable to fuel-cell vehicles. There will be a proliferation of hybrid vehicles in the next few years. And every one of those hybrid vehicle manufacturers is looking ahead to marketing fuel-cell vehicles as their follow-on product line. So I am confident that the vehicle cost hurdle to the hydrogen (transportation) economy is the least serious of the problems to overcome.

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[*Authors respond*: Spurred in large part by the recent development of advanced fuel cells, considerable progress has been made in hydrogen storage in the last decade. This includes fabrication of 10,000-psi high-pressure tanks for gaseous storage, fueling technologies for gaseous and liquid hydrogen, and preliminary examination of the thorny issue of production and delivery infrastructure. In the arena of solid storage, some existing materials have been improved (for example, the kinetics and operating temperature of sodium alanate have been greatly improved by adding titanium dopants), and particularly encouraging is the discovery of some new storage materials, such as the Li-N-H system [1]. These discoveries have not solved the storage problem, but they do provide cause for optimism.

The ultimate vision for the high-energy-density, high-power energy source required by the full fleet of cars and light trucks incorporates these features—it should (1) be nonpolluting (burning fossil fuels inevitably produces pollutants, such as NO_x, at the point of use, typically within large cities), (2) not emit net greenhouse gases such as CO_2 (in most scenarios, this means no emission from the vehicle), (3) not use foreign petroleum, and (4) be sustainable for the foreseeable future.

The list of candidates is rather short. Direct storage of electrical energy would be ideal, but current and forecast electrical storage technologies are not promising for vehicle applications. Indeed, the advent of hybrids is a tacit acknowledgment that batteries alone are not a viable option. That leaves hydrogen at or near the top of the list. Item (2) does allow for bio-derived alcohol fuels, which emit CO_2, but only that which was captured during growth; this may represent another long-range option sought by Mr. Karpman. Fuel-cell vehicles based on hydrogen made by steam reformation of methane will substantially reduce total greenhouse gas emissions and energy utilization compared with gasoline vehicles [2], but they admittedly do not fully meet criteria (2) and (4); hence the emphasis on development of sustainable hydrogen sources in the long term. This is a small part of a much larger picture, namely, the rapid growth in worldwide energy demand requires that we develop a range of sustainable, and preferably renewable, energy sources.

Adopting hydrogen power in vehicles will not be simple. In the meantime, automakers will offer a blend of petroleum-stretching technologies. Many of these, including hybrids, were compared in the well-to-wheels studies cited previously [2], and additional options—such as displacement-on-demand internal combustion engines and engine shutoff at idle—are also in the offing. The highly competitive nature of today's auto industry ensures that such technologies will be available. Looking ahead, we must go beyond petroleum, and, in our view, now is the time to push the envelope of hydrogen technology.

References

1. Chen, P; Xiong, Z.; Luo, J.; Lin, J; Tan, K. L. *Nature* **2002**, *420*, 302.

2. Pinkerton, F. E.; Wicke, B. G. *The Industrial Physicist*, February/March 2004, pp. 20–23.]

Correction

In "Magnetic graphite" (April/May, p. 10), the first sentence should read "highly oriented pyrolytic graphite."

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