Engineering Challenges of the Hydrogen Economy

by **Dr. Robert E. Uhrig, P.E.,** *Iowa Alpha '48*

THE TERM "HYDROGEN ECONOMY" is the title of a recent book *[Rifkin, 2002]*, but the concept of using hydrogen as fuel for transportation systems has been advocated by environmentalists and others for at least three decades. There is no universally accepted definition of the "hydrogen economy," but it is generally viewed as the replacement of the vast majority of petroleum fuels used by transportation vehicles of all kinds (automobiles, trucks, trains, and aircraft) with hydrogen that is burned in internal-combustion engines, external-combustion (jet) engines, or preferably, used in fuel cells to more efficiently generate power for transportation.

A November 2001 meeting of 53 business executives, federal and state energy-policy officials, and leaders of universities, environmental organizations, and national laboratories sponsored by the U.S. Department of Energy resulted in the report "A National Vision of America's Transition to a Hydrogen Economy—To 2030 and Beyond" *[DOE, 2001]*. This led to an April 2002 "National Hydrogen Energy Roadmap" workshop where 250 representatives from 135 organizations looked into their *crystal balls* and projected what would be required to achieve a hydrogen economy *[DOE, 2002a]*. They attempted to define a common set of objectives and the activities by all the participants that are essential to achieve a hydrogen economy. The conclusion was that "Hydrogen has the potential to play a major role in America's future energy system." However, it was further concluded that "Before hydrogen can achieve its promise, all stakeholders must work together to overcome an array of technical, economic, and institutional challenges." This article attempts to clarify and put in perspective these challenges.

Why should it take more than a quarter of a century to achieve the hydrogen economy? In little more than a decade, computers have progressed from a laboratory tool for data processing to almost universal acceptance by the public, taking America into the "Information Age" and revolutionizing the way that we do business and work. Then why is it expected to take so long to achieve the hydrogen economy? One can postulate many reasons—such as the difficulty of the technologies involved, the high costs involved, and competition for public funds with other worthy programs (e.g., education, public health, space exploration, fundamental scientific research, national security, etc.). However, perhaps it is more complicated than that. Public acceptance is a key factor. We will review this issue at the end of the article.

Hydrogen as a fuel

Hydrogen is the lightest (~6.1 x 10^{-3} lb/ft^3) and one of the most abundant elements in the universe. However, it almost always occurs in combined form as in water (H_2O), methane (CH_4), or coal, which contains 2-6% hydrogen by weight. Even when it is separated from other elements, it is stable only when two hydrogen atoms are combined into a single molecule (H_2). Its energy density, due to an electro-chemical reaction or combustion with oxygen on a per-unit-mass basis, is quite high (~51,600 Btu/lb; lower heating value)[1], but on a per-unit-volume basis, it is among the lowest of any fuels (~315 Btu/ft^3 at atmospheric pressure). The energy density on a per-unit-volume basis can be increased by compressing gaseous hydrogen to high pressures (5,000 to 10,000 psi) or by liquefying it at cryogenic temperatures (about 20°K at atmospheric pressure). However, both 10,000 psi gaseous hydrogen and cryogenic liquid hydrogen have volumetric energy densities considerably lower than gasoline and diesel fuel. These properties make hydrogen very difficult to store, particularly on transportation vehicles, and difficult to distribute from one location to another. Hydrogen also burns with an almost invisible flame and is subject to special handling regulations by state and national codes for safety reasons. Clearly, the use of hydrogen as a transportation fuel has many engineering challenges that may be difficult to address.

> *In the final analysis, the economics associated with the hydrogen economy and the benefits it provides will determine its acceptability by the public.*

It is well known that hydrogen, like electricity, is an energy carrier, not an energy resource. It does not occur naturally in nature and must be extracted from other sources such as water, hydrocarbon fuels, or other naturally occurring materials containing hydrogen. This extraction requires energy from other sources, i.e., solar

---

[1] *The lower heating value (~51,600 Btu/lb) is the amount of energy available for use. The higher heating value (~61,000 Btu/lb) is the amount of heat energy needed to produce hydrogen. The difference is the energy lost in the production of hydrogen.*

energy (hydro, wind, or photovoltaic), fossil-fuel combustion, nuclear fission, or combustion of renewable materials (wood, fibrous crops, bagasse, or even garbage). In every case, the energy content of hydrogen is less, often significantly less, than the energy it takes to produce it. This is also true of electricity because its energy is only 30% to 40% of the thermal energy used to produce it. The energy content of hydrogen varies from 20% to 80% of the thermal energy used to produce it, depending upon the method used and the source (i.e., water, methane, coal, etc.). Hence, both hydrogen and electricity are premium energy carriers whose use can be justified only by special benefits associated with their use. In the case of hydrogen, a special benefit is that it can be converted into electricity for transportation using fuel cells with an efficiency that is at least twice as high as the conversion in thermodynamic heat engines. Other benefits include the reduction of pollutants and greenhouse gases being emitted into the atmosphere by transportation vehicles using hydrogen as a fuel.

A recent document indicates that "For transportation-propulsion applications, DOE is focusing on direct hydrogen fuel cells, in which on-board storage of hydrogen is supplied by a hydrogen generation, delivery, and fueling infrastructure" *[DOE, 2003c]*. The essential components of a hydrogen economy are production of hydrogen, storage of hydrogen, distribution or transportation of hydrogen to vehicle fuel stations, dispensing of hydrogen into vehicles, and use of hydrogen in fuel-efficient engines (i.e., fuel cells rather than either internal- or external-combustion engines). Each of these activities constitutes an engineering challenge that will be discussed here.

Present transportation energy situation

Today, the United States uses almost 20 million barrels of oil per day (Mbbl/day), of which about 13 Mbbl/day is used for transportation of all kinds, cars, trucks, aircraft, and trains *[DOE-EIA, 2003d]*[2]. If each barrel of oil contains 5.8 million British thermal units (MBtu), then the transportation energy to be replaced is about 75.4×10^{12} Btu per day. Since the energy content of hydrogen is about 51,600 Btu/lb, the amount of hydrogen required to replace oil would be about 1.46×10^{9} lb/day. If we assume that half of the transportation energy goes to fuel cells that are twice as efficient as heat engines while the remaining half is burned in combustion engines with a 20% increase in efficiency from current engines, then the required hydrogen is reduced to about 0.97×10^{9} lb/day, or about 177 million tons per year. This compares with the current production of 50 million tons of hydrogen per year worldwide for all purposes, including fertilizers, upgrading of hydrocarbon fuels, and chemical-industry feedstock.

A leading manufacturer of electrolysis equipment indicated that 1 MW (megawatt) of electricity can generate 0.52 tons (1,040 lb) of hydrogen per day *[Stuart, 2001]*. Hence, the production of 0.97×10^{9} lb/day of hydrogen by electrolysis would require about 0.93×10^{6} MWe or 930 GWe (gigawatts) of electric generating capacity. This means 930 new 1,000 MWe electric power plants, 93 new 10,000 MWe hydro plants, 930,000 new 1 MWe windmills, or some combination. For comparison, the current U.S. total electric generating capacity is about 850,000 MWe. Hence, the current electrical generating capacity would have to more than double to provide the energy required for the hydrogen economy. Indeed, the additional generating capacity requirements could be significantly greater if the technology chosen were not capable of operating 24 hours per day, as is the case with wind (~30% duty cycle) and photovoltaic (~20% duty cycle) power sources *[Grant, 2003]*[3]. Large-scale storage of electrical energy, perhaps as hydrogen, would also be involved for both windmills and photovoltaic generation of electricity.

Given the situation described above, why are we pursuing the hydrogen economy? Perhaps the primary reason is that the demand for oil and gas is growing rapidly in the developed countries, and it is growing even more rapidly in developing countries because of growing populations, modernization of their infrastructures, and improved quality of life demanded by their citizens. Equally important, it is widely believed that the world is either nearing or has already passed its maximum rate of production of gas and oil. If this is true, then the petroleum fuels that drive the economies of almost all modern nations may become increasingly scarce and more expensive. The impact of such a shortage of oil could be disastrous for many world economies. Indeed, the current political turmoil in the Middle East, which produces a significant fraction of the world's oil, has already created an unstable situation regarding the world's supply.

Many environmental reasons exist to consider hydrogen as a replacement fuel for petroleum to the extent practical. Greenhouse gases, primarily carbon dioxide, and pollutants, such as oxides of nitrogen and sulfur from vehicles and fossil-power plants, are widely believed to impact climate patterns and to be increasing the temperature of the earth's surface. While concerns about such potentially catastrophic effects have not been proven, there is considerable evidence to support the concept of *global warming* and its potential impact on the earth. It is argued that the time to begin to address such a problem is before, not after, the consequences become apparent. The problem is that the impact of implementing the hydrogen economy may be so great that the results could be counterproductive to the national economies of the U.S. and many other countries if it is not implemented properly.

---

[2] *Estimates of the amount of oil used for transportation of all kinds (cars, trucks, trains, and aircraft) vary. This estimate is based on a recent Energy Information Administration report* [DOE-EIA, 2003d] *in which a petroleum flow chart for 2002 shows 13.08 million barrels per day used for all transportation.*

[3] *These estimates of availability of windmills and photovoltaic devices are averaged over an annual cycle. The typical estimates used here are given by Grant. However, the actual averaged experience in Denmark with windmills has been only 16%.*

Hydrogen production

Two methods of producing hydrogen that are proven technology today are: 1) steam methane reforming (SMR) using natural gas (typically more than 95% methane) and water as the sources of hydrogen; and 2) electrolysis of water using electricity.

- **STEAM METHANE REFORMING**

SMR involves a catalytic, endothermic reaction at about 300 psi and 850°C (1,562°F) in which some methane is consumed to provide the heat to drive the endothermic reaction. The process involves releasing hydrogen from both steam and methane and is carried out in a reforming reaction followed by a water-gas shift reaction. The end result of these two reactions is the production of hydrogen and carbon dioxide. Carbon dioxide is also created by the consumption of methane to produce needed heat. Hence, both processes result in greenhouse-gas emissions into the atmosphere. The typical overall efficiency of SMR is about 80% (i.e., the energy content of the hydrogen produced is about 80% of the energy of the methane used to produce it, while about 20% of its energy is consumed in supplying energy for the endothermic reaction).

The availability of natural gas as a feedstock for hydrogen production on the scale needed to meet the needs of the hydrogen economy is a concern. Natural gas is a premium fossil fuel with many advantages (easy and economical to transport by pipeline, clean except for carbon dioxide emissions, and ideally suited as petrochemical feedstock). Indeed, the Fuel Use Act of the late 1970s legislated the *minimization* of natural gas being used to generate electricity because it was *too valuable a natural resource to burn.* The subsequent revocation of this law led to the large-scale introduction of automated combined-cycle natural-gas plants for the generation of electricity because they were relatively inexpensive, efficient, and could be built in less than half the time required for coal or nuclear plants. This resulted in serious fluctuation of natural-gas prices ($2 to $10 per MBtu in a few weeks and back to about $5 per MBtu within a few months) in 2001, similar fluctuations in 2002, and smaller fluctuations in 2003. This price instability has led to cancellation of proposed plants and changes in the priority of dispatching electric-generating plants. Because natural gas is a fossil fuel, often a co-product of pumping oil from the earth and sometimes used interchangeably with oil, its price is directly linked to the price and availability of oil.

The amount of natural gas required to provide hydrogen to replace transportation fuels using only SMR is staggering. If we accept the above estimate of 0.97 x 10^9 lb/day of hydrogen (containing 50.1 x 10^{12} Btu/day) as reasonable for the hydrogen economy and that natural gas contains about 1,000 Btu/cubic foot, then SMR at 80% efficiency would require 22.8 x 10^{12} cubic feet of natural gas per year. This is about 8% greater than the 21.0 x 10^{12} cubic feet per year of natural gas used for all purposes in the United States, including home heating, power generation, and production of hydrogen, in 2002 *[DOE, 2003b]*.

- **ELECTROLYSIS**

Conventional electrolysis of water to produce hydrogen is a well developed technology, and production units as large as 10 MWe are commercially available today. The typical overall efficiency of hydrogen production using electrolysis based on the thermal content of the electric-power-plant fuel is about 25% today, consisting of two components—about 33% efficiency in converting fossil or nuclear energy into electricity and 75% in using electricity to separate water into hydrogen and oxygen. If a high-temperature gas-cooled reactor or a modern combined-cycle gas power plant with a 50-55% thermodynamic efficiency is used to generate the electricity, the overall efficiency of electrolysis increases to about 40%.

Electrolysis also benefits from other considerations: 1) other products produced, primarily oxygen and heavy water, have commercial value in many situations; and 2) electrolyzers can be switched off instantaneously to pick up utility electrical loads dropped when plants shut down unexpectedly. This feature allows the electrical generating capacity reserved for such emergencies (typically the capacity of the largest plant) to be used for electrolysis. This means that the utility's effective net generating capacity has been increased by the amount of its *spinning reserve* with the only capital cost being that of the necessary switch gear.

The key to economic production of hydrogen by electrolysis is low-cost electricity. Surplus electrical generating capacity, particularly nuclear plants where it is desirable to operate at full capacity all the time, can result in very low-price electricity in the middle of the night and during certain parts of the year. Furthermore, virtually every utility deliberately has reserve generating capacity to meet peak loads and unforeseen plant outages. Because the capital costs of this excess capacity are "sunk costs," the actual cost of generating electricity for elective loads, such as hydrogen production by electrolysis, is the fuel and O&M costs.

A recent study by Atomic Energy of Canada Limited *[Miller, 2003]* of the cost for electricity on the Alberta open market for 2002 shows an underlying basic price with intermittent spikes as high as $0.60/kWh ($600/MWh) and an average price of $0.0293/kWh. Further analysis showed that the average annual price for electricity was $0.0224/kWh when prices were $0.06/kWh and below and that the price was above $0.06/kWh for only 5% of the year. It is reasonable to expect comparable results in the U.S., perhaps even lower costs because of low fuel costs for coal- and nuclear-power plants that together produce about 70% of the electricity. Hence, electrolysis may be the production method of choice for hydrogen in a number of situations, particularly during the early years of the hydrogen economy for *in situ* generation of hydrogen at refueling stations using excess electrical generating capacity.

• “WATER-SPLITTING”— THE SULFUR-IODINE PROCESS

There are other methods of generating hydrogen being investigated, but none of them is likely to be available on a production scale in the next decade. Perhaps the most discussed of these methods is thermo-chemical water-splitting, and it is generally envisioned as using nuclear energy to provide the required high temperatures for the process. A survey by the International Atomic Energy Agency [IAEA, 1999] yielded a wide variety of water-splitting methods of which about half a dozen are being explored in significant detail. The most advanced is probably the Sulfur-Iodine (S-I) process being investigated by General Atomic and DOE [Schultz, 2002]. There are at least two hybrid methods combining the S-I process with electrolysis also being investigated.

The S-I water-splitting method of producing hydrogen consists of three processes described by the following equations; the first is the thermal decomposition of sulfuric acid (H_2SO_4), a two-step reaction requiring very high temperatures, described by:

$$H_2SO_4 \xleftrightarrow{600^\circ C} SO_3 + H_2O \xleftrightarrow{850^\circ C} SO_2 + H_2O + {}^1\!/_2\, O_2 \quad (1)$$

These decompositions require 600° C (1,112°F) and 850°C (1,562°F) heat, respectively, plus a catalyst. Note that both processes are reversible and in equilibrium, a fact that is important in a later discussion. At this point, the oxygen is removed as an output product.

The hydrogen is produced by the decomposition of hydrogen iodine (HI) which requires heat at 450°C (842°F) and is described by:

$$2\,HI \xleftrightarrow{450^\circ C} I_2 + H_2 \quad (2)$$

This equilibrium process is dependent upon the temperature and pressure. Only about 16% of the hydrogen iodine is decomposed with the remaining HI being recycled. The hydrogen is removed from the process at this point. The HI required in process (2) is produced by the Bunsen reaction using the SO_2 and H_2O from process (1), the I_2 of process (2), and additional water. This process is described by:

$$I_2 + SO_2 + 2\,H_2O \xrightarrow{120^\circ C} 2\,HI + H_2SO_4 \quad (3)$$

The sulfuric acid [H_2SO_4] is fed back into process (1), the HI is fed back into process (2), and heat is rejected at 120°C (248°F). Process (3) requires excess iodine, and the hydrogen iodine and sulfuric acid separate into two separate liquids to be recycled. However, the overall balance of these three processes results in a closed cycle in which the inputs are heat and water and the outputs are hydrogen and oxygen. The engineering to implement the hydrogen-iodine process to produce hydrogen efficiently is one of the major challenges of the hydrogen economy.

The hydrogen-iodine process requires high temperature, a minimum of about 850°C (1,562°F), to efficiently split water into hydrogen and oxygen. The motivation behind this and other S-I studies is to use an existing high-temperature gas-cooled reactor (HTGR) design to provide the heat. The efficiency of the S-I process, which is dependent upon the high temperature to drive reaction (1), is about 50% when the heat is provided at 950°C (1,742°F). However, the existing HTGR design may be limited to 850°C outlet helium, where the efficiency is only about 40%. The DOE’s Generation IV of reactor concepts being investigated includes two reactor designs capable of producing 950°C heat, the Very High Temperature Reactor and the Molten Salt Reactor *[DOE, 2001]*. Another reactor concept capable of producing 950°C heat being studied at Oak Ridge National Laboratory in Tennessee is the Advanced High Temperature Reactor that uses molten salt as a coolant while using coated fuel particles in a matrix of graphite similar to the HTGR design *[Forsberg, 2003a]*.

Recent research proposes to use an inorganic separation membrane to separate reaction products from process (1), the highest temperature process, and thereby reduce the temperature required to drive the reaction to about 700°C (1,292°F)—while keeping the efficiency near 50%. Because the reaction products SO_2, H_2O, and O_2 are separated from SO_3, the second part of process (1) proceeds at a lower temperature. This has the decided advantages that a current-design HTGR could generate hydrogen at high efficiency while operating at a lower temperature and that liquid-metal-cooled reactors (almost always fast reactors) could produce hydrogen with the liquid metal well below its boiling point. Experimental verification of this approach is under way at Oak Ridge National Laboratory *[Forsberg, 2003c]*.

A Japanese federal laboratory has tested this sulfur-iodine process on a bench scale using a non-nuclear source and is now extending the test to a larger size system. They have also designed and built a 30 MWt high temperature gas-cooled reactor and expect to use it as the high-temperature heat source for a pilot-plant-size sulfur-iodine water-splitting demonstration. This reactor was designed for 950°C exit-gas temperature but is currently operating at 850°C. The U.S. DOE has plans to begin testing the three different processes of the sulfur-iodine process at three different locations and then integrate them at one location later.

• METHANE SPLITTING

Another approach under consideration is *methane splitting* in which very high temperature heat (> 2,500°C) (4,532°F) produced by a plasma or a solar furnace splits methane into hydrogen and carbon black. This process has advantages in that the energy required to produce hydrogen is about half that of SMR and there is no carbon dioxide produced, but it does use more methane than SMR. Although there are some uses for the carbon black in the tire and printing industries, large-scale use of this process would probably saturate these markets and result in a waste product to be disposed of safely.

• HYBRID PROCESSES FOR PRODUCING HYDROGEN

There are several hybrid concepts using various combinations of the SMR, thermo-chemical water-splitting, and electrolysis processes for producing hydrogen. Examples are the use of electrolysis as part of the thermochemical cycles mentioned above, high-temperature electrolysis, and use of nuclear heat to replace the chemical heat provided by methane to drive the SMR process. The use of solar or nuclear energy to provide high-temperature heat or electricity has the decided advantage that there is no production of greenhouse gases.

An economic comparison of the methods of producing hydrogen would have to include many other factors, such as complexity, capital costs, operating and maintenance costs of the production facilities, land costs, and the cost and availability of water or methane. There are environmental considerations that must be addressed, such as whether to accept or limit the impact of the carbon dioxide on the atmosphere. There are many *[Grant, 2003; Scott, 2001]* who argue that it is counter productive for the environment to implement the hydrogen economy unless the hydrogen production and associated power requirements can be provided by *non-carbon emitting* power sources, i.e., solar or nuclear power and use electrolysis or water-splitting for hydrogen production. There are others *[Lovins, 2003; EWEA, 2003]* who argue that distributed- and renewable-energy sources for hydrogen production, and carbon sequestration if necessary, are more appropriate. In either case, the impact of generating hydrogen on the U.S. infrastructure associated with implementing the hydrogen economy, however it is defined, will still be extraordinary.

H_2 Storage

Implementation of the hydrogen economy would require facilities for storing, transporting, and distributing hydrogen to refueling facilities throughout the country. Historically, hydrogen has been stored as a high-pressure gas (2,000 to 3,000 psi) or a cryogenic liquid (~20ºK). Although there is experimentation with liquid hydrogen by one European automaker, most current discussions about storage of hydrogen on automotive vehicles involve gaseous hydrogen at 5,000 psi or higher. The liquefaction of hydrogen consumes about 30% of the energy stored, and there is also a continual loss of energy due to thermal conduction through the insulated walls, whether the liquid is stored in a service station or a vehicle. Even so, there may be applications for liquid hydrogen in heavy vehicles and long-range aircraft, where weight is critical.

• STORAGE OF HYDROGEN AS A HIGH-PRESSURE GAS

An official goal for on-board hydrogen storage is to achieve a 300-mile range with a tank no larger than current automobile fuel tanks *[DOE, 2002b]*. The importance of the goal is reflected in the general belief that failure to meet this goal was a major impediment to the development of battery-powered electric cars, a technology in which the direct storage of electricity in batteries is much simpler than converting electricity to hydrogen, distributing it nationally, and then converting hydrogen to electricity with a fuel cell to drive an electric motor in a vehicle.

On-board storage tanks for gaseous hydrogen on vehicles, made with filament-wound carbon-fibers and lined with an aluminized polyester bladders, have been approved for use up to 5,000 psi by U.S. and up to 10,000 psi by German authorities *[Lovins, 2003]*. Generally, these tanks are cylindrical, and more than one are sometimes used because of the required volume and the low-volumetric-energy density of hydrogen. Even though the higher efficiency of fuel cells partially compensates for this low-energy density, the large size of the tank(s) required for a 300-mile range is a concern, and researchers still seek alternatives. Technologies under serious consideration are metallic hydrides and alanates where hydrogen is adsorbed onto interstitial surfaces. Reports on these two options from a recent conference are summarized below. Adsorption of hydrogen by carbon nanotubes was considered an option a few years ago, but it has not lived up to its initial promise for hydrogen storage.

• METAL HYDRIDES FOR HYDROGEN STORAGE

Hydrogen is a highly reactive element and will form hydrides and solid solutions with hundreds of metals and alloys, as well as form chemical compounds or complexes with many other elements. Metal hydrides are formed by hydrogen bonding to a metal with metallic, ionic, or covalent bonds. Hydrogen is usually bound in the interstitial sites, and it can be removed by applying heat to the metal hydride. Many intermetallic compounds and solid solutions can readily absorb and desorb hydrogen gas at room temperature and atmospheric pressure, but these hydrides can reversibly store only 1 to 3 weight-percent hydrogen, which is not enough for application to vehicle storage. Covalent and ionic hydrides (e.g., MgH_2 and LiH respectively) are capable of storing 7 to 12 weight-percent hydrogen, but they must be heated to above ~325ºC (617ºF) to release the hydrogen at atmospheric pressure. This temperature is much higher than the ~75ºC (167ºF) waste heat that is available from a proton-exchange-membrane fuel cell. Recent work with catalyzed complex hydrides containing mixed ionic-covalent bonding can reversibly store more than 4% hydrogen with operating temperatures below 125ºC *[Bowman, 2003]*. Generally, the volumetric energy density of hydrogen stored in metal hydrides is comparable to that of liquid hydrogen. The primary problems with metal hydrides for vehicle applications are their heavy weight and high cost.

• ALANATES FOR HYDROGEN STORAGE

Alanates, such as sodium alanate ($NaAlH_4$), are aluminum alloys that contain hydrogen. Sodium alanate undergoes a two-step decomposition into sodium hydride (NaH), hydrogen, and aluminum where the gas temperature and pressure determine the equilibrium quantities of reactants and products that release a total of about 5.6% hydrogen. Pure alanates react slowly at ambient conditions, but recent work indicates significant improvement in sorption kinetics by adding transition metal additives *[Meisner, 2003]*. Many other alanates show promise as a storage medium, but they are at an early stage of their development.

H_2 Distribution

Because of its low volumetric energy density, hydrogen is at a disadvantage when compared to other fuels with higher volumetric energy densities (e.g., methane or propane). The power to perform the pumping of hydrogen is reported to be about a factor of 4.6 greater than for methane over a range of high pressures *[Elliason, 2003]*. The total cost of distribution for an equal amount of energy in the form of hydrogen is estimated by the International Energy Agency to be 15 times that of liquid hydrocarbons *[IEA, 2003]*. However, the economies of scale associated with large central hydrogen facilities may partially compensate for the extra distribution costs.

There are perhaps two basic but different configurations of a distribution system that may evolve over the next three decades—with many combinations of the two and other variants. Only the two configurations will be discussed here for illustrative purposes.

• HUNDREDS OF LARGE HYDROGEN PLANTS WITH A NATIONAL DISTRIBUTION PIPELINE GRID

In this scenario, there are many clusters of large hydrogen plants distributed around the country with an interconnected pipeline grid to distribute the hydrogen to control centers, which in turn pipe hydrogen to millions of service stations through a distribution pipe grid. Most likely, the plants would be thermo-chemical water-splitting plants with nuclear power plants providing the heat. This arrangement is directly analogous to the current electric transmission and distribution grids in the United States.

If we accept the required hydrogen production previously calculated at 177 million tons per year for the hydrogen economy, which is equivalent to about 4,500 million standard cubic meters per day (Mscm/d), and that today's *world-class* hydrogen plants produce about 5.7 Mscm/d (the size of each of the two new large hydrogen-production plants being built to upgrade the bitumen from the Athabasca oil sands in Canada into synthetic crude oil) *[Forsberg, 2003b]*, then 790 world-class hydrogen-production plants would be required for the hydrogen economy. These plants might be grouped in 197 clusters of four plants per cluster or an average of four clusters per state. Clearly, more clusters would be needed in the more populous states and fewer plants in the other states. It can be readily shown that the 5.7 Mscm/d output of hydrogen is equivalent to ~775 MWt. Hence, if each world-class plant is operating at 50% efficiency (typical of thermo chemical water splitting plants), we would require ~1,550 MWt per plant, or a total of ~1,225 GWt of heat energy for 790 plants. About 6,200 MWt of heat generation would be required at each of the 197 four-unit clusters of hydrogen plants for the hydrogen economy.

A crude calculation indicates that if the 197 four-unit clusters of plants were laid out uniformly on a square grid throughout the United States, the clusters would be about 80 miles apart and would require about 90,000 miles of interconnecting pipe. These interconnecting pipes would be analogous to the high-voltage transmission lines for electricity. If a hydrogen distribution grid were installed with connections at 10-mile intervals on the interconnecting pipes, an additional 725,000 miles of smaller distribution pipes would be required.

• MILLIONS OF SMALL HYDROGEN PLANTS LOCATED AT HYDROGEN SERVICE STATIONS

The other basic arrangement for distribution of hydrogen to service stations is a distributed array of small hydrogen generators, probably electrolysis units, of sizes selected to provide adequate hydrogen for a local area's need, using electricity from the most economical source. In the hydrogen economy, the total amount of new electrical capacity required for electrolysis, as shown earlier, would be 930 GWe, more than doubling the current electrical generating capacity of the United States. The electrical grid would also have to be doubled in size to carry the needed electricity.

The alternative configuration for providing the required power is a distributed array of windmills or photovoltaic generators. Some 930,000 new 1 MWe windmills would be required if they ran 24 hours a day. With an average availability factor of about 30%, *[Grant, 2003]* the number of windmills would have to be increased significantly. The other option, some 93,000,000 new 10 kWe photovoltaic electric generating units, is also burdened with a low-availability factor, only 20%, and significant additional capacity would be required.

Clearly, the ultimate source of power to provide hydrogen for the hydrogen economy would be some combination of all the options discussed above. There may be others, including fusion plants and fermentation- or solar-driven photo-biological methods currently being studied. Indeed, the power requirements for the hydrogen economy are so large that it seems unlikely that the use of petroleum for transportation could be totally phased out in the next half century.

H_2 at Service Stations

There are several issues of concern associated with dispensing hydrogen into automotive vehicles. The first is that the connection from the station to the vehicle would be complex (with sensors to assure secure attachment without leakage). The valves and other hardware used to control the flow of very high-pressure gases are inevitably complex and expensive. To deliver hydrogen to vehicle tanks at 5,000 psi will require a continuous delivery pressure of perhaps 7,000 psi to keep the refilling time to a reasonable time. As the station uses its supply of hydrogen, the pressure will drop. To keep the pressure high enough to refuel vehicles in a reasonable time would require a compressor to deliver hydrogen into the vehicle.

Automotive Fuel Cells

Although there are many types of fuel cells with very different features and operating characteristics, the PEM (proton-exchange-membrane or polymer-electrolyte-membrane—both names are used) fuel cells are envisioned by DOE as being the standard power unit in transportation vehicles. In a fuel cell, hydrogen and oxygen are combined electro-chemically to produce water and electricity. In effect, the fuel-cell process is the reverse of electrolysis in which electricity splits water into hydrogen and oxygen *[Fuel Cells, 2000]*. The fuel cell has an important advantage over heat engines (e.g., internal- and external-combustion) in that it is a chemical device. Since its performance is not constrained by the thermodynamic limits of heat engines, its efficiency could be two-to-three times that of a heat engine. For fuel cells that operate in a vehicle environment, twice the efficiency of heat engines is a realistic expectation.

The current DOE fuel-cell program is focused on overcoming critical technology barriers with particular emphasis on achieving high efficiency, durability, and low materials and manufacturing costs *[DOE, 2003c]*. This statement identifies three critical needs of fuel cells if they are to be used in the vehicles in a hydrogen economy. To this list should be added the *operability* of the fuel cells in a vehicle environment, (e.g., complexity of and time required for starting, adequate performance over a wide range of temperatures and altitudes, reasonable performance on high-speed interstate highways and in crowded metropolitan streets, ease of refueling, and low environmental emissions).

High efficiency is an inherent feature of the fuel-cell concept, but it is compromised by practical considerations. For instance, automotive fuel cells use air to supply the oxygen, and the inert nitrogen (80% of the air) has to flow through the fuel cell. The presence of contaminants in the air can have a major effect upon the performance of fuel cells. A recent journal article *[Kosanovic, 2004]* notes that air filters are needed to keep a PEM fuel cell free of airborne contaminants that could *kill* the cell quickly. It further indicates that sulfur dioxide at the 5 ppm level (a high level known to exist in heavy city traffic) can incapacitate a fuel cell in fewer than four hours. Air also carries water generated in a cell as the waste product of the electrochemical reaction out of the system. Otherwise, the water would flood the cell. A joint industry-national laboratory team is investigating the influence of 15 air contaminants (including hydrocarbons, sea water, diesel soot, nitrous oxide, sulfur oxide, dust, and salt) upon the performance of fuel cells. There is evidence that a PEM cell can recover from exposure to some contaminants if it is exposed to fresh air.

There is also concern about the environmental consequences of leakage of hydrogen into the atmosphere during all phases of the hydrogen economy, i.e., production, storage, distribution, dispensing, and use of hydrogen in transportation. A recent report in *Science* magazine on the potential environmental impact of hydrogen leakage on the stratosphere has stirred a flurry of letters to the editor indicating clear technical disagreement among the experts on this subject *[Trump, 2003]*. This issue must be addressed as various nations move toward a hydrogen economy.

It appears that most of the technical issues with fuel cells can be resolved adequately for wide use of PEM fuel cells in vehicular applications. However, cost remains a major obstacle. Some estimates indicate that the cost of PEM fuel cells is 5 to 10 times higher than comparable internal-combustion engines, but the cost is reported to be decreasing. It may not be fair to expect fuel cells to compete economically with automotive engines developed over a century of use, but the cost of fuel cells should be no more than double (including an internal-combustion engine tax or a hydrocarbon-fuel tax penalty) to be competitive.

Alternatives to Hydrogen

While the DOE and the transportation industry are pursuing the hydrogen economy, both are still considering alternatives. There is no single alternative that could replace hydrogen, but a combination of several approaches could influence the degree to which a hydrogen economy is implemented. Some of the alternatives involve hydrocarbon fuels, but not from traditional sources. There may even be alternatives within the hydrogen economy concept (one discussed below) that could change the current approach. Each of the alternatives may (or may not) increase costs to individual vehicle operators, but the overall cost might be substantially less than the current approach to the hydrogen economy. The following discussion of a limited number of alternatives is illustrative of many choices that are available.

• INCREASED FUEL ECONOMY FOR AUTOMOTIVE VEHICLES

The CAFE (corporate average fuel economy) standards imposed on the automotive industry over two decades ago resulted in a substantial increase in automotive economy and a consequent reduction in the use of fuel. Current proposals to extend these standards to light-utility vehicles could produce a comparable reduction in fuel consumption in the next two decades.

The successful introduction of hybrid vehicles recently (albeit at subsidized prices) has effectively doubled the gas mileage over comparably sized vehicles without seriously compromising the performance of the vehicles or convenience and safety of the drivers and passengers. Widespread acceptance of such vehicles could significantly reduce petroleum consumption. Crude calculations indicate that if one third of the current automotive and utility vehicles could double their gas mileage, the U.S. could save about 1.5 million barrels of oil a day. This is equivalent to the amount of oil imported from Saudi Arabia.

• ELECTRIC CARS

The enthusiasm for electric cars currently seems to be at low ebb, but it is a technology that totally replaces the use of oil if the electricity is generated using solar or nuclear plants. The critical need is a breakthrough in battery storage and charging technologies. Advanced chemical systems for storage of electricity are currently being tested by utilities. Recent advances in electrical energy storage systems for utilities include the *Regenesis flow batteries* and the *vanadium redox* systems that have 65-70% round-trip efficiencies.

• SODIUM BOROHYDRIDE AS A SOURCE OF HYDROGEN

The current approach to the hydrogen economy suffers from its significant differences with the current petroleum-fuel production, storage, and distribution systems. This is because of the fact that hydrogen is a gas with low volumetric energy density. Virtually all present petroleum-based transportation fuels are liquids. Concepts involving use of on-board reformers to produce hydrogen from liquid fuels have been investigated, but they tend to be complex, expensive, and still require hydrocarbon fuels.

There is, however, a system under development by Millennium Cell LLC *[Millennium, 2003]* that warrants further consideration because it uses a non-petroleum solution to produce hydrogen. This technology involves the use of sodium borohydride ($NaBH_4$), a non-combustible, non-explosive solution that is stable at atmospheric pressure, with an on-board converter to generate hydrogen as needed for automotive vehicles. A catalytic reaction with ruthenium produces hydrogen upon demand without producing greenhouse gases. The hydrogen energy density (Btu/gallon) of the $NaBH_4$ solution is greater than cryogenic liquid hydrogen, is greater than 10,000 psi gaseous hydrogen, and is more than half that of gasoline. $NaBH_4$ is produced from sodium borate $NaBO_2$ (similar to borax, a natural mineral mined in the California desert). Furthermore, $NaBO_2$ is the residual product after the $NaBH_4$ has generated hydrogen, but rather than being a waste product to be disposed, $NaBO_2$ can be recycled to produce more $NaBH_4$ fuel. In effect, this is a closed system in which no external materials are required except for the water that provides the hydrogen in the recharging process. The overall processes are:

Production of Sodium Borohydride ($NaBH_4$) or Recycle of Sodium Borate ($NaBO_2$)

$$\mathbf{NaBO_2 + 2\,H_2O \xrightarrow{\text{Electrolysis}} NaBH_4 + 2\,O_2} \tag{4}$$

Production of Hydrogen onboard a vehicle

$$\mathbf{NaBH_4 + 2\,H_2O \xrightarrow{\text{Ru Catalyst}} 4\,H_2 + NaBO_2 + Heat} \tag{5}$$

The disadvantages of this approach are the current high costs of the ruthenium catalyst and of producing $NaBH_4$ from $NaBO_2$ using electrolysis. An alternate process using a nuclear-assisted plasma technique is being explored at the Idaho National Engineering and Environmental Laboratory.

While the refueling of vehicles (removal of $NaBO_2$ and loading of $NaBH_4$) may seem complicated, the fact that both are liquid solutions at atmospheric pressure and temperature makes the refueling process much simpler than handling 5,000 psi hydrogen gas or cryogenic liquid hydrogen. A fuel tank with an elastic diaphragm or a moveable piston separating the $NaBH_4$ fuel from $NaBO_2$ residual could expedite refueling. The infrastructure for storage, transportation, and distribution of this liquid fuel to produce hydrogen is dramatically simpler than those for gaseous or liquid hydrogen and quite similar to current gasoline- and diesel-fuel storage, transportation, distribution, and fuel stations. Accordingly, some additional cost associated with the production of the $NaBH_4$ *fuel* may be warranted because of much lower new infrastructure costs.

• ALTERNATIVE FUELS

The primary alternate fuel to replace conventional petroleum is bitumen from the Athabasca oil sands in Western Canada. It is estimated that these oil sands contain about 1.6 trillion barrels of oil, some one-third of the world's oil deposits. Another one-third is located in the Venezuelan Orinoco oil sands deposit, with the remaining one-third as conventional oil, much of it in the Middle East *[Nationmaster, 2003]*.

In the last decade, Canadians have developed and implemented an economical *in situ* method of extracting the bitumen by injecting high-temperature steam into the oil sands. The need for upgrading bitumen with hydrogen for transportation fuels has led to the construction nearby of two of the world's largest SMR hydrogen production plants—with even larger plants being designed *[Forsberg, 2003b]*.

Another source of oil, not normally included in estimates of oil reserves, is the oil-shale deposits in the Tennessee and the Rocky Mountain areas. Previous mining and processing of oil shale for kerogen (similar to bitumen) proved to be uneconomical. However, *in situ* methods of extracting the kerogen, perhaps similar to that used for tar sands, might prove economical as the price of petroleum becomes higher. Unfortunately, both the oil sands and oil shale-based synthetic fuels result in the release of more greenhouse gases in their production and refining than for crude oil, and sequestration of carbon dioxide may be necessary to meet national standards that may be imposed.

Public Acceptance

The concept of a hydrogen economy as a way to reduce the U.S. dependence on foreign oil has not stirred opposition by the public. They seem to like the *hydrogen plus oxygen equals electricity plus clean water* concept. However, the public has become uneasy with technological solutions, and many seem to be taking a wait-and-see view. In the three decades it may take to implement the hydrogen economy, there will be many unforeseen developments, and the public will be considering alternatives that look attractive at the time they secure a new or different vehicle, typically every four-to-five years. Indeed, the average life cycle is 10-12 years for automobiles and longer for heavy commercial vehicles. This long life cycle is one of the reasons that it will take so long to implement a hydrogen economy.

The hydrogen economy would eventually affect every motorist personally. Many spend a substantial fraction of their income for automotive transportation. A large increase in the cost of what they consider a *necessity* will not be a welcome change. A significant decrease in performance or loss of comfort features (air conditioning, adequate room, power steering, power windows and locks, etc.) will not be viewed favorably. In the final analysis, the economics associated with the hydrogen economy and the benefits it provides will determine its acceptability by the public.

It is not preordained that the hydrogen economy will be achieved, although it can probably be achieved at some cost. Whether that cost will be acceptable to the general public will depend upon many factors that cannot be foreseen, e.g., technological breakthroughs, geo-political situations, new discoveries of fuel reserves, and luck—that can be either good or bad.

EPILOGUE

The National Environmental Policy Act, passed by Congress in 1969, mandated that before a major project can be undertaken, an environmental impact statement (EIS)—a comprehensive assessment of the benefits of the project and its impact upon all aspects of the environment—must be prepared and presented to the authorizing authority. Nothing remotely resembling the environmental impact statement required for construction of a nuclear power plant or other large projects (an EIS for off-shore oil drilling had ~32,000 pages) has been undertaken for the hydrogen economy. It would seem that, given the extraordinary magnitude of the requirements for power, water, fuels, and infrastructure of all sorts, that at least a *scoping* study of the environmental and economic consequences of the hydrogen economy should be undertaken now.

Engineers are intimately involved with the tradeoffs between benefits and costs. Each of the problems discussed in this article is an engineering challenge. The nature of the transportation system in 2050 may or may not look like the current vision of the hydrogen economy. However, if engineers do their jobs competently and thoroughly with appropriate inputs from society, whatever results should be the right solution to our transportation fuel problem at that time.

REFERENCES

Robert C. Bowman Jr. and Gary Sanrock, "Metal Hydrides for Energy Storage and Conversion Applications," Proceedings of GLOBAL 2000 Atoms for Prosperity, American Nuclear Society meeting, New Orleans, LA, Nov. 16-20, 2003.

Department of Energy, "A National Vision of America's Transition to a Hydrogen Economy—to 2030 and Beyond," National Hydrogen Vision Meeting, Washington, DC, Nov. 15-16, 2001.

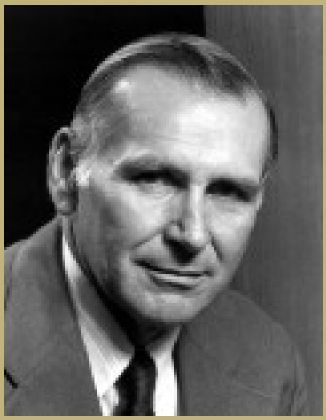
DOE "National Hydrogen Energy Roadmap," National Hydrogen Energy Roadmap Workshop, Washington, DC, April 2-3, 2002a.

DOE, "Hydrogen, Fuel Cells and Infrastructure Technologies Program," Annual Progress Report, 2002b.

DOE, Nuclear Energy Research Advisory Committee Report, March 2003a.

DOE, Energy Information Administration, "Natural Gas Consumption in the United States, 1997-2003," *www.eia.doe.gov*, 2003b.

DOE, "Hydrogen, Fuel Cells, & Infrastructure Technologies



Dr. Robert E. Uhrig, P.E, *Iowa Alpha '48,* is a distinguished professor of nuclear engineering emeritus at the University of Tennessee and distinguished scientist emeritus of the nuclear science and technology division at Oak Ridge National Laboratory, having retired from a joint appointment at both institutions in 2002. He received the B.S.M.E. from the University of Illinois in 1948 and M.S. and Ph.D. degrees in theoretical and applied mechanics from Iowa State University, and he graduated from the advanced management program of the Harvard Business School.

Dr. Uhrig was a vice president at Florida Power & Light Company in 1973-86, deputy assistant director for research for the Department of Defense in 1967-68, dean of engineering at the University of Florida during 1968-73, and was appointed dean emeritus in 1989. Previously, he chaired the department of nuclear engineering sciences at UF, was an associate professor and an engineer for the Atomic Energy Commission's Ames Laboratory at Iowa State University, and taught at the U.S. Military Academy while on active duty with the U.S. Air Force.

Dr. Uhrig served on committees for the Nuclear Regulatory Commission, the NSF, and the National Academy of Science/National Research Council. He is the author of 250 technical articles and the book *Random Noise Techniques in Nuclear Reactor Systems* and co-author of a book entitled *Fuzzy and Neural Approaches in Engineering*. He received the 1992 Glenn Murphy award for outstanding contributions to nuclear engineering education from the ASEE and the 1969 Richards memorial award of the ASME. He is a member of Phi Kappa Phi and ΤΒΠ and is a fellow of the American Nuclear Society, the American Association for the Advancement of Science, and the ASME. He lives in Gainesville, FL, and may be reached at *ruhrig@utk.edu*.

Program," Multi-Year Research, Development and Demonstration Plan, draft, page 3.57, June 3, 2003c.

DOE, Energy Information Administration, "Petroleum Flow 2002," *Annual Energy Review*, at *www.eia.doe.gov/emeu/aer/diagram2.html*, 2003d.

Baldur Eliasson and Ulf Bossel, "The Future of the Hydrogen Economy: Bright or Bleak?" Nature, Vol. 424, pp 129-130, July 1, 2004.

European Wind Energy Association policy statement, *www.ewea.org*, 2003

Charles Forsberg, "Production of Hydrogen using Nuclear Energy," Presentation to National Research Council/National Academy of Science, Jan. 22, 2003a.

Charles Forsberg, "Production of Hydrogen Using Nuclear Energy, Second International Symposium, Nizhniy Novgorod region, Russia, Aug. 18-21, 2003b.

Charles Forsberg, Brian Bischoff, Louis Mansur, and Lee Trowbridge, "Nuclear Thermo-Chemical Production of Hydrogen with a Lower-Temperature Iodine-Westinghouse-Ispra Sulfur Process," Second Information Exchange Meeting on Nuclear Production of Hydrogen, OECD Nuclear Energy Agency, Argonne, IL, Oct. 2-3, 2003c.

Fuel Cells 2000, Types of Fuel Cells, *www.fuelcells.org*, The Online Fuel Cell Information Center, 2000.

Paul Grant, "Hydrogen Lifts Off—with a Heavy Load," *Nature*, vol. 424, July 10, pp 129-130, 2003.

International Atomic Energy Agency document, "Hydrogen as an Energy Carrier and Its Production by Nuclear Power," IAEA-TECDOC-1085, May 1999.

International Energy Agency report, "Moving to a Hydrogen Economy: Dreams and Realities," IEA/SLT 5, Jan. 30, 2003.

Lisa Kosanovic, "Running on Air," *Mechanical Engineering* magazine, pp 40-42, January 2004.

Amory Lovins, "Twenty Hydrogen Myths," Rocky Mountain Institute, Snowmass, CO, June 20, 2003.

Gregory P. Meisner, "Hydrogen Storage in Alantes: Materials and Measurements," Proceedings of GLOBAL 2000 Atoms for Prosperity, American Nuclear Society meeting, New Orleans, LA, Nov. 16-20, 2003.

Millennium Cell, "Company Overview," *www.millenniumcell.com*, 2003.

Alistair Miller and R.B. Duffy, "Hydrogen and High Temperature Reactors: a Source Map," Proceedings of GLOBAL 2000 Meeting, American Nuclear Society meeting, New Orleans, LA, Nov. 16-20, 2003.

Nationmaster.com, Factoid #37, Encyclopedia: Athabasca Tar Sands, updated December 14, 2003.

Jeremy Rifkin, *The Hydrogen Economy*, Tarcher/Putnam Publisher, ISBN 1-58542-193-6, 2002.

Ken Schultz, "Efficient Production of Hydrogen from Nuclear Energy," Presentation to the California Hydrogen Business Council, June 27, 2002.

David Sanborn Scott, "The Energy System, Architecture, Trajectory, and Role of Nuclear-Driven Hydrogen," Presentation at American Nuclear Society, Reno, NV, Nov. 12, 2001.

Sandy Stuart, "Nuclear-Electrolysis Synergies: For Neat Hydrogen Production and Cleaner Fossil Reserves Harvesting," ANS president's special session: Hydrogen Systems, ANS Meeting, Reno, NV, Nov. 11-15, 2001.

T.K. Tromp, *et al*, "Potential Environmental Impact of a Hydrogen Economy on the Stratosphere," *Science* magazine, p. 1740, June 13, 2003.