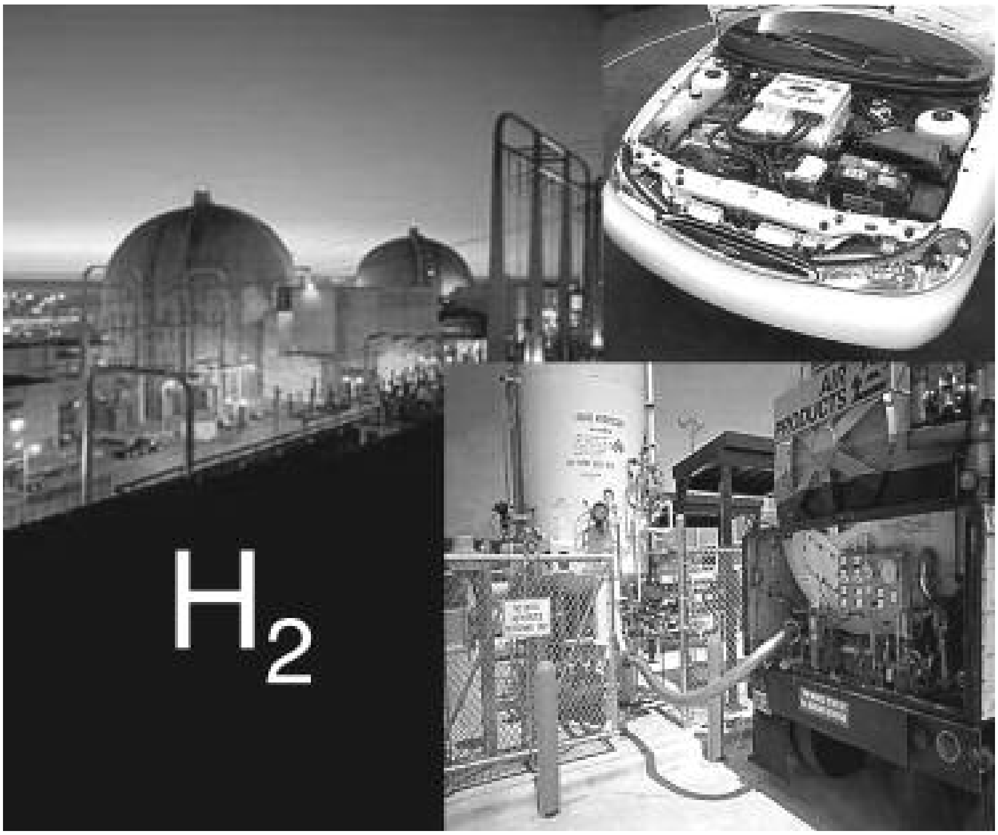
Hydrogen From Nuclear Power

by Masao Hori



ANL; Ford Motors; Air Products and Chemicals

Nuclear energy will produce the hydrogen needed for the fuel of the future. Here, a hybrid car and a hydrogen tank filling up.

The Age of Coal and Oil is giving way to the Age of Hydrogen. An international expert in nuclear technology examines the necessary role of nuclear power in ushering in this new era.

The energy sources we use for industrial and consumer purposes are called *energy carriers.* These are sources of energy which are derived from primary energy sources. Gasoline and electricity are familiar examples of energy carriers (Figure 1). After electricity, hydrogen is one of the most promising energy carriers for the future, because hydrogen is not only clean and efficient, but also storable. Essentially, water is the only emission when hydrogen is used.

The chemical energy of hydrogen can be converted to power most efficiently by a device known as a fuel cell. Combustion of hydrogen, as in an engine, could also be used for obtaining power. Hydrogen is easier to store than electricity, but hydrocarbons, especially liquid fuels, are much easier to store than hydrogen.

Hydrogen is the most abundant element in the universe. However it does not normally exist on Earth as a gas (H_2), but is rather found in the form of chemical compounds. It is most often found combined with oxygen in water (H_2O). It is also found combined with carbon in the various hydrocarbons. Examples include the gas methane (CH_4), which is the principal component of natural gas; the heavier liquid hydrocarbons which make up petroleum; and coal. To produce H_2 from compounds, it is necessary to use energy to break the chemical bonds which hold the hydrogen.

Hydrogen gas can be obtained from fossil fuels (hydrocarbons) by the steam reforming process. There are drawbacks to production processes using fossil fuels, however. Not only are resource reserves of fossil fuels limited, but as environmental regulations intensify in the future, it will be necessary to take measures, such as carbon capture and storage, or sequestration, to reduce CO_2 emissions. As for renewable energies like wind and solar, they are inherently dilute, so their hydrogen production capacity is naturally limited.

The merits of using nuclear energy for hydrogen production are that there is no CO_2 emission, a sustainable bulk supply capability, and a high energy density, facilitating energy security. These advantages also apply to using nuclear energy for electricity generation.

About one-third of the world's primary energy is converted to electricity at present. The remaining two-thirds are consumed in such non-electric applications as process-heat for industry, space heating, and transportation. Although the ratio of electricity will likely increase to about one-half at the end of the 21st Century, that still leaves one-half of the world's primary energy being used for non-electric purposes. As it is essential to reduce the global use of fossil fuels, it is important to explore the feasibility of nuclear energy replacing fossil fuels as the power source for non-electric applications. The most promising and realistic way to fulfill this need is to use nuclear energy to produce hydrogen, an excellent energy carrier.

Nuclear Hydrogen As a Future Energy Source

In the future, nuclear energy will be needed for more than just electricity production. According to the World Energy Council, the world primary energy demand in 2100 will be about four times that of 1990, in its middle course scenario (Table 1). In this scenario, nuclear energy is expected to supply 24 percent of the total primary energy for electricity production, which corresponds to the output of about 5,200 plants of 1,000 megawatts-electric (MWe) capacity.[1] The supply of fissile fuel for all of these plants is feasible, assuming natural uranium resources of 16.3 Mton, as estimated in the "Red Book" (*Uranium Resources, Production, and Demand,* jointly prepared by Organization for Economic Cooperation and Development/Nuclear Energy Agency and the International Atomic Energy Agency), and the recycling use of plutonium by fast breeder reactors with a breeding ratio of 1.2 to 1.3. These fast reactors would be introduced from 2030 to 2050.

Optimizing the recycling of plutonium in fast breeder reactors could increase the quantity of nuclear supply by 1.5 times in 2050 and by 2.0 times in 2100, the World Energy Council scenario estimates. By effectively utilizing nuclear energy, this excess supply capacity of nuclear energy could replace the fossil fuel share in the World Energy Council scenario, thus developing a "proactive nuclear scenario," as shown in Table 1. The extra nuclear capacity could, and should, be used for hydrogen production, not just electricity generation.

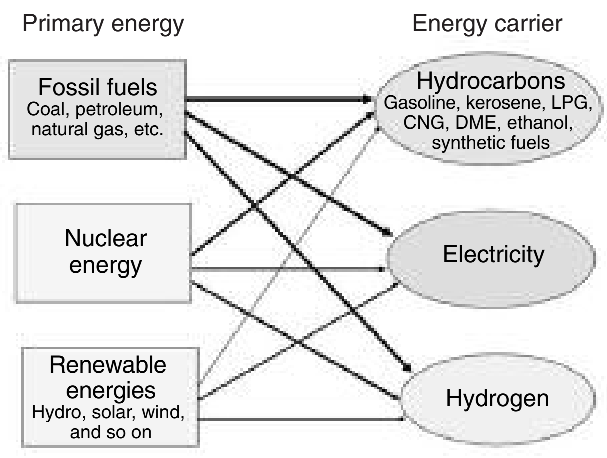


Figure 1
ENERGY CARRIER PRODUCTION FROM PRIMARY ENERGY

In such a scheme, the global use of fossil fuels in 2100 would become smaller than it was in 1990, thus stabilizing atmospheric carbon dioxide concentration, even in the face of global growth of energy use by a factor of four.

Actually, all of the primary energies (fossil fuels, nuclear energy, and renewable energies) must be used concurrently and in parallel to fill global demand in the 21st Century. Hence, it is essential to utilize these energies as efficiently as possible, from production of energy carriers to applications at the demand end, for the security of global resources, the environment, and the economy.

Prospects for the Hydrogen Economy

By the term Hydrogen Economy, I mean a society which uses predominantly electricity and hydrogen for its energy carriers, replacing the now-dominant hydrocarbons (such as

	1990	2050	2100
Fossil	6.9	12.7- >11.4	15.0- >5.0
Nuclear	.45	2.7- >4.0	8.3- >18.3
Renewables	1.6	4.4	11.4
Total	9.0	19.8	34.7

Table 1
ESTIMATION OF PRIMARY ENERGY SUPPLY IN GIGATONS OF OIL EQUIVALENT (1990-2100)
The arrows denote the change from the World Energy Council's middle course (WEC-B) to the proactive nuclear scenario.[1]

gasoline, kerosene, and natural gas) with hydrogen.

Utilization of hydrogen in automobiles, through fuel cell technology, is one of the primary goals of the Hydrogen Economy. A fuel cell is a device which combines hydrogen gas with the oxygen in the air to produce electricity. By putting an electric current through water, the hydrogen and oxygen components of the water can be split as gases, in a process called electrolysis. A fuel cell can be thought of, in first approximation, as electrolysis in reverse. The hydrogen and oxygen gas go back together, with help of a catalyst, producing water vapor and an electric current which can power motors attached to the wheels of the vehicle.

There are still major problems to be solved before commercialization of hydrogen fuel cell vehicles (FCV) can be realized. The biggest challenge we face is the cost of the fuel cell. Other challenges are the method of storing hydrogen on board to ensure an adequate cruising range, the creation of hydrogen distribution infrastructure, and so on. Still, because hydrogen is the most promising energy carrier, it is expected that the Hydrogen Economy will evolve steadily by breakthroughs in solving these problems we encounter now, although it might take three decades or more.

Producing Hydrogen from Nuclear Power

Hydrogen, as well as electricity, can be produced from any of the primary energy sources (fossil fuels, nuclear energy, and renewable energies). But nuclear hydrogen, because of its characteristics, will be expected to supply the base load.

Many processes have been proposed for production of hydrogen using nuclear energy (Figure 2). The leading processes presently under research and development are:

- electrolysis of water by nuclear electricity,
- high temperature electrolysis of steam by nuclear electricity and heat,
- thermo-chemical splitting of water by nuclear heat, and
- nuclear-heated steam reforming of natural gas, or other hydrocarbons.

Although it is not certain what course the commercialization of nuclear hydrogen production will take, a typical prospect based on the current state of knowledge could be as follows:

(1) In the near term, electricity generated by light water reactors (LWR) can be used to produce hydrogen gas from water by electrolysis. This process can be commercialized, in

The Sulfur-Iodine Cycle for Hydrogen Production

For centuries the world has been moving toward primary chemical energy sources with higher energy densities, from wood to coal, to oil, to natural gas (Table 1). At the same time, these chemical energy sources are characterized by a rising ratio of hydrogen to carbon: 1 to 5 for wood, 1 to 2 for coal, 2 to 1 for oil, 4 to 1 for methane. Now, the world is poised to develop the capacity to produce hydrogen directly, without combustion of a carbon intermediary at all, and to do this cheaply and efficiently enough for commercial purposes. The key to this development is to utilize the process heat of the most efficient primary energy source yet commercialized—nuclear power.

Using the process heat from a nuclear power plant, hydrogen can be produced directly by several processes, including electrolysis and thermochemical water splitting. There are hundreds of thermochemical cycles which can be used for splitting water to generate O_2 and H_2, but of these, only two are being actively developed for eventual commercial use: the UT-3 cycle, developed by the University of Tokyo, which uses a cycle of reactions involving calcium, bromine, and iron, and the Sulfur-Iodine (S-I) cycle of General Atomics Corp. The UT-3 cycle will generate hydrogen at lower temperatures, but the efficiency of the reaction is limited to around 40 percent.

The Sulfur-Iodine cycle, using process heat from a high temperature nuclear reactor (HTR), is the most promising thermochemical method of splitting hydrogen from water. At a temperature of 950°C, hydrogen production by this method could exceed 50 percent efficiency.

Table 1
COMPARISON OF HEATS OF COMBUSTION FOR SEVERAL FUELS

Energy source		kcal/kg
Hydrogen	(H_2)	34,200
Methane	(CH_4) (Natural gas)	13,200
***n*-Heptane**	(C_7H_{16}) (Gasoline)	11,499
Ethanol	(C_2H_5OH)	7,140

Source: Data are from James B. Conant, *The Chemistry of Organic Compounds* (New York: Macmillan, 1934).

The Sulfur-Iodine cycle basically involves three carefully coupled chemical reactions (Figure 1). Temperatures of at least 850°C are required to drive the decomposition of sulfuric acid into sulfur dioxide, water, and oxygen. The reformation of sulfuric acid from iodine, sulfur dioxide, and water at the end of the cycle is exothermic, and can be accomplished at 120°C. The cleavage of the hydrogen iodide to iodine and hydrogen requires about 450°C. The water is not regenerated in this cycle, as it is cleaved into oxygen and hydrogen gases. The brute-force splitting of water into oxygen and hydrogen gases by heat alone, would require temperatures in excess of 2,500°C; however, using some cases by using off-peak power, because the relevant technologies are already proven.

(2) In the intermediate term, nuclear-heated steam reforming[2] of natural gas, using medium-temperature reactors could be utilized, in spite of some carbon dioxide emissions, because of its advantages in economic competitiveness and in technical feasibility. Also, high-temperature reactors could be used to carry out high-temperature steam electrolysis, with higher conversion efficiency and fewer materials problems.

(3) In the long term, high-temperature reactors would be coupled to thermochemical water splitting. These bulk chemical processes benefit from economy of scale, and may turn out to be the best for very-large-scale nuclear production of hydrogen for a mature global hydrogen energy economy. (See box.)

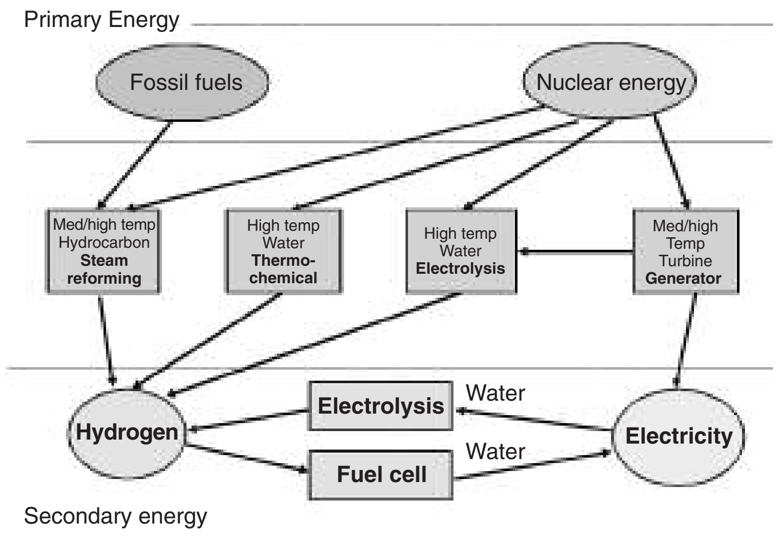


Figure 2
METHODS OF HYDROGEN PRODUCTION BY NUCLEAR ENERGY

coupled reactions under advantageous conditions, one can accomplish the same end result at high efficiency, at a temperature achievable by nuclear technologies already developed in several countries.

Some of the advantages of combining nuclear power with the S-I thermochemical cycle for hydrogen production are: No pollutants are generated; the hydrogen gas comes off at high pressure, allowing it to be easily transported from the reactor through pipes; and the efficiency is high. The disadvantages include: high temperature is required; highly corrosive chemical reactants and products require the development of special glasses, ceramics, and metals for containment; and very complex separation and concentration steps are necessary to achieve the high efficiency potential.

The S-I cycle was initially studied by General Atomics in the 1970s, spurred by the gasoline crisis of that period. As gas prices dropped, interest in producing hydrogen from the S-I cycle dropped, with only the Japanese continuing investigations until recently.

With the upsurge of interest in the Hydrogen Economy, General Atomics and others are again pursuing the S-I cycle for hydrogen production. General Atomics envisions using modular 600-MW helium-cooled HTRs to produce temperatures up 950 degrees, plenty high enough to push hydrogen-production efficiency above 50 percent.

India is considering a similar course, and engineers at Bhabha Atomic Research Center have developed a proposal for a 600-MW HTR which would produce hydrogen at 850°C, and then use the waste heat to produce electricity and to desalinate water. They estimate that 80,000 cubic meters per hour of hydrogen could be produced, while still producing 18 megawatts of electricity and 9,000 cubic meters of fresh water per day. —*Christine Craig*

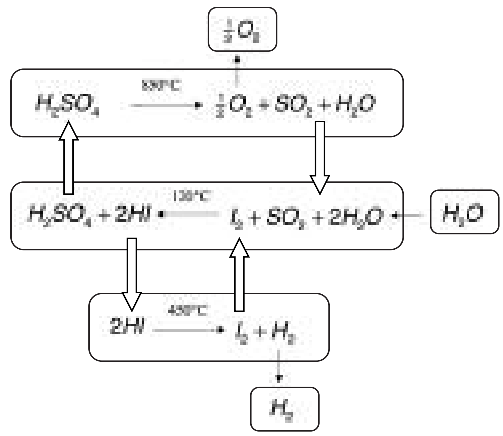


Figure 1
THE SULFUR-IODINE CYCLE
Sulfuric acid (H_2SO_4) is collected, concentrated, and decomposed at 850°C to oxygen gas (O_2), sulfur dioxide (SO_2) and water (H_2O). The O_2 gas is removed. The addition of iodine (I_2) and more water to the other products of the first reaction readily leads to reformation of the sulfuric acid at 120°C. The hydrogen iodide product of that reaction is then heated to 450°C, whereupon iodine is regenerated and hydrogen gas (H_2) comes off as the required final product. The overall reaction is simply water breaking down into oxygen gas and hydrogen gas.

Air Products and Chemicals

This Carson, California plant produces hydrogen by the steam-reforming of methane.

Industrial Applications for Nuclear Hydrogen

Hydrogen will be increasingly consumed in the petroleum industry for refining or upgrading heavier (lower hydrogen-to-carbon ratio) oils and oil sands. Usually, hydrogen is produced by reforming of natural gas or other fossil fuels, releasing CO_2 in the process. If nuclear-produced hydrogen is used in these industrial processes, overall CO_2 emissions per vehicle-mile can be decreased. In the future, hydrogen may be used for aircraft propulsion to reduce the impacts of aircraft exhaust on stratospheric chemistry and climate. Nuclear hydrogen could respond to such large, industrial-scale demands.

The reforming process presently used requires a considerable amount of heat. In the conventional process, the heat is supplied by burning some of the fossil fuel feed. Switching to the use of nuclear heat for the production of hydrogen by steam reforming of fossil fuels would effectively reduce the fossil fuel consumption and CO_2 emission by about 30 percent.

This synergistic process can efficiently convert nuclear heat to chemical energy, thus facilitating efficient conversion of primary energies into energy carriers. It will become more attractive as the cost of nuclear power drops. It could be applied extensively not only to produce hydrogen, but also for upgrading hydrocarbons and generating electricity, thus both conserving energy resources and enabling the "noble use" of fossil fuels.

Alternatives to Fuel Cells for Transportation

Figure 3 shows the energy flow to different types of alternative fuel vehicles. These include battery electric

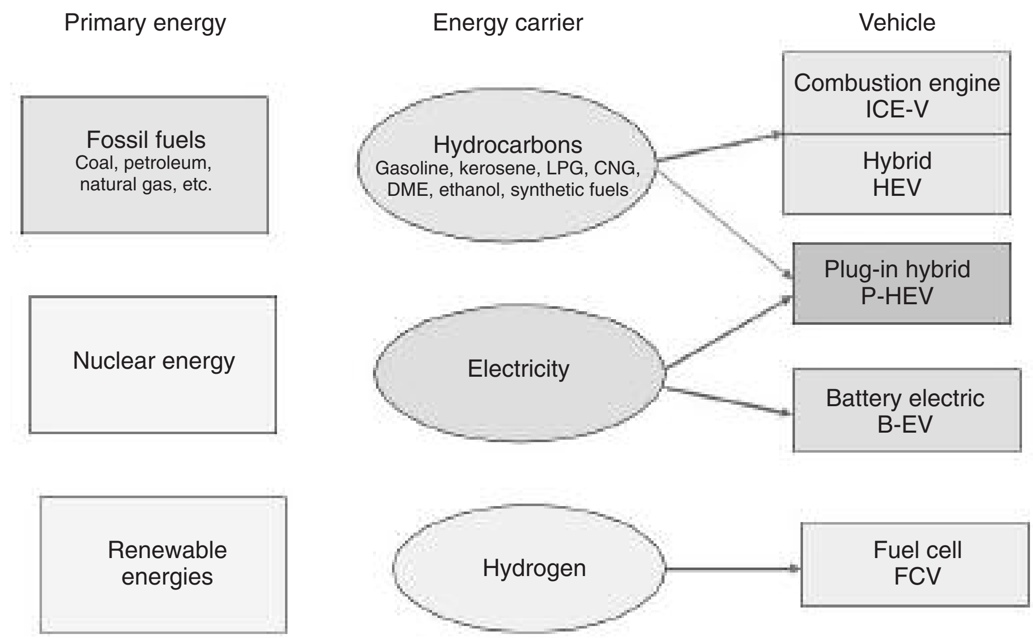


Figure 3
ENERGY FLOWS TO VEHICLES WITH VARIOUS DRIVE TRAINS

vehicles (B-EV) and plug-in hybrid electric vehicles (P-HEV) which are as efficient as fuel cell vehicles (FCV), and could be powered by nuclear electricity.

A plug-in hybrid electric vehicle is a hybrid electric vehicle (HEV) which has been provided with increased battery capacity, capable of being recharged from an external electrical plug. Up to a certain distance, which depends upon the battery capacity, the plug-in hybrid electric vehicle is powered solely by the battery, like a battery electric vehicle. Only after that distance, does the plug-in hybrid electric vehicle have to rely on an internal combustion engine like an hybrid electric vehicle. By this means, the plug-in hybrid electric vehicle can save on fuel consumption as compared to an ordinary hybrid. All of the energy powering an hybrid electric vehicle comes from petroleum (gasoline or diesel), while the energy powering a plug-in hybrid electric vehicle comes from both petroleum and the primary energy which has generated the electricity used to charge the battery when plugged in.

It is estimated that on any given day, on average, 50 percent of U.S. vehicles are driven less than 20 miles. Thus, a battery capable of powering a plug-in hybrid electric vehicle for a certain distance, say 30-60 miles—which is far less than the capacity required for an ordinary battery electric vehicle—could power the plug-in hybrid electric vehicle by electricity alone, and thus save a substantial amount of gasoline.

With the recent rapid evolution in battery technology, especially in lithium ion batteries, there is a possibility that plug-in

NASA/NREL

Lightweight hydrogen powers the Shuttle's main engines.

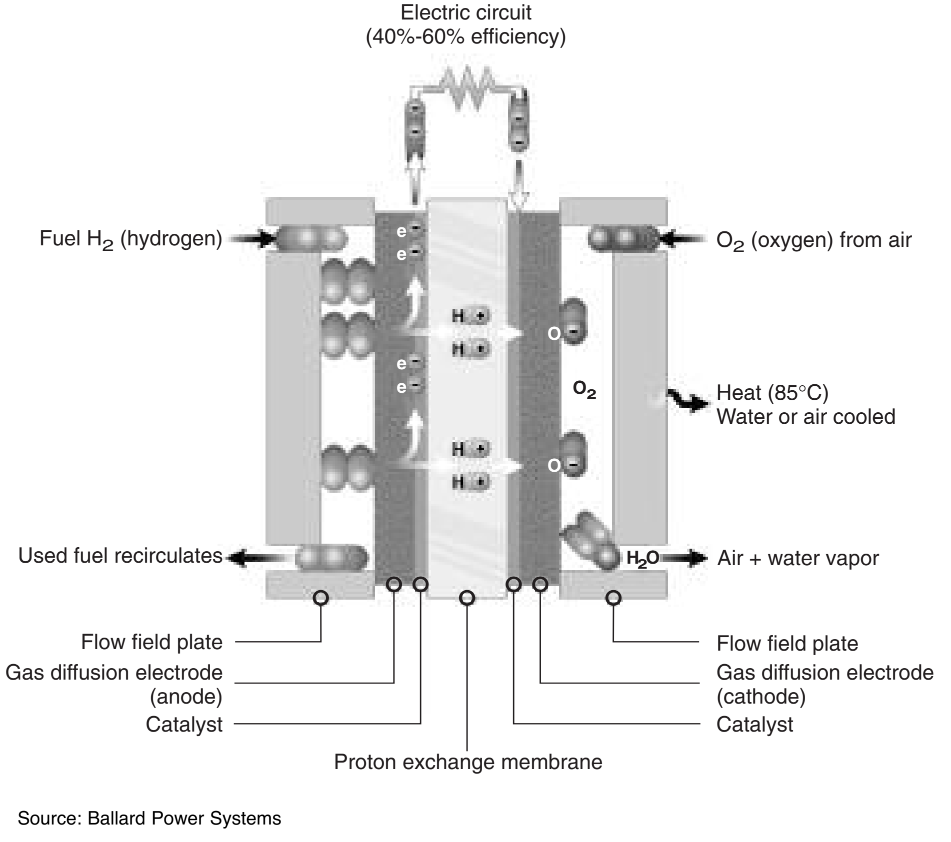


Figure 4
HOW THE FUEL CELL WORKS

The core of the Ballard fuel cell consists of a membrane electrode assembly (MEA) which is placed between two flow-field plates. The MEA consists of an anode and a cathode separated by a proton exchange membrane (PEM). The flow-field plates direct hydrogen to the anode and oxygen to the cathode. When hydrogen reaches the catalyst layer of the anode, it separates into protons (hydrogen ions) and electrons.

The free electrons, produced at the anode, are conducted in the form of a usable electric current through the external circuit. At the cathode, oxygen from the air, electrons from the external circuit, and protons combine to form water and heat.

Daimler Chrysler

The Mercedes plug-in hybrid Sprinter is hitting the streets in New York.

hybrid electric vehicles (more so than battery electric vehicles) can be commercialized within a decade. Now the U.S. government is pushing the development of advanced battery technology to be applied to plug-in hybrid electric vehicles. In Japan, also, the plug-in hybrid electric vehicle is drawing attention. At a recent plug-in hybrid electric vehicle workshop held in Tokyo, participants came from a wide range of sectors, including research institutes, auto and electric-appliance producers, utility companies, and government.

Nuclear can supply energy to the transportation sector by generating the charging electricity for plug-in hybrid electric vehicles. As half of U.S. electricity is produced by coal-fired power plants at present, increasing the share of nuclear power for the future will be beneficial for the environment as well as for energy security.

Hybrid Vehicle Impact in the U.S. and Japan

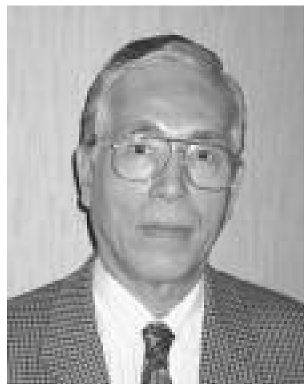
According to Robert E. Uhrig, Professor Emeritus of the University of Tennessee, who analyzed the effect of introducing plug-in hybrid electric vehicles into the United States, transportation petroleum use could be reduced by about 74 percent by powering the plug-in hybrid electric vehicle with electricity from a battery of 35-mile cruising capability.[3] Assuming that all of the 225 million light transportation vehicles (automobiles, SUVs, pickups, vans, etc.) are plug-in hybrid electric vehicles, then 422 GWe would be required to charge the batteries during eight hours at night. He concluded that, considering spare generating capacity at night, perhaps 200 new 1,000-MWe nuclear power plants are needed.

I analyzed plug-in hybrid electric vehicle introduction into Japan using the same methodology. Assuming that plug-in hybrid electric vehicles are introduced in the category of private passenger vehicles, about a 70 percent savings in gasoline would be realized by using batteries with a range of 20 to 40 miles, depending on the size of the vehicles. For powering all of the 54 million private passenger vehicles in Japan, the electric power needed for charging the batteries in 8 hours at night would be 35 GWe. Since there is about a 50-GWe difference between the peak hours and the night time usage currently in Japan, the power for plug-in hybrid electric vehicles could be supplied by the existing spare generating capacity. Because nuclear power is presently used as the base load in Japan, additional power requirements would have to be supplied by increasing the operation of fossil-fuel-powered plants. For energy security and the global environment, it were better to shift the power supply structure to more nuclear electricity, replacing fossil fuel electricity and converting vehicles to plug-in hybrid electric.

So, for our energy security and the environment, we would look forward to evolving from hybrid electric vehicles to plug-in hybrid electric vehicles, and further to the battery electric vehicle/fuel cell vehicle in a few decades. Also, there are possibilities for vehicles powered by synthetic fuels (hydrocarbons) or bio-fuels (ethanol), which may well be upgraded or produced using nuclear energy synergistically.

Whether essential energy carriers for the transportation sector, or more broadly, for our society in general, become electricity, hydrogen, synthetic fuels, and/or bio-fuels, nuclear energy will become an increasingly important primary energy source to produce these energy carriers.

Masao Hori, based in Tokyo, has served in the nuclear industry for many years and has worked to promote nuclear development internationally. He was chairman of the committee on Vision for the Second Fifty Years of Nuclear Energy, *which published its report in 1996. More recently, he chaired the International Nuclear Society's Task Group on Nuclear Energy's Role in the Future, which in 2004 published the groundbreaking work,* Nuclear Production of Hydrogen—Technologies and Perspectives for Global Deployment. He can be reached at mhori@mxb.mesh.ne.jp.



Notes

1. M. Hori, "Role of Nuclear Energy in the Long-Term Global Energy Perspective," OECD/NEA First Information Exchange Meeting on Nuclear Production of Hydrogen (Paris, October 2000). See also James Muckerheide, "How to Build 6,000 Nuclear Plants by 2050," *21st Century*, Summer 2005.
2. Steam reforming of natural gas produces hydrogen by combining the oxygen in steam with the carbon in natural gas, thus releasing hydrogen from steam, as the natural gas (which consists of carbon and hydrogen) is decomposed.
3. Dr. Robert E. Uhrig, "Using Plug-in Hybrid Vehicles to Drastically Reduce Petroleum-Based Fuel Consumption and Emissions," *The Bent of Tau Beta Pi,* Spring 2005.