lack of funds," says one institute scientist. The institute receives a guaranteed $1 million each year from the National Foundation for housekeeping costs but must raise the rest of its $5 million budget from public and private sources. A hiatus between resources and ambitions that became apparent some 2 years ago has left the institute unable to make more than limited progress with its humanist programs. Hopes of establishing large groups in neurobiology and aging have had to be shelved. Instead, the institute has been sucked into cancer research because that is where the money is, both from federal sources and private donors. Even so, nearly two floors of the building, containing some 40,000 feet of floor space, are still vacant.

Another result of financial uncertainty is that the institute cannot offer any tenured positions in addition to those of the existing fellows. This, and the policy of relying on the fellows to attract large grants on behalf of their group—all of whom are jeopardized if the grant fails to come through—has made it harder to keep younger people. "I think the place was slow in building up young people as independent investigators," says Holley. "One of the side benefits of the financial problems is that this will probably change."

If the Salk Institute is something of a pauper in rich man's clothing, even to have stayed financially viable is no mean achievement for a pure research organization dependent on public support. The institute seems now to have put its financial affairs on a firmer basis, and a new executive officer, Frederic de Hoffman, a physicist and former member of the San Diego business community, is trying to raise an endowment. Though tenure is a problem for some, there are others who prefer to remain at Salk than accept tenured posts elsewhere. With its unrivaled setting, and the virtual absence of teaching duties, the institute is an attractive enough place to do research, as evidenced by its ability to draw researchers such as Holley from Cornell or Guillemin from Houston.

"The institute is a useful refuge for people who in the last 3 or 4 years have found the increasing teaching burdens at university made it difficult to do research," says one scientist. And Salk himself, referring to the tendency of others to make a public figure of him, said on a CBS program some years ago, "I sometimes think that the idea of creating the institute was to create a shelter for myself." The institute may not yet have produced anything with the public impact of Salk's polio vaccine, but its continued vitality suggests that Salk's second experiment can probably be counted a success.

—NICHOLAS WADE

RESEARCH NEWS

Hydrogen: Synthetic Fuel of the Future

ENERGY

It may take 50 years, 100 years, or longer, but the time is approaching when gas, oil, and coal will no longer be available for use as fuels. Possibly, reserves of these fuels will be depleted by then. Probably, production will not be able to keep pace with demand (Fig. 1). But most likely, the remaining reserves will become far too valuable as feedstocks for chemical production to be simply burned for their energy content.

By that time, of course, nuclear fission and fusion—and perhaps solar energy—will almost certainly be the major energy sources and should, in theory, be capable of supplying all our energy needs. Most developmental work on these sources has emphasized the production of electricity, however, while only about 10 percent of energy end use is supplied by electricity. The remainder is supplied by the combustion of fuels to produce heat energy that is used in industry, homes, and transportation. It is likely both that electricity will play a larger role in supplying future energy demands and that heat energy from nuclear reactors will be utilized in large nuclear/industrial complexes, or nuplexes. Nonetheless, there will remain a strong demand for portable, fluid fuels, particularly for applications in transportation, and the most likely response to this demand will be vastly increased production of hydrogen.

Hydrogen, of course, is not an alternative primary energy source, because large amounts of energy will be required to produce it. Rather, it holds promise of being a highly efficient energy carrier that would prove valuable in situations where transfer of energy as electricity is inefficient, impractical, or impossible. It is this potential that has generated such widespread interest in the possibility of a "hydrogen economy."

In many ways, hydrogen is virtually an ideal fuel. When it is burned in air, the only possible pollutants are nitrogen oxides derived from the air itself, and concentrations of these are generally lower than concentrations produced by other fuels. When it is burned in pure oxygen, the only product is water and there are no pollutants at all. The ignition energy of hydrogen is about 0.02 millijoules, less than 7 percent that of natural gas, so that it can readily be used in low-temperature catalytic burners that also produce no pollutants.

The energy content of hydrogen gas is 325 British thermal units per standard cubic foot (1 Btu/scf=2.98×10^5 joules per cubic meter), less than a third that of natural gas (about 1000 Btu/scf). The lower viscosity of hydrogen permits a threefold increase in flow capacity of a pipeline, however, and one pipe can carry nearly equal energy contents of either fuel—although hydrogen transmission requires a greater pumping capacity. The energy content per unit mass of liquid hydrogen is about 2.75 times greater than that of hydrocarbon fuels, so that the liquid form is an ideal fuel for rockets and airplanes. The volume of liquid hydrogen is much greater than that of a comparable weight of hydrocarbons, however, since its specific gravity is only 0.07.

There is some concern—often called the "*Hindenburg* syndrome"—about the safety of hydrogen, but most such fears seem exaggerated. Hydrogen has a higher diffusivity than natural gas, so that it leaks faster, but this diffusivity also allows it to dissipate faster. Hydrogen also has a wider range of explosive concentrations in air than does natural gas, but the lower explosive limit is the crucial one, and this limit is nearly the same for both gases. Also hydrogen does not produce toxic by-products of combustion, such as carbon monoxide. Large quantities of hydrogen are shipped and used, both in this country and in Europe, with a high degree of safety.

The most obvious application of hydrogen is in transportation, both because of the need for a portable energy source and because of the potential for pollution abatement. Several investigators, such as K. V. Kordesch of Union Carbide Corporation's Parma Research Laboratory, Cleveland, Ohio, have demonstrated the use of hydrogen fuel cells to power automobiles. A simpler approach, however, is to burn hydrogen in an internal combustion engine.

Roger J. Schoeppel of Oklahoma State University, Stillwater, has shown that the torque, power, and efficiency of hydrogen-fueled engines are comparable to those of gasoline-powered engines with only minor modifications. Nitrogen oxides are the only pollutants emitted by such engines, and the amounts produced are much lower than in conventional engines (Fig. 2). Robert R. Adt, Jr., of the University of Miami, Coral Gables, Florida, has also demonstrated the conversion of automobile engines to run on hydrogen. Adt suggests that the efficiency of such engines is as much as 50 percent greater than that of gasoline engines.

The problems of conversion are so minor, in fact, that the major impediment to hydrogen use is the provision of an adequate fuel storage capacity. Gaseous hydrogen, even when highly pressurized, is far too bulky and requires containers too heavy to give a reasonable operating range; liquid hydrogen requires a costly, potentially dangerous cryogenic storage tank.

One approach to this problem has been presented by Harold Sorenson of International Materials Corporation, Boston, Massachusetts. IMC has developed a compact conversion system that reforms unleaded gasoline into hydrogen and carbon dioxide by catalytic cracking. Fuel storage is thus accomplished with a conventional gasoline tank, and hydrogen is produced only as it is needed. But such a system is useful only while there are adequate supplies of hydrocarbon fuels, and thus might find service only until better storage techniques are developed.

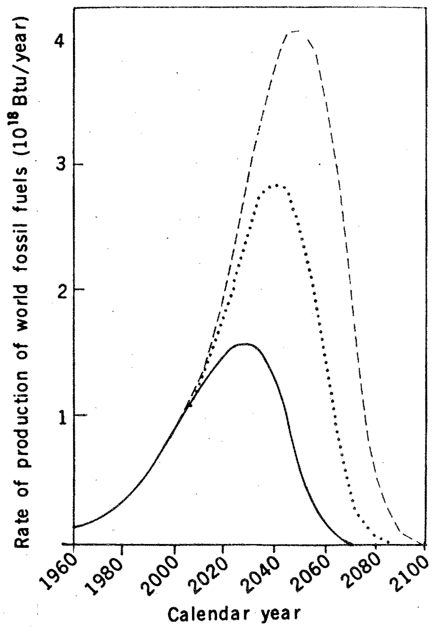

Fig. 1. Rate of world production of fossil fuels if total reserves are assumed to be 85×10^{18} Btu (solid line), 155×10^{18} Btu (dotted line), or 226×10^{18} Btu (dashed line). [Source: Martin A. Elliott, Texas Eastern Transmission Corporation]

One promising alternative is storage in the form of metal hydrides. Because of its small molecular size and high diffusivity, gaseous hydrogen is able to penetrate the lattice structure of solid metals or alloys and bind at various sites in the unit cell of the crystal. For many metals, such as titanium, the penetration is so great that the concentration of hydrogen per unit volume is actually greater than in liquid hydrogen. The hydrides are formed by simply exposing the metal to pressurized hydrogen. Hydride formation is exothermic and can be reversed by the application of heat; waste heat from the combustion process can thus be used to free the hydrogen.

Philips Research Laboratories, Eindhoven, Netherlands, has found that hydrogen can be stored efficiently by intermetallic compounds of the type AB_5H_x, where A is a lanthanide rare earth element, B is nickel or cobalt, and x can be as large as 6. R. H. Wiswall, Jr., and J. J. Reilly of Brookhaven National Laboratory, Upton, New York, have obtained similar results, and have also found that the hydrides of vanadium, niobium, and their alloys are also efficient in storing hydrogen. Each of these systems, however, suffers from the high cost of the metals used and, thus, the high capital investment required for a storage tank. Less expensive metals will probably be required to make hydride storage practical.

Cryogenic storage would be adequate for subsonic or supersonic aircraft, and might even be necessary for hypersonic aircraft, according to Robert D. Witcofski of the National Aeronautics and Space Administration's Langley Research Center. The greater energy content of liquid hydrogen would more than compensate for the increased weight of cryogenic storage tanks, he says, and would provide superior range or payload capabilities. Liquid hydrogen, moreover, has more than 30 times the heat-sink capacity of conventional jet fuel, and could thus be used for cooling the aircraft surfaces at hypersonic speeds. Emissions of nitrogen oxides from such planes, he contends, would be less than 25 percent of those projected for a conventional supersonic transport.

Many problems must be solved before such aircraft could be built. Foremost among them is obtaining liquid hydrogen at a low enough cost (5 to 10 cents per pound, compared to today's price of about 45 to 60 cents per pound) to make the aircraft economically viable. Other problems include insulation of the storage tanks and the development of construction materials that retain their strength despite gross temperature variations.

A less obvious, but equally important, use of hydrogen would be the transmission of energy over long distances. Transmission and distribution now account for about 45 percent of the delivered cost of electricity, about $2.22 out of a total cost of $4.89 per million Btu. That share will rise sharply as environmental considerations mandate more use of underground transmission lines.

Transmission and distribution costs for natural gas average only about $0.47 per million Btu, although similar costs for hydrogen might be 20 to 120 percent higher. Part of this price advantage is also abrogated by inefficiencies in converting electricity to hydrogen. Even with currently available technology, nonetheless Derek P. Gregory of the Institute of Gas Technology, Chicago, Illinois, calculates that electrical transmission by hydrogen is less expensive at distances greater than 400 kilometers if the energy is to be used to produce heat. If underground electrical transmission lines are required, hydrogen is less expensive at distances of only 32 km.

Another advantage of hydrogen transmission is increased efficiency of the power plant. Because of large time variations in electrical demand and the great difficulties of storing electrical energy, the electric industry frequently operates at as little as 50 percent of installed capacity. Since hydrogen can be stored readily, the industry could operate near 100 percent of its capacity at all times, and the stored hydrogen could be used to meet peak demands for power.

Widespread use of such a distribution system will probably depend on two factors—increased efficiency of conversion of hydrogen to electricity in fuel cells (to be discussed in a subsequent article), and increased efficiency of conversion of nuclear (or perhaps solar) energy to hydrogen. At least four techniques for production of hydrogen from water are generally considered: electrolysis, endothermic chemical decomposition, photolysis, and bioconversion. (More than half of the hydrogen used today is produced by catalytic cracking of hydrocarbons, but this route is impractical if hydrogen is to be a hydrocarbon substitute.) Only electrolysis has been proved in practice.

Commercial electrolyzers typically operate at efficiencies of about 60 to 70 percent—although some high-pressure prototypes may reach 85 percent— because the operating voltage is substantially higher than that ideally required. Gregory points out that, in theory, the maximum electrical efficiency of electrolyzers is close to 120 percent, because an ideal unit would absorb heat from its surroundings and convert this into hydrogen also. An operating efficiency of around 100 percent thus appears to be a reasonable practical goal for commercial installations. The overall efficiency of hydrogen production would then be limited by the efficiency of generation of electricity, which might be expected to be between 35 and 45 percent.

One way to sidestep this limitation is direct thermal decomposition of water within a reactor. This process requires temperatures of about 2500°C, however, and commercial nuclear reactors are not expected to operate at temperatures much above 900°C. But it should be possible to use a multistep reaction that can be carried out at lower temperatures.

Gianfranco de Beni and Cesare Marchetti of the Euratom research center in Ispra, Italy, have developed a four-stage reaction sequence in which dissociation of water is accomplished at temperatures below 730°C:

$$CaBr_2 + 2H_2O \rightarrow Ca(OH)_2 + 2HBr \quad (1)$$

$$Hg + 2HBr \rightarrow HgBr_2 + H_2 \quad (2)$$

$$HgBr_2 + Ca(OH)_2 \rightarrow CaBr_2 + HgO + H_2O \quad (3)$$

$$HgO \rightarrow Hg + \tfrac{1}{2}O_2 \quad (4)$$

The overall reaction is thus

$$H_2O \rightarrow H_2 + \tfrac{1}{2}O_2$$

with a thermal efficiency, de Beni contends, of greater than 50 percent.

The reaction sequence has been tested only in the laboratory, but de Beni hopes to build a pilot plant at Ispra. Many problems remain: The kinetics and equilibria of the four steps are still somewhat uncertain, and materials to contain the corrosive intermediates at high temperatures and pressures will require further development. Nonetheless, it is possible that the Euratom sequence or one like it will eventually provide a higher overall efficiency than the combination of electrical generation and electrolysis.

A third alternative, proposed by Bernard L. Eastlund of the Atomic Energy Commission, would use ultraviolet radiation from the plasma of a fusion reactor for direct photolysis of water vapor. Injection of heavy elements, such as aluminum into a hydrogen plasma, he says, would produce photons of the correct wavelength for photolysis, which would then take place in water vapor circulating around the plasma chamber. Experimental confirmation of Eastlund's scheme will require development of an operating fusion reactor, but it seems possible that such a process, in conjunction with electrical generation, could increase the efficiency of a fusion power plant.

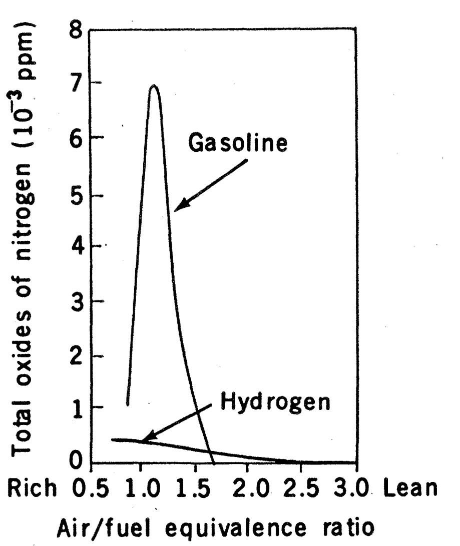

Fig. 2. Emissions of nitrogen oxides (in parts per million) from single-cylinder laboratory engines operating on gasoline and hydrogen. [Source: Roger J. Schoeppel, Oklahoma State University]

The final alternative is direct production of hydrogen from water by algae, proposed by Lester O. Krampitz of Case Western Reserve University, Cleveland, Ohio. Under the stimulation of light, the photosynthetic apparatus of some algae can increase the oxidation potential of electrons from water to a level as much as 0.3 volt more negative than the hydrogen electrode. It is thus possible, he contends, to couple the reducing potential of these electrons with a hydrogenase enzyme from algae or bacteria and convert hydrogen ions to hydrogen gas. Only preliminary work has been done on the project, but Krampitz recently received a National Science Foundation grant to continue the work under the Research Applied to National Needs program.

No matter what method is used to produce hydrogen, the amounts required will be very large. Current U.S. consumption of hydrogen is slightly more than 2.28 trillion scf per year, and world consumption is about 6 trillion scf. According to the Institute of Gas Technology, it would require almost 60 trillion scf of hydrogen simply to provide the energy equivalent of U.S. natural gas consumption in 1968. With current electrolyzer efficiencies, production of that amount of hydrogen would require more than 1 million megawatts of electricity, or more than three times the current U.S. generating capacity. Hydrogen replacement of fossil fuels for all uses other than the generation of electricity, the institute estimates, would require 295 trillion scf by the year 2000.

How much this hydrogen will cost is anybody's guess, but it is certain that its cost will reflect that of electricity. Gregory estimates it would cost \$1.50 to \$2.50 per million Btu (natural gas currently wholesales for \$0.50 to \$1.00 per million Btu) if electricity costs 0.4 to 0.7 cents per kilowatt-hour. This estimate may be somewhat optimistic, since current costs of electricity vary from about 0.6 to 0.9 cents per kilowatt-hour, and many groups expect the cost of electricity to rise rather than fall. The cost of hydrogen could thus easily be double Gregory's estimate.

The limiting factor, however, will not be the absolute cost of hydrogen, but its cost relative to fossil fuels, and the price of these fuels is certain to climb steeply during the next 30 years. Another factor governing the cost of hydrogen, of course, will be credits obtained in the sale of byproduct oxygen.

The availability of relatively inexpensive hydrogen and oxygen in large quantities could bring about extensive changes in U.S. industry. Initially, during a transition to a hydrogen economy, they might be used in the production of other fuels. Coal gasification, for example, is expected to require about 1500 scf of hydrogen for every 1000 scf of methane produced. Most gasification proposals now envision production of this hydrogen from the coal itself, so the availability of alternative sources would greatly increase the amount of synthetic natural gas that might be produced from a given quantity of coal and extend the lifetime of coal reserves.

Petroleum refining uses increasingly large amounts of hydrogen to improve the quality of the products and to desulfurize the crude oil. By the year 2000, the American Petroleum Institute predicts a consumption of more than 600 scf of hydrogen per barrel of crude oil will be commonplace. Production of shale oil would require even more processing, and perhaps as much as 1300 scf of hydrogen per barrel.

Inexpensive hydrogen might also make it possible to produce synthetic fuels that are not derived from fossil sources. K. R. Williams and N. L. Campagne of Shell International Petroleum Company, London, suggest that it might be possible to make methanol or Fischer-Tropsch gasoline from atmospheric carbon dioxide for as little as 30 to 45 cents per gallon with low-priced hydrogen. Others have suggested that calcium carbonate would be a good carbon source for the production of these fuels.

Ammonia synthesis now accounts for more than 40 percent of hydrogen consumption, and the quantities of hydrogen required can be expected to increase as food demand rises. Hydrogen could also find wide use for the direct reduction of iron ore, particularly as supplies of coking coal become more expensive. Production of 1 ton of iron, the American Iron and Steel Institute estimates, would require some 20,000 scf of hydrogen.

The quantities of oxygen available as a byproduct of hydrogen production would be unprecedented. By weight, oxygen is currently the third largest industrial chemical produced in the United States—11.3×10^9 kilograms, or about 313×10^9 scf in 1971—but the quantities produced in a hydrogen economy would dwarf these figures. A wide variety of new or expanded uses for oxygen would thus be opened—or might, in fact, become necessary to bolster the economics of hydrogen production. Some of the oxygen might be used to support combustion in applications where atmospheric gases are not desirable, such as in coal gasification. Large quantities would also be used in the production of steel. An even larger market might be developed in the treatment of municipal sewage. But for now, however, the use of this oxygen remains the least-studied of all aspects of the hydrogen economy.

—THOMAS H. MAUGH II

Particle Physics: Many Results, Surprising Disclaimers

Research from a new accelerator facility at the European Organization for Nuclear Research (CERN) seemed to dominate the discussions at the 16th International Conference on High Energy Physics, a biennial meeting of scientists who study some of the smallest structures and most fundamental symmetries of nature. Two rather exciting new experiments reported from CERN may be additional evidence for granularity in the structure of the proton, a feature that was suggested by experiments at the Stanford Linear Accelerator Center about five years ago. Other experiments may signal changes in the accepted understanding of the structure of elementary particles. But the most surprising bits of news from the conference were the many reversals and retractions of previous results. The mood of the conference participants was optimistic; particle physics seemed to be progressing by increments on many fronts, with some backtracking, but certainly not lacking new ideas or creative experiments.

The conference, which was attended by 800 foreign and American physicists, was held at the site of the world's largest accelerator, the new National Accelerator Laboratory at Batavia, Illinois. The rough textures of the still unfinished buildings of the laboratory contrasted sharply with the cosmopolitan tone of the conference, at which the dinners were served with good wines and the day's discussions were followed by evenings with excellent chamber music and jazz. The scientific contributions from the new accelerator were restricted because it has not yet reached full-scale operation, but the conference participants seemed to find the early results, particularly from a small bubble chamber, provocative.

The list of reversals of previous experiments presented at the 1972 international meeting was fairly long. In the previous year many physicists had been puzzled because of the failure to observe decay of the long-lived K-meson into two muons in an experiment performed at Berkeley. This was particularly disturbing because it indicated that a rather basic principle of interactions, called unitarity, had been violated. Unitarity means that the probability of all decay modes, taken together, equals one. But in an experiment reported at the Illinois conference by David Nygren, William Carrithers, and associates at Columbia University, Brookhaven National Laboratory, and CERN, six examples of the decay in question were found, apparently enough to satisfy the unitary principle.

A heated controversy over another experiment that had been argued in round robin style at all the particle physics conferences of the last five years was apparently laid to rest. The debate started when a group at CERN reported that a meson thought to be a single entity, the A_2-meson, actually existed as two particles differing only slightly in their masses. Succeeding experiments yielded no evidence for a mass difference, however, and the rapporteur at the Illinois conference judged the preponderance of evidence in favor of a single meson after all.

Another experiment that had been closely watched because it was possible