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The Hydrogen Economy

A case is made for an energy regime in which all energy sources would be used to produce hydrogen, which could then be distributed as a nonpolluting multipurpose fuel

by Derek P. Gregory

The basic dilemma represented by what has been termed the "world energy crisis" can be simply stated: At the very time that the world economy in general and the economies of the industrialized countries in particular are becoming increasingly dependent on the consumption of energy, there is a growing realization that the main sources of this energy—the earth's nonrenewable fossil-fuel reserves—will inevitably be exhausted, and that in any event the natural environment of the earth cannot readily assimilate the byproducts of fossil-fuel consumption at much higher rates than it does at present without suffering unacceptable levels of pollution.

What is not generally recognized is that the eventual solution of the energy problem depends not only on developing alternative sources of energy but also on devising new methods of energy conversion. There is, after all, plenty of "raw" energy around, but either it is not in a form convenient for immediate use or it is not in a location close enough to where it is needed. Most of the research-and-development effort in progress in the U.S. on the energy problem is devoted to finding ways to convert chemical energy (derived from fossil fuels), nuclear energy (derived from fission or fusion reactions) and solar energy (derived directly from the sun) into electrical energy.

At present nuclear-fission plants supply about 1.6 percent of the electricity consumed in the U.S. (Of the remainder, fossil-fuel plants supply about 82 percent and hydroelectric plants about 16 percent.) Assuming that the development of economically feasible "breeder" reactors will soon eliminate any short-term concern about the resource limitation of nuclear energy, then by the year 2000 nuclear plants may be supplying as much as half of the nation's electricity.

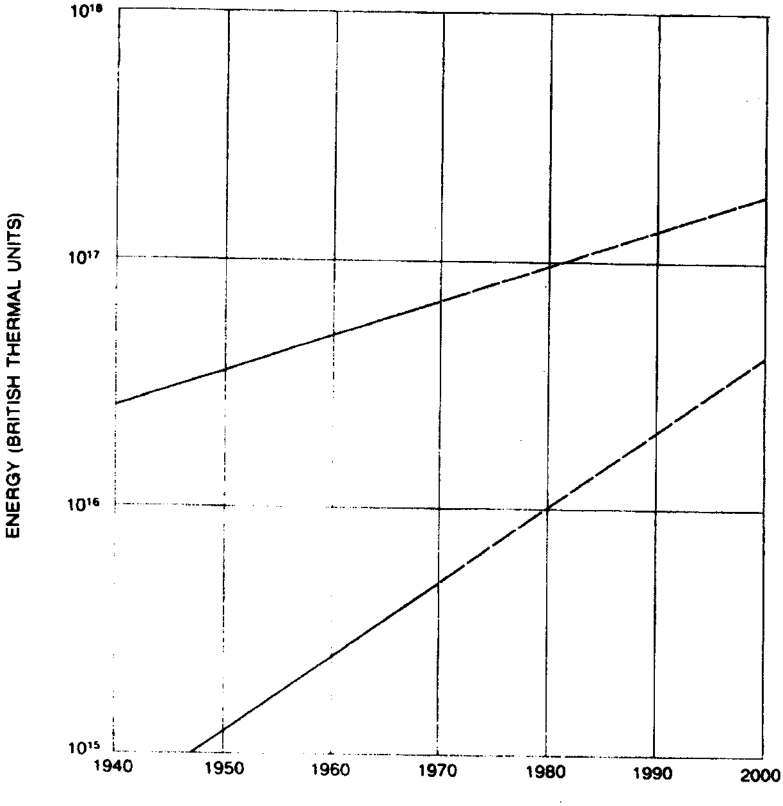
If this projection is correct, and if the "energy gap" of the future is to be filled with nuclear power made available to the consumer in the form of electricity, then the U.S. will have gone a long way toward becoming an "all-electric economy." This trend can be detected already: the demand for electricity is currently growing in the U.S. at a much higher rate than the overall energy demand [*see illustration on next page*]. It has been estimated that whereas the overall U.S. energy consumption will double by the year 2000, the demand for electricity will increase about eightfold, raising the electrical share of total energy consumption from about 10 percent to more than 40 percent.

The question naturally arises: How desirable is this trend toward a predominantly electrical economy? Specifically, are there any other forms of energy that can be delivered to the point of use more cheaply and less obtrusively than electrical energy can? Consider such major energy-consumption categories as transportation, space heating and heavy industrial processes, all of which are primarily supplied today with fossil-fuel energy, mainly for reasons of economy and portability. As the fossil fuels run out, they will become more expensive, making the direct use of nuclear electrical energy relatively more economical. In this situation a case can be made for utilizing the nuclear-energy sources indirectly to produce a synthetic secondary fuel that would be delivered more cheaply and would be easier to use than electricity in many large-scale applications. In this article I shall discuss the merits of what I consider to be the leading candidate for such a secondary fuel: hydrogen gas.

In many respects hydrogen is the ideal fuel. Although it is not a "natural" fuel, it can be readily synthesized from coal, oil or natural gas. More important, it can be produced simply by splitting molecules of water with an input of electrical energy derived from an energy source such as a nuclear reactor. Perhaps the greatest advantage of hydrogen fuel, however, at least from an environmental standpoint, is the fact that when hydrogen burns, its only combustion product is water! None of the traditional fossil-fuel pollutants—carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrocarbons, particulates, photochemical oxidants and so on—can be produced in a hydrogen flame, and the small amount of nitrogen oxide (NO) that is formed from the air entering the flame can be controlled. Moreover, assuming that the energy options are restricted to the use of effectively "unlimited" materials such as air and water, hydrogen is by far the most readily synthesized fuel.

In principle, then, one can envision an energy economy in which hydrogen is manufactured from water and electrical energy, is stored until it is needed, is transmitted to its point of use and there is burned as a fuel to produce electricity, heat or mechanical energy [*see illustration on opposite page*]. Such a hypothetical model is not without its problems and disadvantages, but on balance the benefits appear to be so great that I believe at the same time that we are moving toward an "electric economy" we should also be moving toward a "hydrogen economy."

Just as the food and beverage industry has found it uneconomical to collect and reuse empty containers, so the present energy industry cannot afford to collect and recycle used "energy containers": the by-products of the combustion necessary to produce the energy. The drawback in both cases is that the "no deposit, no return" system throws the burden of recovery and recycling onto the environment. Apart from the obvious harmful effect on the earth's atmosphere, this kind of energy cycle suffers from the further disadvantage of having an extremely slow step of several million years' duration for the re-formation of fossil fuels from atmospheric carbon dioxide [*see illustration on page 16*]. That is the basic reason we are running out of fossil-fuel reserves. In the hydrogen cycle, in contrast, only water is deposited into the atmosphere, where it rapidly equilibrates with the abundant and mobile water supply on the earth's crust. At another location the water is reconverted to hydrogen. The system is characterized by negligible delay and does not disturb the environment, yet it relies on the environment to carry out the "return empty" function. Assuming the availability of an abundant supply of nuclear or solar energy, this system can be operated as rapidly as the demand requires without depleting any natural resources.



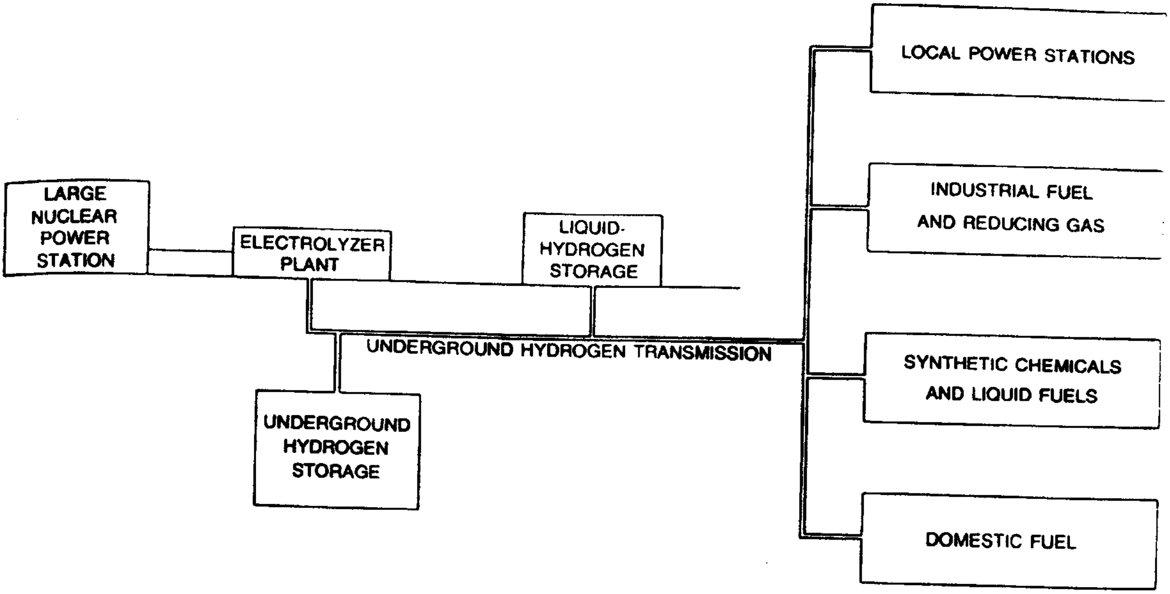
ACCELERATING TREND toward an "all electric" economy is evident in this graph, which shows that the demand for electricity (*bottom line*) is growing in the U.S. at a much higher rate than the overall energy demand (*top line*). Assuming that the trend continues, the U.S. is heading for a predominantly electrical economy sometime in the 21st century. The data are from the U.S. Department of Commerce and the Edison Electric Institute.

The idea of using hydrogen as a synthetic fuel is far from new. In 1933 Rudolf A. Erren, a German inventor working in England, suggested the large-scale manufacture of hydrogen from off-peak electricity. He had done extensive work on modifying internal-combustion engines to run on hydrogen, and the main object of his suggestion was to eliminate automobile-exhaust pollution and to relieve pressure on the importation of oil into Britain. (It is interesting to note that 40 years later the U.S. is concerned with the same two problems: automobile pollution and an increasing dependence on oil imports.)

Others have suggested using hydrogen as a fuel or as a means of storing energy. F. T. Bacon, a pioneer in the development of fuel cells in England since the 1930's, has always had as his ultimate objective the development of a hydrogen-energy storage system using reversible electrolyzer fuel cells. More recently the U.S. Atomic Energy Commission sponsored a series of studies during the 1960's of "nuplexes"—nuclear-agricultural-industrial complexes that derive all their energy from a single nuclear reactor. The AEC studies included the concept of water electrolysis to provide hydrogen as a precursor to the manufacture of fertilizers and chemicals. Within the past two years several articles have appeared in engineering and scientific journals proposing active studies of the production, transmission, storage and utilization of hydrogen in both combustion appliances and engines. Such studies are in progress at several universities and industrial research laboratories in the U.S. and abroad, including my own institution, the Institute of Gas Technology in Chicago, where our work is sponsored by the American Gas Association.

The difficulty of transporting hydrogen has historically prevented its use as a fuel. Clearly some better method than compressing it in steel cylinders has to be found. Storage and transportation as liquid hydrogen are already in use; metal hydrides and synthetic organic or inorganic hydrides have also been considered and have promise. There is no reason, however, why hydrogen should not be distributed in the same way that natural gas is distributed today: by underground pipelines that reach most industries and more than 80 percent of the homes in this country.

Before weighing the merits of the hydrogen-economy concept, it is instructive to consider the alternative: the all-electric economy. Suppose for a mo-



HYDROGEN ENERGY ECONOMY would operate with hydrogen as a synthetic secondary fuel produced from water in large nuclear or solar power stations (*left*). The hydrogen would be fed into a nationwide network of underground transmission lines (*center*), which would incorporate facilities for storing the energy, either in the form of hydrogen gas underground or in the form of liquid hydrogen aboveground. The hydrogen would then be distributed as it is needed to energy consumers for use either as a direct heating fuel, as a raw material for various chemical processes or as a source of energy for the local generation of electricity (*right*).

ment that one does not consider synthesizing a secondary chemical fuel; then one must face the prospect of generating and transmitting very large quantities of electricity. To meet the rising demand for electricity in the U.S. new generating stations are already being constructed in sizes larger than ever before. A few years ago a 500-megawatt power station was considered a giant. Today 1,000-megawatt stations are typical, and the electrical industry is contemplating 10,000-megawatt installations for the future.

In spite of the intensive efforts of their designers, the efficiency of steam-driven electric-power stations is still fairly low: about 40 percent for a modern fossil-fuel plant and 33 percent for a nuclear plant [see "The Conversion of Energy," by Claude M. Summers; Scientific American, September, 1971]. As a result the waste heat released from these large plants, or clusters of plants, is considerable. Accordingly they must be located near large bodies of water where ample cooling is available or in open country where cooling to the atmosphere will have no adverse local effects. Concern over the safety of nuclear reactors is also having a strong influence on the location of such plants. Because of these constraints the huge power stations of the future are likely to be built at distances of 50 miles or more from the load centers. Power stations located on offshore platforms floating in the ocean are already planned for the U.S. East Coast.

Power must be moved from the generating stations to the load centers. High-voltage overhead cables are expensive, in terms of both equipment costs and the land they occupy, and they are vulnerable to storm damage. Moreover, the electrical industry is encountering considerable resistance to the continued stringing of overhead power-transmission lines in many areas. Underground cables for carrying bulk power cost at least nine times (and sometimes up to 20 times) as much as overhead lines and thus are far too expensive to be used over long distances. Underground transmission is used only where the expense is justified by other considerations, such as aesthetic appearance or very expensive right-of-way. Much work is being done to develop cryogenic superconducting cables, which would allow large currents to be carried underground at a reasonable cost. At present, however, the technology is still at an early stage of development.

Some form of electrical storage would be of great value to the electrical industry, because power stations work most efficiently when operated at constant output at their full rated load. Since consumer demand varies widely both seasonally and during the day, however, the generating rate must be adjusted continuously. The only practical way available today to store large quantities of electrical energy is the pumped-storage plant, a reversible hydroelectric station; unfortunately only a limited number of sites are geographically suitable for such systems.

Thus it appears that several of the problems faced by the electrical industry—the siting of power stations, the expense of underground transmission and the lack of storage—are being amplified by factors that lead to larger and more remote power stations. The hydrogen-economy concept could help to alleviate these problems.

Hydrogen can be transmitted and distributed by pipeline in much the same way that natural gas is handled today. The movement of fuel by pipeline is one of the cheapest methods of energy transmission; hydrogen pipelining would be no exception. A gas-delivery system is usually located underground and is therefore inconspicuous. It also occupies less land area than an electric-power line. Hydrogen can also be stored in huge quantities by the very same techniques used for natural gas today.

Let us take a look at the existing gas-transmission network in the U.S. In 1970 a total mileage of 252,000 miles of trunk pipeline was in operation, carrying a total of 22.4 trillion cubic feet of gas during the year [*see illustration on pages 18 and 19*]. Such a pipeline system is eded because natural-gas sources are cated in certain parts of the country, hereas markets for the gas exist in other eas.

In the hydrogen economy hydrogen is would be produced from large nuear-energy (or solar-energy) plants loited in places that provide optimum oling and other environmental facilies. Even coal-fueled hydrogen generars, located close to the mine mouths, uld be integrated into this power-genation network. A pipeline transmission stem would grow up to link these locaons to the cities in a way analogous to e growth of the natural-gas transmison system.

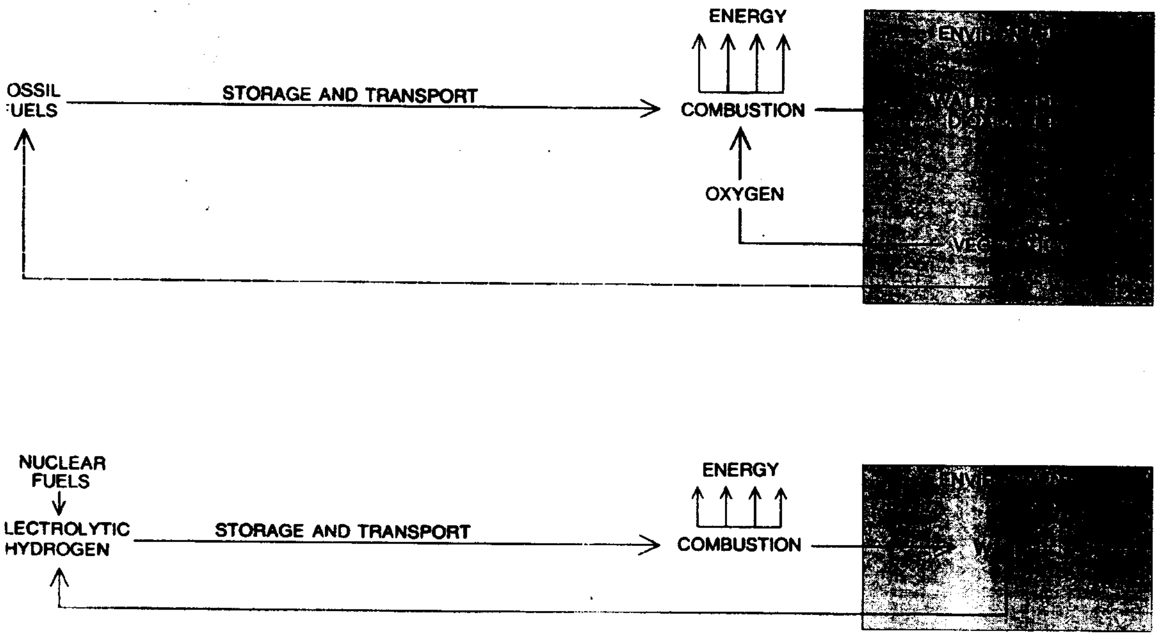
The technology for the construction id operation of natural-gas pipelines as been well developed and proved. A pical trunk pipeline, 600 to 1,000 miles ng, consists of a welded steel pipe up 48 inches in diameter that is buried nderground with appropriate protecon against mechanical failure and/or ectrochemical corrosion. Gas is pumped ong the line by gas-driven compressors aced along the line typically at 100-ile intervals, using some of the gas in e line as their fuel. Typical line presires are 600 to 800 pounds per square ich, but some systems operate at more than 1,000 pounds per square inch. A typical 36-inch pipeline has a capacity of 37,500 billion British thermal units (B.t.u.) per hour, or in electrical equivalent units 11,000 megawatts, roughly 10 times as much as a single-circuit 500-kilovolt overhead transmission line.

Natural gas is not the only gas to be moved in bulk pipelines, although no other gas is moved on such a scale. Carbon dioxide, carbon monoxide, hydrogen and oxygen are all delivered in bulk by pipeline. So far industry has had no incentive to pipeline hydrogen in huge quantities over great distances, but where it now pipelines hydrogen over short distances it uses conventional natural-gas pipeline materials and pressures. There is no technical reason why hydrogen cannot be pipelined over any distance required.

Because of the lower heating value of hydrogen (325 B.t.u. per cubic foot compared with about 1,000 B.t.u. per cubic foot for natural gas) three times the volume of hydrogen must be moved in order to deliver the same energy. Hydrogen's density and viscosity are so much lower, however, that the same pipe can handle three times the flow rate of hydrogen, although a somewhat larger compressor energy is required. Thus where existing pipelines happen to be suitably located, they could be converted to hydrogen with the same energy-carrying capacity.

In the hydrogen economy it will be possible to store vast quantities of hydrogen to even out the daily and seasonal variations in load. Natural gas is stored today in two ways: in underground gas fields and as a cryogenic liquid. At 337 locations in the U.S. natural gas is stored in underground porous-rock formations with a total capacity of 5,681 billion cubic feet. Whether hydrogen can be stored in underground porous rock can be finally ascertained only by future field trials. At present, however, 30 billion cubic feet of helium, a low-density gas with leakage characteristics similar to those of hydrogen, is stored quite satisfactorily in an underground reservoir near Amarillo, Tex.

Cryogenic storage of natural gas is a rapidly growing technique; at 76 locations in the U.S. "peak shaving" operations involving liquefied natural gas are in use or under construction. There is no technical reason why a similar peak-shaving technique cannot be employed with liquid hydrogen. Liquid hydrogen used to be considered a hazardous laboratory curiosity, but it is already being used as a convenient means of storing



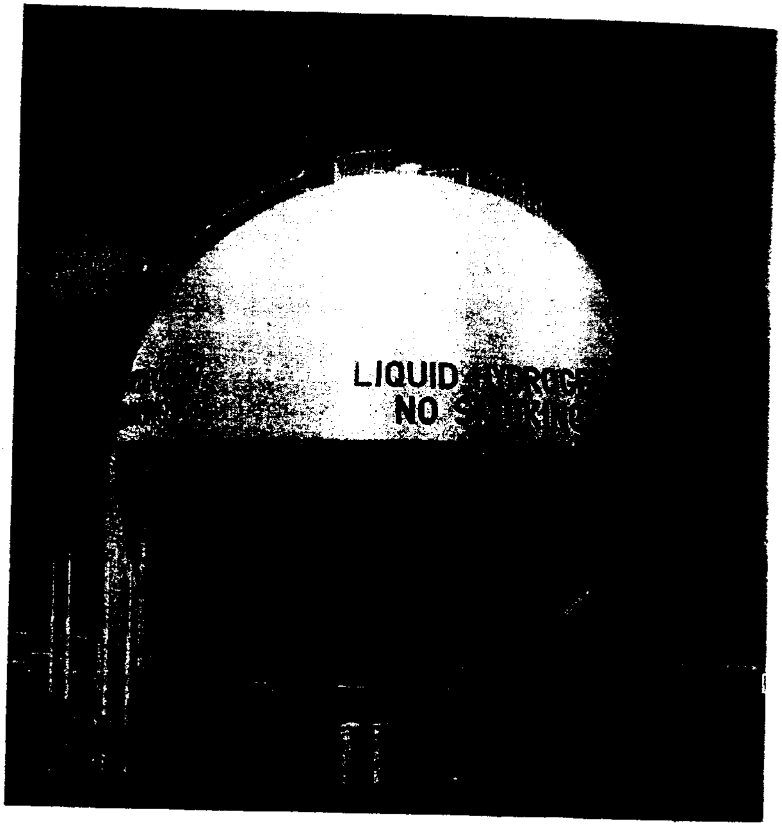
NVIRONMENTAL EFFECTS of the present fossil-fuel energy ycle and the proposed hydrogen-fuel energy cycle are compared iere. When fossil fuels are burned to release their stored energy *top*), the environment is relied on to accommodate the combusion by-products. The re-formation of the fossil fuels from atmospheric carbon dioxide takes millions of years (*broken line*). On the other hand, when hydrogen is burned as a fuel (*bottom*), the only combustion product is water, which is easily assimilated by the environment. The fuel cycle is completed rapidly without depleting limited resources or accumulating harmful waste products.

and transporting hydrogen over long distances. Liquid hydrogen is regularly shipped around the U.S. in railroad tank cars and road trailers. The technology for the liquefaction and tankage of hydrogen has already been developed, mainly for the space industry. Indeed, the largest liquid-hydrogen storage tank is at the John F. Kennedy Space Center; it has a capacity of 900,000 gallons, equivalent to 37.7 billion B.t.u. or 11 million kilowatt-hours [*see illustration at right*]. Although the energy content of this tank is only about 4 percent of the energy content of a typical liquid-natural-gas peak-shaving plant, its energy capacity is 73 percent of the capacity of the world's largest pumped-storage hydroelectric plant, located at Ludington, Mich.

The cryogenic approach to energy storage has the advantage of being applicable in any location, no matter what the geography or geology, factors that limit both underground gas storage and pumped hydroelectric storage.

The simplest way to manufacture hydrogen using nuclear energy is by electrolysis, a process in which a direct electric current is passed through a conductive water solution, causing it to decompose directly into its elementary constituents: hydrogen and oxygen. Complete separation of the two gases is achieved, since they are evolved separately at the two electrodes. Salts or alkalis, which have to be added to the water to increase conductivity, are not consumed; thus the only input material required is pure water.

A number of large-scale electrolytic hydrogen plants are operated today in locations where hydrogen is needed (for example in the manufacture of ammonia and fertilizers) and where cheap electric power (usually hydroelectric power) is available. One of the largest commercial electrolyzer plants in the world is operated by Cominco, Ltd., in British Columbia [*see illustration on page 20*]. This plant consumes about 90 megawatts of power and produces about 36 tons of hydrogen per day for synthesis into ammonia. The by-product oxygen is used in metallurgical processes. Similar large plants are located in Norway and Egypt. Many smaller plants exist where hydrogen is produced from unattended equipment.



ENERGY STORAGE in the form of liquefied hydrogen is already a routine practice in th space industry. This vacuum-insulated cryogenic tank at the John F. Kennedy Space Center for example, contains 900,000 gallons of liquid hydrogen for fueling the Apollo rockets. I is the largest facility of its kind in existence. In terms of energy its contents are equivalen to 37.7 British thermal units (B.t.u.) of heat or 11 million kilowatt-hours of electricit

The theoretical power required to produce hydrogen from water is 79 kilowatt-hours per 1,000 cubic feet of hydrogen gas. In practice the large industrial plants are only about 60 percent efficient; a typical power-consumption figure is 150 kilowatt-hours per 1,000 cubic feet of hydrogen. This power requirement represents a major part of the plant's operating cost. Thus there is a considerable incentive—indeed, a real need—to increase the operating efficiency of such plants if one is to consider using electrolytic hydrogen as a fuel.

The fuel cell, the subject of intensive research and development as part of the space program over the past 15 years, is really an electrolyzer cell operating in reverse. The simplest fuel cell to build and operate is one that operates on hydrogen and oxygen, yielding water and electric power as its products. Hydrogen-oxygen fuel cells were selected and developed for both the Gemini and the Apollo programs because of their high efficiency, which reduces the amount of fuel needed aboard the spacecraft to supply its electric power. Much effort has gone into developing fuel cells with high efficiencies. This same technology can be applied to increase the efficiency of the reverse process: electrolysis. Electrolytic cells are operating in aerospace laboratories today with an efficiency of more than 85 percent.

Increasing the electrolyzer efficiency alone has relatively little merit as long as the present power-station efficiency in converting nuclear heat to electric power is only about 33 percent. This efficiency loss can, however, also be circumvented. For example, Cesare Marchetti at the Euratom laboratories in Italy has designed a chemical process for the thermal splitting of water to hydrogen and oxygen directly using the heat energy produced by a nuclear reactor. If water is to be split into its elements directly, it must be heated to very high temperatures—about 2,500 degrees Celsius—to achieve dissociation. Not only are such temperatures not available from nuclear reactors but also the gases cannot conveniently be separated from each other before they recombine. It is possible to conceive of a two-stage reaction in which a metal, say, reacts with steam at a reasonable temperature to produce hydrogen and a metal oxide. The hydrogen is easily separated from the metal oxide, which in turn could be decomposed to oxygen and the metal by the application of heat. Unfortunately there does not appear to be any suitable metal that undergoes such a series of reactions at temperatures low enough to be compatible with nuclear reactors, whose construction materials limit operating temperatures to about 1,000 degrees C.

Marchetti's concept, therefore, is a far more complex reaction sequence involving calcium bromide ($CaBr_2$), water (H_2O) and mercury (Hg), in which, except for the hydrogen and oxygen, all the reactants are recycled. Each of the reactions proceeds at temperatures below 730 degrees C., which can be achieved in a nuclear reactor. Although the process appears to be feasible, development work is still required to try to bring the overall efficiency up and the cost down to practical limits.

The quantities of hydrogen that the hydrogen economy would require are immense. For example, if we were to produce today an amount of hydrogen equivalent to the total production of natural gas in the U.S., we would have to provide during one year the same fuel value as 22.5 trillion cubic feet of gas, or 22.5 quadrillion (10^{15}) B.t.u. of energy. This corresponds to about 70 trillion cubic feet of hydrogen, which, if we could produce it at a steady rate all year round from nuclear electrolytic plants, would require an electrical input of more than a million megawatts. The present total electrical generating capacity in the U.S. is 360,000 megawatts, so that we are envisioning a fourfold increase in generating capacity, which would require the construction of more than 1,000 new 1,000-megawatt power stations. That is in addition to the rapidly increasing demand for electric power for other uses. During the past five years, in contrast, the electrical generating capacity in the U.S. has grown by "only" 105,000 megawatts.

Such a formidable task of increasing capacity, however, does not follow solely from our turning to a hydrogen economy. As our huge consumption of fossil fuels declines in future years, we must provide at least an equivalent alternative energy source. Such numbers give a taste of the energy revolution that must take place within the next half-century.

At present the cheapest bulk hydrogen is made from natural gas. Clearly since hydrogen from such a source cannot be cheaper than the starting material, it cannot therefore be expected to replace natural gas as a fuel. Electrolytic hydrogen is even more expensive, unless very cheap electric power is available. Today's electricity prices are based on supplying a fluctuating load, but the capability of hydrogen storage would even out the load and might reduce the price of electricity somewhat.

Although the cost of hydrogen produced from electricity must always be higher than the cost of the electricity, it is the lower transmission and distribution cost of hydrogen compared with electricity that makes it advantageous to the user. The latest economic figures published by the gas and electrical industries can be used to derive the production, transmission and distribution shares of average prices, charged to all types of customers, for gas and electricity, and these data can be compared in turn with corresponding figures for hydrogen made by electrolysis [*see illustration on page 21*]. The figures for hydrogen are derived from the hypothetical assumption that all the electricity generated in the U.S. in 1970 was converted to hydrogen, which was sent through the existing natural-gas transmission network (for an average distance of 1,000 miles) and was delivered to customers as a gaseous fuel. The electrolysis charge of 56 cents per million B.t.u. is derived from AEC estimates of the cost of building advanced electrolyzer cells. The hydrogen transmission and distribution costs are based on natural-gas costs, adjusted to take account of the different physical properties and safety factors for handling hydrogen.

Two things are obvious from such a comparison. One is that today it is far cheaper for the average customer to buy energy in the form of natural gas than it is in the form of electricity. The other is that it should already be possible to sell hydrogen energy to the gas user at a lower price than he now pays for electricity. Clearly, however, this hydrogen will find no markets while natural gas is as cheap as it is.

Looking to the future, we see that natural-gas prices, together with all fossil-fuel prices, will increase rapidly. These rises are brought about by their short supply, by the influence of pollution regulations and by such social pressures as land conservation and employee welfare applied to the mining industry. In contrast, the price of nuclear energy, although apparently rising fast now, can be expected to stabilize somewhat in the breeder-reactor era because there will then be no severe supply limit.

It is not possible at this time to forecast accurately what the cost of hydrogen energy is likely to be, but one can certainly look forward to considerably increased prices for all forms of energy. Even so, in the long run delivered hydrogen will be cheaper than delivered natural gas and very probably also cheaper than delivered electricity.

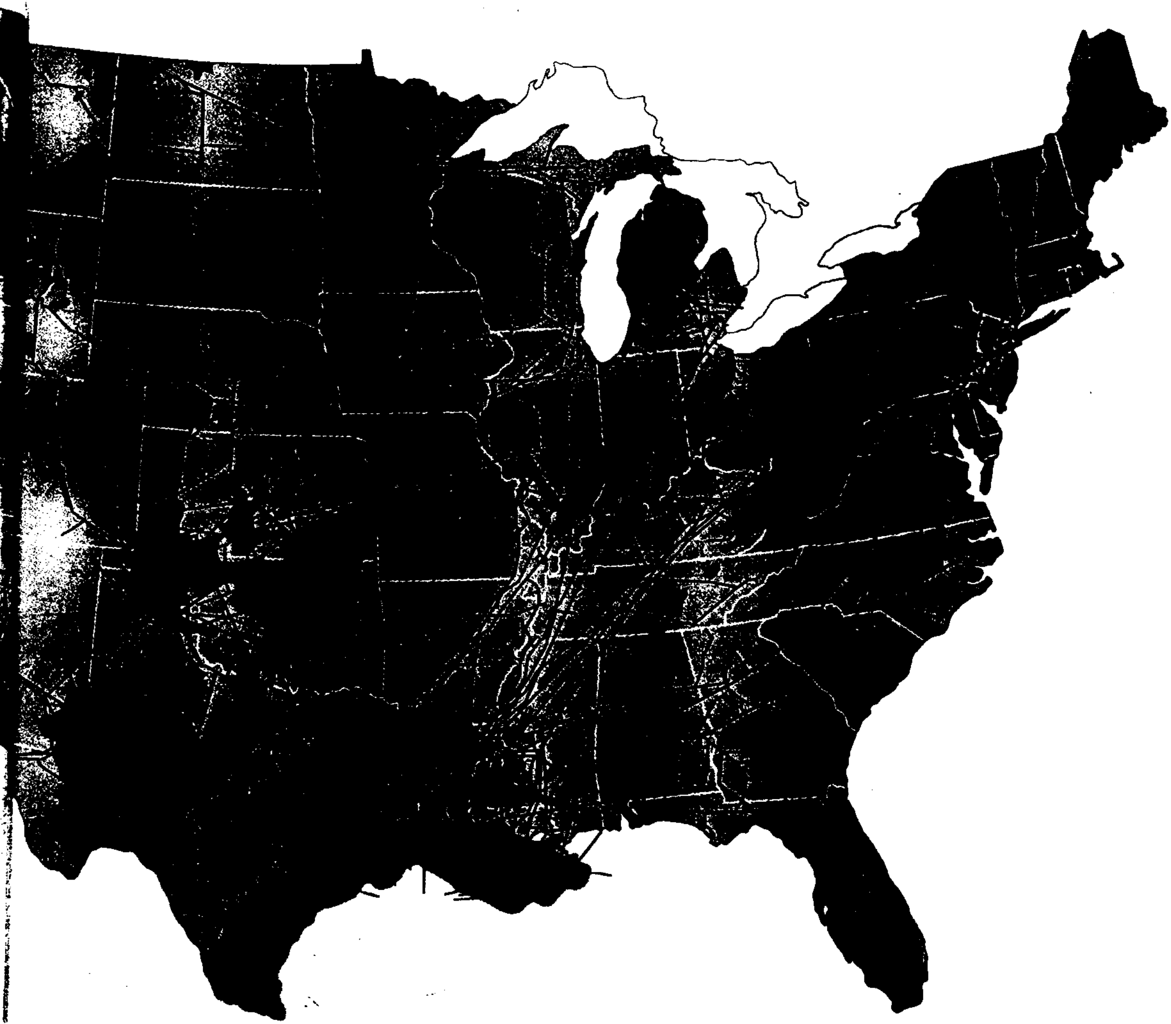
When hydrogen becomes as universally available as natural gas is today, it will easily perform all the functions of natural gas and others besides. Hydrogen can be used in the home for cooking and heating and in industry for heating; in addition it can serve as a chemical raw material in many industries, including the fertilizer, foodstuffs, petro-

TRUNK PIPELINES extending for 252,000 miles (*black lines*) already exist in the U.S. for transmission of natural gas from areas chemical and metallurgical industries. Hydrogen can also be used to generate electricity in local power stations.

The combustion properties of hydrogen are considerably different from those of natural gas. Hydrogen burns with a faster, hotter flame, and mixtures of hydrogen with air are flammable over wider limits of mixture. These factors mean that burners of hydrogen must be designed differently from those of natural gas and that modification of every burner will be necessary on changeover. Such widespread modification is not without precedent. A similar operation was carried out when the U.S. changed from manufactured gas (about 50 percent hydrogen) to natural gas; several European countries have recently undertaken the same conversion.

Hydrogen, because it burns without noxious exhaust products, can be used in an unvented appliance without hazard. Hence it is possible to conceive of a home heating furnace operating without a flue, thereby saving the cost of a chimney and adding as much as 30 percent to the efficiency of a gas-fired home heating system. More radical changes are possible, moreover, because without the need for a flue the concept of central heating itself is no longer necessary. Each room can have its heat supplied by unflued peripheral heating devices operating on hydrogen independently of one another. Indeed, the vented water vapor would provide beneficial humidification. Another radical change is the potential use of catalytic heaters. Since hydrogen is an ideal fuel for catalytic combustion, true "flameless" gas heating is possible, with the catalytic bed being maintained at any desired temperature, even as low as 100 degrees C. This prospect promises to revolutionize domestic heating and cooking techniques in the future. With such low temperatures it is virtually impossible to produce nitrogen oxides, thus eliminating the only possible pollutant from a hydrogen system.

Hydrogen is also the ideal fuel for fuel cells. The technological problems that have faced the development of practical, commercially economical fuel cells for

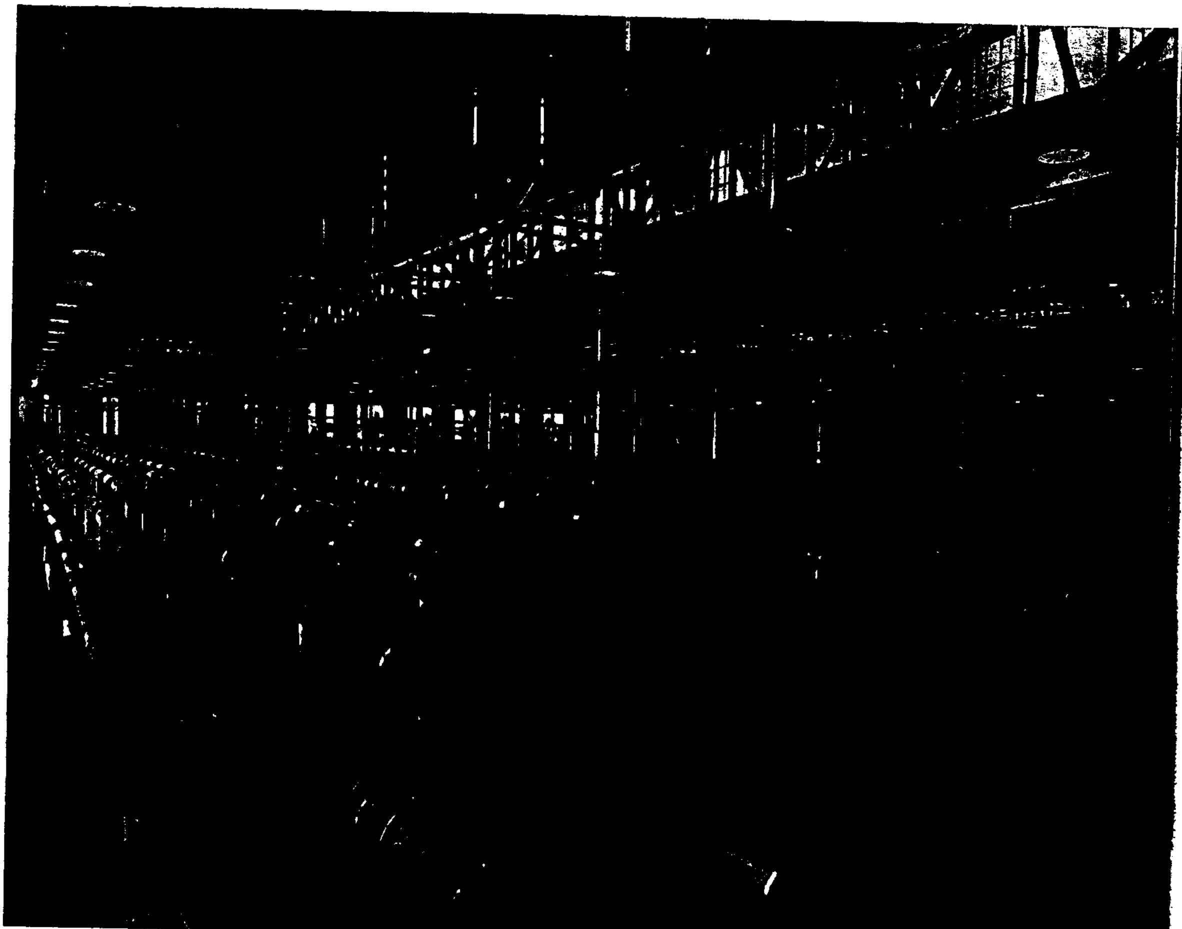


here the gas is produced (*gray*) to areas where it is consumed. he system, which is constructed almost entirely of welded steel ipe, carries approximately 61.4 billion cubic feet (or 1.5 million tons) of natural gas per day. Similar networks of underground hydrogen-gas pipelines would enable the giant nuclear (or solar) power stations of the future to be located far from the load centers.

more than a decade are very much reduced if hydrogen can be used as fuel. Fuel-cell electricity generators operating on hydrogen should be at least 70 percent efficient and can realistically be expected to find a place in the home, in commercial and industrial buildings and in industry. Larger, urban electrical generating stations could be fuel-cell systems or could be hydrogen-fueled steam stations. An earlier concept of operating a closed-cycle steam-turbine system on a hydrogen-oxygen fuel supply could become practical through the use of rocket-engine technology. Workers at the Massachusetts Institute of Technology have proposed such a system for submarines; it has been reported that an overall efficiency of 55 percent can be anticipated from it.

Hydrogen is an excellent fuel for gas-turbine engines and has been proposed as a fuel for supersonic jet transports. For this kind of use fuel storage and tankage as liquid hydrogen are practical. Although the large volume required may make its use less attractive for subsonic aircraft, the very considerable saving in weight over an equivalent fuel load of kerosene gives hydrogen a distinct advantage. Conventional internal-combustion engines will also operate on hydrogen if they are suitably modified or redesigned. R. J. Schoeppel of Oklahoma State University and others have shown that if hydrogen is injected into the engine through a valve in a manner similar to the way fuel is injected into a diesel engine, the preignition characteristics of hydrogen are overcome. Others, including Marc Newkirk of the International Materials Corporation and Morris Klein of the Pollution Free Power Corporation, have reported satisfactory operation of conventional automobile engines on hydrogen using carburetor and manifold modifications. Meanwhile William J. D. Escher of Escher Technology Associates has proposed a radically different approach to automobile engine design, using a steam system fueled by both hydrogen and oxygen. The use of liquid hydrogen as a routine private-automobile fuel is questionable on the ground of safety, although it is probably applicable to fleet users, such as bus lines and taxicab fleets.

Richard H. Wiswall, Jr., and James J. Reilly of the Brookhaven National Laboratory have proposed the use of metallic hydrides to store hydrogen as a fuel for vehicles. A magnesium-alloy hydride will store hydrogen energy as efficiently (on a weight basis) as a tank of liquid hydrogen, but some technical problems must still be overcome. At present there seems to be no single, obvious way in which automobiles can be operated on hydrogen fuel, but considerable work is



LARGE ELECTROLYZER PLANT for the production of hydrogen by the electrical decomposition of water is operated by Cominco, Ltd., in British Columbia. The 3,200 electrolytic cells, which cover more than two acres, consume about 90 megawatts of power and produce about 36 tons of hydrogen per day for synthesis into ammonia. By-product oxygen is used in metallurgical processes.

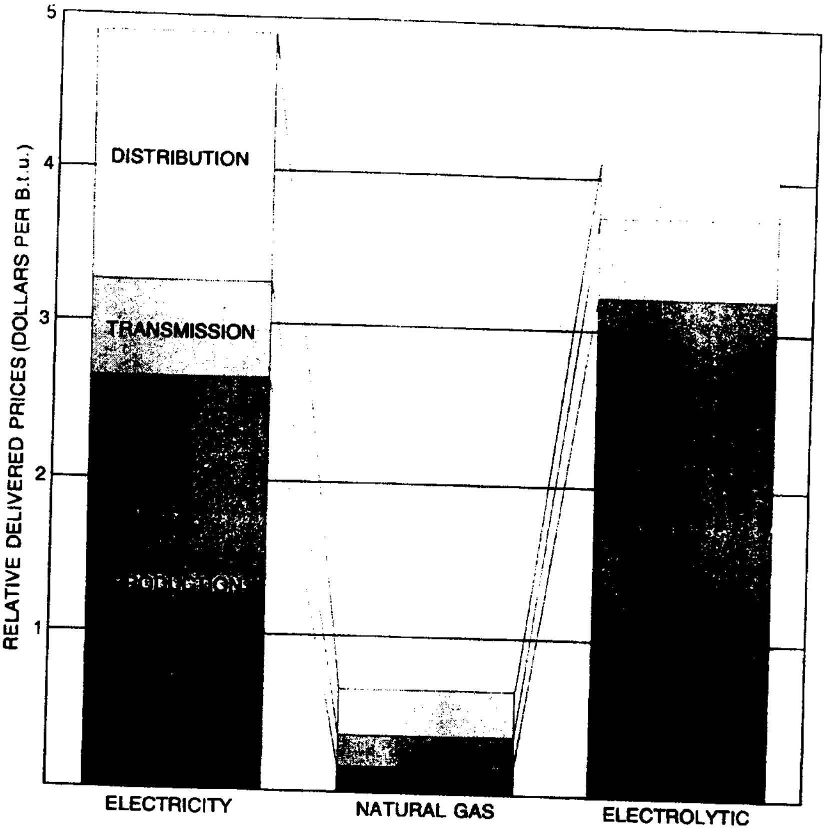
going on to investigate the various options available. If one has to synthesize a suitable liquid fuel for automobiles and aircraft, the starting material for the fuel must be hydrogen in any case.

One of the main criticisms of the hydrogen-economy concept is that hydrogen is too dangerous for use in this way. Undoubtedly hydrogen is a hazardous material and must be handled with all due precautions. If it is handled properly, however, in equipment designed to ensure its safety, anyone should be able to use it without hazard.

In the days of manufactured gas (gas made from coal), which consisted of up to 50 percent hydrogen and contained about 7 percent carbon monoxide, people managed to live with the fire and explosion hazards of hydrogen as well as the toxic hazards of carbon monoxide. Of course, it takes only one major disaster to alert everyone to a hazard. The most famous hydrogen accident, the *Hindenburg* airship disaster of 1937, is still remembered with awe. Indeed, the almost universal fear of hydrogen has been described as the "*Hindenburg* syndrome." Spectacular as it was, however, that fire was almost over within two minutes, and of the 97 persons on board, 62 survived.

Very strict codes are enforced for the use of natural gas today; even stricter ones are applied to industry for the use of hydrogen. Most of these codes are realistically based on reducing the chances of accidents. Just as we have designed apparatus and procedures to enable us to fill our automobile tanks with gasoline and carry the resulting 20-gallon "fire bomb" at speeds of up to 70 miles per hour along a crowded highway and park it overnight right inside our homes, we can surely devise safe practices for handling hydrogen.

Hydrogen cannot be detected by the senses, so that a leak of pure hydrogen is particularly hazardous. Odorants are routinely used to make natural-gas leaks obvious, however, and no doubt the same can be done with hydrogen. Hydrogen flames are also almost invisible and are therefore dangerous on this score. Hence an illuminant may have to be added to the gas to make the flame visible. The flammability limits of hydrogen mixed with air are very wide, from 4 to 75 percent. It is the lower limit, almost the same as that for methane (5 percent in air), that causes the fire hazard with a gas leak. On the benefit side, however, since hydrogen is so much lighter than air and diffuses away at a far greater rate than methane, a hydrogen leak could actually be less hazardous than a natural-gas leak. The most significant hazardous property of hydrogen is the extremely low energy required to ignite a flammable mixture: only a tenth of the energy required to ignite a gasoline-air mixture or a methane-air mixture and well within the energy levels of a spark of static electricity (a probable cause of the *Hindenburg* fire, which occurred just after a thunderstorm). Thus safety practices will have to be based on the assumption that if a hydrogen fire can occur, it will! Huge quantities of hydrogen are handled in industry quite safely and without accident precisely because proper precautions are taken.



RELATIVE DELIVERED PRICES of various forms of energy are broken down in this bar chart into the shares represented by production (*solid color*), transmission (*intermediate color*) and distribution (*light color*). The comparison reveals that at present it is much cheaper to buy energy in the form of natural gas than in the form of electricity. Moreover, the breakdown shows that although the cost of hydrogen produced from electricity must always be higher than the cost of the electricity, the lower transmission and distribution costs of hydrogen already make it possible to sell hydrogen energy to the gas user at a delivered price lower than what he now pays for electricity. It is expected that natural-gas prices, together with all fossil-fuel prices, will increase rapidly in the future.

To recapitulate briefly, our recoverable fossil-fuel supplies will sooner or later become exhausted; we are already feeling the effects of the limited supply by having to pay more for fossil-based energy. Within the next 50 years we must be prepared to pay considerably more for energy from all sources, particularly for fossil fuels. One way of handling nuclear and other energy sources is to use them to convert water to hydrogen in large central plants and then to use hydrogen as a clean, nonpolluting fuel. Technically this is already feasible; only relatively simple developments have to be made, not approaching the magnitude of the technical tasks of developing the alternative energy sources—breeder reactors and solar engines—themselves. Economics and safety are the two obstacles to developing such a hydrogen economy. A combination of technical development and the expected adjustment in relative energy prices can justify the economics, and proper practices and design can ensure safety. If and when we move into a hydrogen economy, the world will undoubtedly be a far cleaner place to live in than it is today.