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THE FUTURE ROLE OF HYDROGEN FUEL IN AN ELECTRICAL SOCIETY

by

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Summary

Present trends indicate that the use of electrical energy is growing faster than the consumption of other forms of energy and that many nations are becoming "electrical societies". As fossil fuels become depleted and new forms of energy are introduced, this trend is expected to accentuate (see The Race for Unlimited Energy by G. N. Patterson - Ref. 1). In such a society, can electrical energy meet all the requirements? A study of this question indicates that there is still a need for an abundant chemical fuel that is technically feasible, environmentally acceptable, and economically viable.

This review suggests that hydrogen is the universally available fuel that best meets these requirements: its technology is already reasonably well understood; effluents and products of combustion that are not easily assimilated into the environment are minimal; safe procedures for its use are in an advanced state of development; hydrogen fuel will become economically competitive relative to alternatives as fossil fuels become more expensive and scarce. It is expected that in the future hydrogen will play a major role as a peakshaving medium at electric power plants, as a fuel for transportation, and as a diversely-used feedstock for industry. The manufacture, storage, and use of hydrogen for peakshaving purposes, vehicular power plants, and as a chemical raw material are discussed and programs for future development are indicated. It is concluded that plans for the future use of hydrogen on a large scale should be initiated now.

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INTRODUCTION

As shown in Ref. 1, the production of fossil fuels (coal, oil, gas) will parallel escalating demand until high costs relative to those of other alternative sources, reflecting a growing scarcity of reserves, cause it to falter and then begin an irreversible decline. Estimated depletion dates (Ref. 1) suggest that, from the points of view of environmental impact, economic viability, and available resources, fossil fuels will be essentially unavailable by about the middle of the next (21st) century. Accordingly, national economies must shift from expendable fossil fuels to new, "inexhaustible" sources of energy in such a way that reasonable demand will be met without interruption. A fundamental question is: In what form is this energy to be delivered to the consumer?

The use of electrical energy is growing at more than twice the rate at which the overall use of energy is increasing. As pointed out in Ref. 1, increasing reliance on new, nonfossil sources of energy (nuclear, geothermal, solar, etc.) will encourage this trend; the "electrical society" will draw ever closer. The answer to the above question is, therefore: In the future energy will be supplied more and more in the electrical form. But forecasts of future trends go a step further: Nuclear plants will carry the main responsibility for the supply of electric power. Hence another basic question is: Can nuclear electrical energy meet all requirements, directly or indirectly?

In the fossil-fuel era we became accustomed to fuels that were readily available, storable, and transportable. We took for granted that the tank of an automobile could be filled anytime, that the gasoline was stored for our use as required, and that it could be transported according to our travel plans. Can an all-electric economy meet these requirements? Despite the considerable effort expended in the development of rechargeable batteries, their use in high-performance vehicles such as cars, trucks, trains, ships is still not feasible. Electrically powered aircraft are not considered to be a likely prospect. It is evident that a nonfossil, chemical fuel must be available in the nuclear-electric age for transportation.

A nonfossil chemical fuel is needed for another important reason. Nuclear plants operate most economically at a constant power level, yet they are required to meet the variable demand of the load centres. The oversizing of nuclear power plants to meet peak demand can be avoided by designing them for a constant power output below the peak level to operate in conjunction with an energy storage system using a chemical fuel manufactured by the nuclear plant during periods of low demand. The storage system could be designed to provide fuel not only for peak period electricity but also for insurance against temporary shutdown and for cars, trains, ships, airplanes.

The purpose of this report is to recommend a nonfossil chemical fuel that best meets the requirements of technical feasibility, environmental control, economic viability, and available, inexhaustible, indigenous resources, and to outline the future programs needed to bring on stream this substitute for depleting fossil fuels.

HYDROGEN FUEL

The prime criteria for a chemical fuel to replace fossil fuels are that it must be technically feasible, environmentally acceptable, economically viable, and available in unlimited quantity. A proposed fuel must be readily manufactured at a nuclear plant; it must be free of effluents and products of combustion that are not acceptably assimilated into the environment; it must be supplied to the user at prices that compare favourably with the costs of alternatives; it must be available from abundant materials. An assessment of these criteria suggests that only constituents of the waters of the earth and its atmosphere should be considered as basic materials.

It is technically feasible to produce hydrogen from water, ammonia from hydrogen and nitrogen, hydrazine from ammonia and nitrogen, and methanol and other hydrocarbons from hydrogen and carbon dioxide in the air. Of these possible fuels, we note that hydrogen is the easiest to make and that it must be available for the manufacture of the other alternatives; if any of these synthetic fuels are adopted, the large-scale production of hydrogen is always a prerequisite. Technical feasibility suggests, therefore, that the use of "plain" hydrogen is preferable (Ref. 2).

An assessment of the environmental impacts of these various fuels shows that hydrogen is the cleanest of all fuels. Combustion of hydrogen in air produces only water vapor if the formation of nitrogen oxides is prevented by maintaining a low (catalytic) temperature. But environmental hazards associated with the utilization of hydrogen do require particular attention.

Hydrogen is not commercially competitive with fossil fuels at present because of high production costs, but as fossil fuels become relatively more costly, owing to depletion, hydrogen fuel will become more economically viable.

An overwhelming case can be made for selecting hydrogen as the chemical fuel of the future:

(1) All primary energy sources (nuclear, geothermal, direct and indirect solar energy, tidal power) can be used to produce hydrogen by the electrolysis of water; where a heat cycle is available, thermochemical processes may be possible.

(2) Hydrogen can be readily stored on a large scale as a gas or cryogenic liquid.

(3) Hydrogen can play an important role in transportation; both piston and gas-turbine engines operate satisfactorily on hydrogen; the prospects are good that hydrogen can be stored, transported, and handled on a small scale as required for automobiles, trains, ships, aircraft.

(4) Hydrogen can be used in three different modes to produce the shaft power needed to generate electricity: by combustion in air to drive a conventional engine (reciprocating engine, gas turbine, steam engine); by direct reaction with oxygen and injection of water to produce steam at any desired temperature and pressure; by direct electrochemical conversion in a fuel cell from hydrogen to electricity.

(5) Hydrogen is an effective substitute for nearly all fuel uses; it can be used in place of natural gas for all present applications.

(6) Hydrogen is a precursor for other chemical fuels and food products; as an industrial chemical, it already plays a significant role in the marketplace.

A useful comparison of the properties of hydrogen, methane, and gasoline is given in Table 1.

Table 1

Comparison of the Properties of Hydrogen, Methane, and Gasoline

	Hydrogen	Methane	Gasoline
Heat of combustion (low heating value, Joules/gm)	120,000	50,000	44,000
Density (liquid, gm/cu cm)	0.071	0.424	0.702
Boiling point (Celsius)	-253	-162	+125
Relative fuel to equal hydrogen heat content:			
(1) by weight	1.0	2.4	2.6
(2) by volume (liquid)	1.00	0.43	0.26

Let us summarize. It has been indicated (see Introduction) that in many nations electrical energy will continue to grow faster than other energy forms and that the new primary sources (nuclear, geothermal, direct solar, biomass, hydro, wind, tidal), which will replace fossil fuels in the long term, will encourage this trend. We have seen also that direct electrical energy cannot meet our requirements entirely and that a chemical fuel is required for transportation and as a medium for the storage of electrical energy. It has become apparent that a strong case can be made for adopting hydrogen as the chemical fuel to serve these purposes; hydrogen is an inexhaustible, "universal" fuel that can effectively replace fossil fuels as they become expensive and scarce.

We now examine in detail the technical feasibility, environmental impact, and economic viability of hydrogen, keeping in mind that many nations are becoming essentially electrical societies; that is, they will not likely adopt a "complete hydrogen economy" but will depend to a limited extent only on hydrogen fuel (Refs. 1, 2).

TECHNICAL FEASIBILITY

The technical feasibility of the production, storage, and utilization of hydrogen fuel must be established before it can be seriously considered as a long-term substitute for fossil fuels.

PRODUCTION

In some countries the primary concern in the long term will be with the production of hydrogen fuel from nuclear plants, generated by electric power or directly by reactor thermal energy without the use of fossil fuels in any form. Because nuclear power plants require large-scale cooling systems, they are usually sited along the shorelines of large bodies of water. An abundant source of hydrogen is available, therefore, and we can turn our attention to the technical feasibility of splitting water into hydrogen and oxygen using nuclear energy.

Water can be separated into its elements, hydrogen and oxygen, by the injection of an amount of energy equivalent to the combustion energy of hydrogen. The required energy for separation can be supplied in three ways:

(1) Electrolysis, in which a direct current is passed between two electrodes immersed in an electrolyte, for example, a solution of potassium hydroxide;

(2) Thermal decomposition, in which considerable heat is applied to form the hydrogen and oxygen, which must then be separated out;

(3) Thermochemical decomposition, in which a sequence of chemical reactions forms products that can be thermally decomposed, but the heat is somewhat below that required for direct thermal decomposition.

The electrolysis of water is the only process currently available; large-scale electrolysis plants exist in many parts of the world to produce hydrogen for the ammonia and fertilizer industries. Research on the thermal and thermochemical processes is in progress; these investigations show promise of higher efficiencies because the nuclear reactor heat is used directly and the inefficiency of producing electricity as an intermediate stage is avoided.

In water electrolysis the reaction is

$$H_2O \text{ (liquid)} + \text{energy input} \rightarrow H_2 \text{ (gas)} + \frac{1}{2} O_2 \text{ (gas)}$$

Since the hydrogen forms at the cathode (negative electrode) and the oxygen at the anode (positive electrode), separation is inherent in the process. The energy input to promote this reaction is the change in heat content (enthalpy) needed to produce the required change of state. It should be noted that only part of this energy input must be supplied as electrical energy because, theoretically, the remainder can be provided as thermal energy from the surroundings or from the thermal energy generated by electrical losses. In general the performance of the process improves as the temperature increases.

The electrical efficiency of the electrolysis process is given by the ratio

$$\frac{\text{Heating value of } H_2 \text{ output}}{\text{Electrical energy input}}$$

Commercial electrolysis plants currently develop electrical efficiencies between 57% and 72%. More advanced processes can operate at efficiencies up to 85%; electrical efficiencies greater than 100% are possible if the cell is operated in an endothermic (heat absorbing) mode in which thermal energy from the surroundings is also supplied. This is not accounted for in the definition of electrical efficiency. It should be emphasized that the overall efficiency of hydrogen production by electrolysis is limited not only by the efficiency of the process itself (85% - 100%) but also by the efficiency of conversion of reactor thermal energy to electrical energy (30% - 40%).

At a given electrical efficiency, the specific power consumption is directly proportional to cell voltage. The design and operational characteristics of a cell are selected to achieve a minimum cell voltage consistent with low capital and maintenance costs and a long service life.

Two major types of electrolyzer are commercially available, classified according to their construction: a uni-polar (tank type) electrolyzer, and a bi-polar (filter-press type) electrolyzer. Both types have an electrical efficiency of close to 100%.

The uni-polar electrolyzer consists of an assembly of large iron tanks, each containing an alkaline electrolyte in which a number of electrodes of alternate polarity are suspended. Each tank operates as one cell. Electrodes of the same polarity are connected in parallel, and hence a uni-polar cell operates at low voltage (2 volts), equivalent to that of one pair of electrodes, and at high current. This design requires special attention to electrical rectification. An assembly of these cells, connected in series, facilitates repair since one cell can be by-passed without interrupting the production of hydrogen. Commercial uni-polar electrolyzers have a life of some 25 years and can be maintenance-free for 10 years or more.

The bi-polar electrolyzer contains alternate layers of electrodes and separating diaphragms, constructed in a similar way that a filter press is built. The electrodes are bi-polar; one side of an electrode is the cathode for one cell and the other side is the anode for the adjacent cell. Each pair of electrodes forms a separate cell. The electrodes are insulated from each other and connected in series. Individual cell voltages of approximately 2 volts each are additive; a bi-polar electrolyzer operates in the range 60-1200 volts DC, depending on output capacity, and at a low current. The bi-polar design eliminates bus bar connections, simplifies electrical rectification, and requires less floor space compared with the older uni-polar design, but production can be lost when repair or renovation is necessary.

Every design of electrolyzer has a unique investment/efficiency characteristic that must be considered for each individual project and optimized according to prevailing conditions at the site. A considerable capability for the design and manufacture of custom-built electrolyzers has existed in the United States, Canada, and Europe for many years.

The thermal decomposition of water into hydrogen and oxygen by the direct application of heat is termed "thermal water-splitting". When water is heated to about 4000°C, it will split to form hydrogen and oxygen which must be separated out before they recombine. This process is not presently applicable to conventional nuclear fission plants because maximum reactor temperatures are limited by materials of construction to the range 540°C to 700°C. Even if much higher reactor temperatures were available, such as in a nuclear fusion plant, it does not appear that envisaged improvements in heat-resistant materials will permit sufficiently high temperatures for direct thermal water-splitting.

Alternatively, the splitting of water into hydrogen and oxygen can be accomplished at a lower temperature through a sequence of chemical reactions — termed "thermochemical water splitting". Hydrogen and oxygen are among the products of the reactive sequences, and other products can be recycled within a closed system. No practical technology for thermochemical water splitting exists today, but multistep decomposition at 730°C has been demonstrated. This puts the process within the capability of high temperature nuclear reactors now being developed, but this operational temperature is still above the present capability of conventional thermal reactors. Nevertheless, this concept will continue to receive attention because of the promise of a higher overall efficiency for hydrogen production by the direct application of reactor heat as opposed to electrolysis which requires the generation of electricity as an intermediate stage.

STORAGE

An important characteristic of hydrogen fuel is that it can be readily stored as a gas or cryogenic liquid. In this section we consider the large-scale, on-site storage of hydrogen required for peakshaving at an electric power plant. The small-scale transportation storage of hydrogen fuel is discussed in the next section (Transportation).

The storage of electrical energy in some form at a power plant is needed (a) to match variations in consumption with the steady rate of power generation necessary to maintain a high efficiency, and (b) to facilitate temporary shutdowns and unpredictable, short-term fluctuations in demand. A storage system must meet seasonal, daily, and hourly needs; it must be capable of evening out over the whole year the seasonal variations caused by space heating in winter and air-conditioning in summer; it must be able to cope with the fluctuations in demand caused by changing needs between work days and weekends or by changing weather conditions from day to day; it must be available to cover peak demand periods on an hourly basis. The essential gain from such a storage system is that a power station needs to be sized to meet the average demand only and not to meet the maximum demand.

A facility for storing hydrogen on-site that first comes to mind is the high-pressure container. Special vessels or assembled lengths of pipe can be used. A possible technical problem to be monitored regularly is a tendency toward the embrittlement of steel containers by the action of hydrogen at very high pressures. Further problems may arise from the tendency of hydrogen to be more "leaky" than other gases such as natural gas. Both effects will limit the operating pressure and temperature. Workable design limits have been established; many high-pressure hydrogen containers and pipelines have been in successful operation in industry for many years.

The storage of liquefied hydrogen in spherical, vacuum-jacketed containers is already being done at Cape Kennedy where containers capable of storing 4 million litres (one million gallons) have been in use for some time as part of the U.S. space program. The spherical shape results from the requirement for vacuum-jacketed insulation. The materials used for the inner liner, such as stainless steel or aluminum alloys, must be compatible with liquid-hydrogen temperatures. Compared with natural gas, hydrogen requires about four times more heat extraction to produce a cryogenic liquid, and refrigeration processes operate at lower efficiency owing to the much lower temperatures involved (see Table 1). On the other hand, since from the nature of its manufacture hydrogen is "cleaner" than natural gas produced from a well, many cleanup steps needed to prepare natural gas for liquefaction can be eliminated in the case of hydrogen. In general, compared on an equal stored-energy basis, cryogenic hydrogen storage facilities will be significantly larger than those for liquefied natural gas.

Where it is geologically available, the underground storage of hydrogen gas has been shown to be feasible. Underground storage can make use of depleted gas and oil reservoirs in sedimentary formations, of aquifers in which hydrogen replaces the water in the pores of the sedimentary structure, and of mined caverns and salt cavities in which large void spaces are available. The caprock structures on top of a depleted field or aquifer operate as a seal because water fills the voids of the caprock and can be expelled only by the high pressure needed to overcome capillary resistance. Below this threshold pressure, the caprock is an effective seal against the escape of any gas. By contrast, mined caverns and salt cavities must be subjected to complex structural analysis to establish feasibility, and questions of leakage and dissolution in brine must be resolved.

Underground storage of natural gas in depleted fields is now used extensively in the United States; an aquifer has been utilized in France to store large volumes of coke-oven manufactured gas containing hydrogen for peak-storing purposes; the conversion of salt cavities for the storage of natural gas was initiated in the United States some twenty years ago. If sedimentary formations are not conveniently available to a power generating site, underground caverns produced by mining activities or naturally occurring salt domes should be given consideration.

Chemical storage of hydrogen as a binary with a metal is a concept for further study. The metal hydride involves a reversible reaction of hydrogen with such metals as magnesium-copper from which hydrogen can be liberated at a controlled rate by the application of heat at a moderate pressure. This heat is given off again when the metal bed is recharged and returns to the hydride form. The heat required is quite large — about 25% of the heating value of the hydrogen produced. Preliminary investigations of hydrides have indicated that a large number of binary and tertiary storage systems are available.

TRANSPORTATION

In the electrical society of the future, hydrogen is likely to be used mainly as a means for storing electrical energy for peakshaving requirements, as a fuel for transportation, and as a raw material for industry. The electric power plant will become a source of hydrogen fuel for automobiles, trucks, trains, ships, aircraft, and a feedstock for industry. Turning our attention now to transportation, it becomes immediately apparent that, if hydrogen is to have a role in transportation in the post fossil-fuel period, then we must be satisfied that (1) it has promising potential as a vehicle fuel, and (2) it can be handled, stored, and transported on a small scale.

It has been demonstrated that hydrogen fuel can be used to power conventional engines (reciprocating engines and gas turbines) with little modification. As a fuel for an internal combustion engine, hydrogen has advantages arising from very wide flammability limits, high volatility, low flame incandescence, clean burning, and low ignition energy. Successful tests have already been carried out using hydrogen as the fuel for automobile and aircraft engines. An aircraft fueled with hydrogen flew in 1957.

Although engine conversion problems are minimal, the handling, storage, and transportation of hydrogen on a small scale present greater difficulties. Storage of hydrogen gas at high pressures on vehicles requires containers of considerable weight and this possibility does not appear to be realistic. On the other hand, the (small-scale) storage of hydrogen on vehicles as a cryogenic liquid is certainly technically feasible; both the transfer and trucking (handling) of liquid hydrogen are routine operations. In the future perhaps the chemical storage of hydrogen as a hydride may be adaptable to vehicles.

Compared on the basis of equal energy (Table 1), the weight and volume of liquid hydrogen are, respectively, 0.38 and 3.9 times the weight and volume of gasoline. Because a liquid hydrogen tank has a larger volume and incorporates vacuum insulation, it will be heavier than the corresponding gasoline tank; but the overall weight of the two fuel systems will still be comparable because of the difference in fuel weight. This weight comparison improves in favor of hydrogen as the size of the storage system increases (e.g. for ships, trains, aircraft), but the large volume of cryogenic hydrogen compared with that of gasoline for given energy makes a hydrogen fuel system less attractive. While fossil fuels are available, hydrogen fuel will not replace them; however, when fossil fuels become depleted, necessity will turn us to the solvable problems of hydrogen use. Technology is already available for the design and construction of liquid-hydrogen storage systems that would be acceptable when the need arises.

Metal hydrides are already being investigated as a possible alternative to cryogenic hydrogen. Compared on the basis of equal energy, the weight of carrier and fuel of presently conceived hydride systems is about twice that for a liquid hydrogen installation. Metals of lower density are needed; the efficient utilization of the heat evolved when the metal is recharged is another requirement.

INDUSTRIAL USES OF HYDROGEN AND OXYGEN

Although hydrogen is not now used to any extent as a fuel, its utilization in industry is diverse, well established, and increasing. Hydrogen is produced in huge quantities mainly from natural gas at present and can be derived from coal in the future. It is a major intermediate in chemical and petrochemical manufacture. About half is used for ammonia synthesis, essentially for the manufacture of fertilizer, about a third for petroleum refining, and the remainder for the synthesis of methanol, hydrochloric acid and other heavy chemicals, for the hydrogenation of unsaturated fats and oils for foodstuffs, and as a metallurgical reductant. In the future hydrogen may be used extensively in the gasification of coal and the processing of heavy oils and oil sands to lighter fractions.

Hydrogen is now used as a feedstock in the rubber, plastics, pharmaceuticals, detergents, and foodstuff industries. Its use to provide process heat is expected to increase steadily in the steel, ceramic, and cement industries. When power plants are designed to provide hydrogen for peakshaving and transportation, the needs of chemical industries should be kept in mind.

The production of hydrogen from water will also produce oxygen as a byproduct. Large-scale, water-splitting plants at a power station, while producing hydrogen for peakshaving, vehicular, and industrial requirements, will also generate large quantities of oxygen. It is noted, however, that oxygen is a major constituent of the atmosphere and in that sense is already available. For this reason oxygen will not normally be piped more than 50 kilometers from the production site; beyond that distance it will be preferable to separate it from the air on-site. If major users of oxygen, such as the steel industry or sewage treatment plants, can be located adjacent to a power plant electrolyzer, then electrolytic oxygen may play a significant role as an industrial raw material. Otherwise it may be preferable to consume the oxygen in the generation of peakshaving power.

ENVIRONMENTAL IMPACT

The cycle envisaged for the production and use of hydrogen at the nuclear power plant of the future is suggested in Fig. 1.

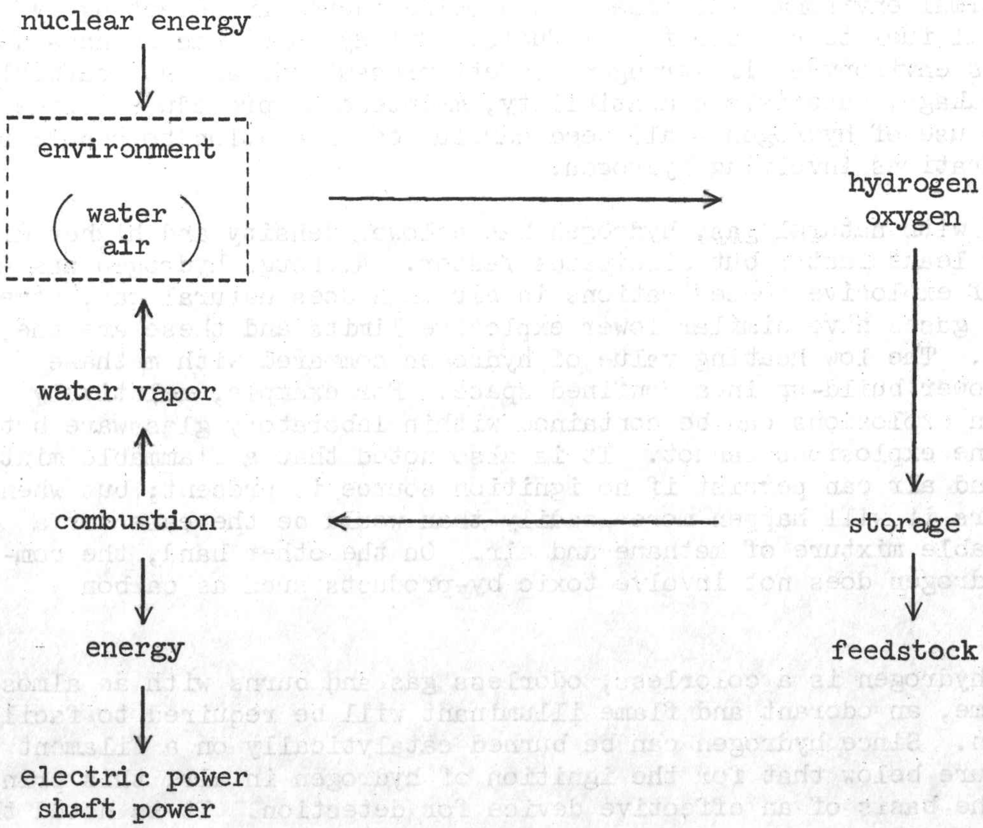

Figure 1

In this cycle both hydrogen and oxygen are produced on-site by nuclear energy and stored. Then the hydrogen may be recombined with oxygen (combustion) to provide peakshaving electrical energy as required; it may be burned with air to produce shaft power for vehicles; it may be transported to industry for use as a chemical raw material. The essential environmental feature is that only water vapor is ejected to the atmosphere if the hydrogen and oxygen are recombined. If hydrogen is burned in air, then small quantities of nitrogen oxides are ejected as well as water vapor. No carbon monoxide, carbon dioxide, solid particulates, or hydrocarbons result from this cycle. Unlike the corresponding fossil-fuel cycle, this hydrogen-fuel cycle proceeds rapidly. Furthermore, water is so abundant and mobile on the earth's surface that it can be split up at one point and reconstituted at another without significant environmental disturbance.

The combustion of hydrogen in air can occur in two ways. One is a homogeneous or gas-phase (flame) combustion in which high local temperatures are attained under invariant conditions because of the purity of the hydrogen, and low amounts of nitrogen oxides are emitted as well as water vapor. A second is catalytic oxidation or surface combustion which occurs below the normal flame temperature, avoids or substantially reduces the formation of nitrogen oxides, reduces fire hazards characteristic of open flames, and may not require a chimney. This second form of combustion is possible because hydrogen has a very low ignition temperature (less than 7% of that of natural gas) and it readily oxidizes in air on an active platinum catalyst. The first form of combustion will be used in the engines of vehicles with a minimum requirement for anti-pollution devices; the second can be adapted to the production of clean process heat in industry.

This minimal environmental impact is a prime factor in selecting hydrogen as the chemical fuel to replace fossil fuels. But hydrogen can be hazardous to man and his environment if stringent safety precautions are not carefully observed. Leakage, materials compatibility, maintenance procedures, codes governing the use of hydrogen—all need careful consideration to ensure the safety of operations involving hydrogen.

Compared with natural gas, hydrogen has a lower density and higher diffusivity—it leaks faster but dissipates faster. Although hydrogen has a wider range of explosive concentrations in air than does natural gas, nevertheless, both gases have similar lower explosive limits and these are the most critical. The low heating value of hydrogen compared with methane indicates a lower build-up in a confined space. For example, relatively small hydrogen explosions can be contained within laboratory glassware but similar methane explosions cannot. It is also noted that a flammable mixture of hydrogen and air can persist if no ignition source is present; but when ignition occurs it will happen more readily than would be the case for a similar flammable mixture of methane and air. On the other hand, the combustion of hydrogen does not involve toxic by-products such as carbon monoxide.

Because hydrogen is a colorless, odorless gas and burns with an almost invisible flame, an odorant and flame illuminant will be required to facilitate leak detection. Since hydrogen can be burned catalytically on a filament heated to a temperature below that for the ignition of hydrogen in air, this principle can be made the basis of an effective device for detection. It is noted that liquid hydrogen is contained by materials at temperatures above the boiling point of cryogenic hydrogen and, therefore, gaseous hydrogen appears when a leak occurs in a liquid hydrogen system and regular methods of leak detection apply.

The practice of storing hydrogen on a large scale at high pressures has directed attention to the compatibility of various materials with hydrogen. Designers should be aware of the safety problems that could arise from the hydrogen embrittlement of materials of both intergranular and surface types. Fractures may occur if pressures are pushed beyond limits in normal use today. But operational conditions may also be a factor; hydrogen embrittlement may arise from multiple cycling of pressure vessels owing to frequent filling and emptying. The extent to which hydrogen embrittlement is a real problem is not clear at present. The fact is that many hydrogen containers and pipelines have served well over many years in different parts of the world without embrittlement failures.

The running-in and maintenance of hydrogen systems will require established safety codes. Reliable procedures for purging tanks and pipes with inert gases to sweep out the air during the running-in of new facilities or when servicing the system later are essential requirements. Practical, safe techniques for working in the neighborhood of hydrogen-air mixtures must be developed and approved: welding operations should be undertaken at safe mixture ratios (75% or more); leak detection and repair may require the use of spark-proof tools and clothes; an oxygen-level indicator is necessary for purging and maintaining a hydrogen system.

Because of the U.S. space program and the growing use of hydrogen in industry, procedures for the safe handling of cryogenic hydrogen are already well established. Liquid hydrogen is routinely delivered by rail and road tankers from production plants to central storage tanks by trained personnel. Remote handling of cryogenic hydrogen is necessary only when liquid oxygen is present.

Considerable experience in the production, storage, transportation, and utilization of hydrogen has been accumulated in industry. It can be concluded with confidence that, because of a universal recognition of the hazards involved and the mounting of a considerable effort to develop reliable safety codes, the same safety standards can be achieved with hydrogen fuel that have already been accepted for other gaseous fuels such as natural gas.

ECONOMIC VIABILITY

The economic viability of hydrogen fuel can be discussed only for developed systems: the economics of the electrolytic process for producing hydrogen can be assessed, but a parallel evaluation of thermochemical water-splitting must await further development of this promising process; the economics of the large-scale storage of hydrogen can be considered, but an extension of the discussion to small-scale (vehicular) storage can be made only after further research and development.

The cost of producing electrolytic hydrogen depends essentially on the (fixed) capital cost of the plant and on the (variable) operating costs which are proportional to the input power costs. In order to minimize overall costs, a trade-off must be made. Lower capital cost can be obtained by designing for high current densities; but high current densities lower the electrical efficiency which implies an increase in the power consumption per unit of hydrogen generated. Analysis shows that, under optimum conditions, electrolytic hydrogen will be produced in a price range per unit of energy close to that of the electric power used; therefore, a source of low cost power is essential.

The production of electrolytic hydrogen at a nuclear power plant has economic advantages:

(1) Nuclear-generated electric power, which must carry the main responsibility for providing electricity in the long-term future (Ref. 1), is already more economical than fossil-fuel power;

(2) The production and storage of hydrogen to maintain a constant power level at a nuclear plant reduces the size of the nuclear plant and, therefore, the cost of the electric power generated;

(3) The costs of production of electrolytic hydrogen are kept low by using off-peak electric power, consistent with the power-leveling function of hydrogen fuel at a nuclear power plant.

The economic viability of thermochemical water-splitting is difficult to establish at the time of writing since this process has not been developed to the point where meaningful cost estimates can be made. In principle the use of thermal energy direct from the reactor and the recycling of process chemicals suggest that the production of hydrogen by thermochemical decomposition is economically attractive. Large savings per unit of energy compared with electrolytic hydrogen are not expected, but, in view of the considerable scale on which hydrogen may eventually be produced, even a small percentage reduction in unit cost should provide an incentive for further investigation.

The costs per unit of energy of storing hydrogen on a large scale differ according to the method used. The cost of the large-scale storage of hydrogen gas at high pressure is prohibitively high compared with other methods owing to the high capital cost of the pressure vessel and the cost of compression, combined with the relatively low density of hydrogen gas achievable at even the highest attainable pressures. Despite the need for insulation and liquefaction, the overall cost of storing liquid hydrogen is less than that for compressed hydrogen. But the least costly, large-scale method of storing hydrogen is to use depleted oil and gas fields, aquifers, or mined caverns.

A comparison of storage costs for hydrogen and natural gas favors the latter. Because the boiling point of hydrogen is much lower than that of natural gas, the costs of liquefying and storing hydrogen are substantially higher than the corresponding costs for natural gas. The current emphasis on techniques for the storage of hydrogen as part of the U.S. space program is leading, however, to improved methods and cheaper designs that show promise of reducing this difference in cost. With regard to underground storage, again costs are greater for hydrogen than for natural gas by virtue of the lower energy content of hydrogen for the same volume and pressure (Table 1) and the additional cost of converting the field to hydrogen.

Because the costs per energy unit of producing and storing hydrogen are currently somewhat higher than the corresponding costs for fossil fuels, the use of hydrogen as a chemical fuel will be economically feasible only when the rise in the costs of fossil fuels, concomitant with their depletion, removes this difference. The average price of fossil fuels will escalate at a rate higher than that caused by inflation; on the other hand, the price of nuclear-based hydrogen is expected to climb at the normal inflationary rate because basic resources are essentially unlimited. Many unpredictable factors make it impossible to forecast when hydrogen will become competitive with fossil fuels; for example, the all-electric home does not use the cheapest form of energy for heating. We pay for convenience. Furthermore, we cannot say that economics will be the only factor to influence decisions on when to introduce the widespread use of hydrogen; for example, environmental benefits may override economics.

FUTURE PROGRAMS

RESEARCH AND DEVELOPMENT

The preceding review indicates that there are no insuperable obstacles to the ultimate substitution of abundantly available hydrogen fuel for depleting fossil fuels to provide those requirements in an electrical society that are not met directly by electrical energy — peakshaving, mobile power, feedstock. It is recognized that the production, storage, and adaptation to the needs of society of hydrogen fuel are technically feasible now; it is agreed that hydrogen fuel introduces basically no serious environmental problem so long as safety codes are carefully observed; it is expected that hydrogen fuel will become more economically viable as the prices of fossil fuels escalate above the inflationary rate, concomitant with the inevitable depletion of this source of energy.

The introduction of a new chemical fuel on a large scale will require extensive planning, considerable capital investment, pressures on the labor market, and long periods of construction. A long lead time is required, therefore, to make a transition from fossil fuels to a new chemical fuel if interruptions of services are to be avoided. If a nuclear-power-hydrogen-fuel economy is to replace the existing fossil-fuel economy, then many new installations are required; therefore, design criteria and prototype systems should be under investigation now. It is definitely unwise to await the time when fossil-fuel prices are no longer competitive and the substitution of hydrogen fuel becomes economic and urgent. Governments, industries, and universities should commit themselves now to programs of research and development designed to introduce hydrogen fuel gradually into the national economy.

A gradual transition to hydrogen can be initiated conveniently now by producing it from coal, oil sands, or heavy oils; it can be manufactured almost as cheaply as can pipeline gas. Later, when fossil fuels are no longer available and other inexhaustible sources take over the production of hydrogen, peakshaving installations, hydrogen-powered vehicles, and developed feedstock applications will exist already and the appropriate utilization of hydrogen can continue without interruption. But this transition will not begin if we do not look sufficiently far ahead now to commit ourselves to the ultimate copartnership of hydrogen fuel with electric power in the long-term future.

It has been pointed out that the replacement of fossil fuels by hydrogen fuel is technically feasible. The need now is for design criteria, construction techniques, and codes for operation and maintenance that depend so heavily on accumulated experience. Canada needs a few carefully chosen, demonstration experiments on a scale sufficiently large to permit reliable assessments of technological, environmental, and economic factors. These demonstration experiments could include research and development (1) on hydrogen production, including improvements in the efficiency of electrolyzers and exploratory investigations of new methods for thermochemical water-splitting, (2) on large-scale tankage for cryogenic hydrogen, tests of procedures for underground storage, and further basic research on metal hydrides, (3) on applications to transportation, including the design and testing of aircraft fueled with hydrogen, and (4) on systems optimization of nuclear-electric-electrolysis power systems. Some of the proposed demonstration experiments are a Canadian responsibility; some can be done in cooperation with other nations.

The adverse effects of hydrogen fuel on the environment are minimal; this is a major inducement for the early introduction of hydrogen-fuel systems. On the other hand, the elimination of hazards associated with the use of hydrogen requires established procedures to build confidence in the safety of hydrogen systems — a high-priority area for research and development. Confidence that safe procedures can be established is justified by the fact that industry already handles hydrogen safely in many feedstock operations. The safety of hydrogen systems should be an important part of any large-scale demonstration experiment. In particular, attention should be given to techniques that guarantee the "leak-tightness" of hydrogen systems, that provide reliable purging of new and operating facilities, that permit effective monitoring for possible embrittlement failure. A manual dealing with all aspects of the safety of hydrogen systems is a requirement of high priority.

Research and development to produce technical improvements and more effective environmental controls must also focus on cost reduction. Technical innovation that leads to higher efficiency and modified environmental constraints that eliminate unnecessary stringency will reduce costs. Such investigations as these along with strictly economic considerations, such as low-cost materials and fabrication, will provide a reasonably complete coverage of economic aspects. All these studies can be carried out effectively as part of a well-organized demonstration experiment. Special attention could be given (1) to cost comparisons of processes for the interim production of hydrogen from coal, oil sands, and heavy oils, (2) to wider markets for liquid oxygen, (3) to the economics of small-scale, mobile storage of hydrogen fuel, (4) to cost studies of various types of hydrogen-powered, mobile power plants, including evaluations of the cost of converting existing engines to hydrogen fuel, and (5) to the broad subject of the economies of scale which become important when hydrogen fuel is used extensively.

PUBLIC EDUCATION

Public education on the use of hydrogen must emphasize safety. The widespread publicity given the Hindenburg accident has blown the hazards of hydrogen out of proportion to those of other materials in regular use. In industry so much attention has been given to the potential hazards of hydrogen that its safe use is now an accomplished fact and the same safety standards as those attained for natural gas are now achievable for hydrogen. In some ways hydrogen is safer than some materials now handled routinely. It is important that public confidence in the safe use of hydrogen for all proposed future applications be established through demonstration experiments and accumulated experience.

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THE FUTURE ROLE OF HYDROGEN FUEL IN AN ELECTRICAL SOCIETY

Patterson, Gordon N. 19 pages 1 figure

1. Electrical society 2. Hydrogen fuel 3. Energy options 4. Environmental impact
5. Economics of energy 6. Energy R & D

Present trends indicate that the use of electrical energy is growing faster than the consumption of other forms of energy and that many nations are becoming "electrical societies". As fossil fuels become depleted and new forms of energy are introduced, this trend is expected to accentuate (see The Race for Unlimited Energy by G. N. Patterson). In such a society, can electrical energy meet all the requirements? A study of this question indicates that there is still a need for an abundant chemical fuel that is technically feasible, environmentally acceptable, and economically viable.

This review suggests that hydrogen is the universally available fuel that best meets these requirements: its technology is already reasonably well understood; effluents and products of combustion that are not easily assimilated into the environment are minimal; safe procedures for its use are in an advanced state of development; hydrogen fuel will become economically competitive relative to alternatives as fossil fuels become more expensive and scarce. It is expected that in the future hydrogen will play a major role as a peakshaving medium at electric power plants, as a fuel for transportation, and as a diversely-used feedstock for industry. The manufacture, storage, and use of hydrogen for peakshaving purposes, vehicular power plants, and as a chemical raw material are discussed and programs for future development are indicated. It is concluded that plans for the future use of hydrogen on a large scale should be initiated now.

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