A HYDROGEN-ENERGY SYSTEM

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INTRODUCTION

For some years now, interest has been growing in the use of hydrogen as a universal fuel — hydrogen that is produced from unlimited seawater by nuclear energy to provide a clean, universally useful fuel and chemical raw material. Early interest in the concept dates back before the availability of nuclear power and was stimulated by the fact that hydrogen could be manufactured by the electrolysis of water using off-peak electricity. Rudolf Erren,[6] working in Germany and later in England in the early 1930's, foresaw the need to utilize off-peak power to reduce oil imports into Britain and to reduce pollution from vehicle emissions. In 1933, he published a paper in which he outlined the use of hydrogen as a fuel for automobiles and steam locomotives.

Among others who have since given their attention to the hydrogen fuel concept are Weinberg,[16] Steinberg,[12] and others at Brookhaven National Laboratory, who considered hydrogen as an essential part of the nuclear-agricultural complex concept; Winsche et al.[17] of Brookhaven, who looked at hydrogen as an urban fuel; Murray and Schoeppel[9] at Oklahoma State University, who stimulated work on the use of hydrogen as an internal combustion engine fuel; Bacon[2] at Cambridge, England, who saw in the reversible hydrogen fuel cell a simple way of storing off-peak electricity; Rosenberg[11] at the Institute of Gas Technology, who saw the uniquely favorable qualities of hydrogen as a fuel for domestic appliances; and Marchetti[4] at Euratom, Italy, who realized the inherent inefficiencies of producing hydrogen from nuclear energy via an electrolytic process. These are but few of the many who have proposed or studied various aspects of what we shall call "The Hydrogen Economy." Today reasons why an overview of the whole concept of hydrogen as a fuel should be made are even more pressing.

ENERGY SUPPLY

The economy of the civilized world today is geared to the use of energy. Many studies show that the usual measure of prosperity, the gross national product per capita, has grown in almost every country of the world at a rate directly related to the growth rate of the per-capita use of energy. Almost all of this energy comes from combustion of fossil fuels, fuels which, although they have taken millions of years to form, are being consumed in a few hundred. The signs are already here that we are approaching the end of our fossil fuel supply: In the U.S., we are now consuming natural gas at a rate faster than the rate at which new reserves are being discovered. The U.S. is importing an ever-increasing portion of its oil requirements, anu the cost of coal is rising rapidly as we bite into less readily worked deposits.

Elliott[5] has shown that patterns of producibility of the fossil fuel resources of the U.S. and Canada can be used to predict that the maximum rate of production of fossil fuels will occur early in the next century. After that time, the amount of available fossil fuel energy will fall year by year, although our overall energy demands are expected to continue to rise. It is therefore vital to develop nuclear or solar energy sources.

NUCLEAR ELECTRIC POWER

The development of nuclear power stations has been described by the Federal Power Commission as a "race for our lives" to meet our energy needs. Let us hope that we win the race, but let us also observe that almost the whole research and development effort in nuclear energy today is directed toward the conversion of nuclear energy to electrical energy. This same observation can also be made about the relatively smaller efforts going on to harness solar energy and geothermal energy: The goal is to produce electricity.

Electrical energy is a convenient, clean, and universal energy source in its end use, but it suffers from a number of technical disadvantages that prevent it from having already become the universal "fuel." First, it cannot be stored without conversion to another form. Storage batteries are relatively expensive and heavy, and sites for pumped storage systems are limited. This limitation requires that the generation rate match, almost exactly, the consumption rate, responding instantaneously to fluctuations in demand. The result is an expensive and necessarily "overdesigned" supply system. Second, it is incredibly expensive to transmit electric power over long distances without the use of unsightly overhead cables and towers. Underground power lines of similar capacity to those more familiar overhead cross-country systems cost 10-40 times as much as overhead lines.[14]

NUCLEAR CHEMICAL POWER

Since we use a very large proportion of our energy directly as heat, perhaps it makes more sense to satisfy this portion of our needs by burning fuel directly rather than using the intermediate and inefficient conversion to electricity. We should look, then, for a synthetic fuel that can be used to store and transport the energy produced by nuclear power stations.

It is possible to conceive of a number of synthetic chemical fuels that could be produced from a nuclear heat source. The choice is severely limited, however, if we consider the use of the atmosphere as a carrier to return the "spent" fuel to the synthesis station. We certainly cannot consider any synthetic high-energy chemical that produces a noxious or voluminous combustion or oxidation product, and, except for specific applications, we cannot afford to collect and transport the spent fuel back to its point of origin.

To obtain compatibility with the atmosphere, therefore, we must limit the combustion products to water, nitrogen, and carbon dioxide, from which the fuel itself must also be synthesized. Although alcohols, hydrazine, and ammonia fall into this category, their combustion raises the possibility of production of noxious carbon or nitrogen compounds, including carbon monoxide and the oxides of nitrogen. Hydrogen has the unique combination of being readily synthesized from water, being readily auto-ignited and undergoing low-temperature combustion on a catalytic burner, and, in doing so, forming a completely clean combustion product — water.

HYDROGEN FUEL

Two major criticisms can be leveled at the use of hydrogen as a fuel: 1) It is too expensive to produce, and 2) its transportation to the point of use is costly because it requires heavy compressed-gas cylinders. Neither of these criticisms is valid if an imaginative approach is taken to the problem. Very large electrolysis plants running off the entire output of a large nuclear power station are technically feasible. Since we are accustomed to moving huge quantities of natural gas across the country in pipelines, the same approach can be applied to hydrogen. We will show that even today, the concept of making hydrogen on a large scale and delivering it to a nationwide transmission and distribution system should be able to provide delivered energy more cheaply than the average selling price of electricity.

Hydrogen Production

Today, most of the enormous quantity of hydrogen produced in the United States — over 2500 billion cubic feet per year and growing fast — comes from the reaction of natural gas with steam. Smaller quantities are made by electrolysis of water where cheap electricity is available, or where extreme reliability is needed. These are the key words of the future: Nuclear power will provide "cheap electricity" — perhaps not cheaper than today, but cheap in comparison with the future cost of fossil fuel energy — and any energy supply system must be endowed with "extreme reliability." Electrolysis therefore appears to be one logical choice of process. Studies carried out in 1965-66 by Allis-Chalmers for the Atomic Energy Commission[3] and subsequent cost analyses published by Oak Ridge National Laboratory[8] are the most reliable and recently published sources of predictions on the cost and availability of large-scale electrolyzers. These studies investigated two sizes of plants intended to produce hydrogen for ammonia production in an agricultural-nuclear complex. Table 1 gives the estimated costs of the larger of the plant sizes studied and other relevant details of the plant's characteristics.

Table 1. INSTALLED COST OF ELECTROLYTIC HYDROGEN PLANT*

	$	% of Total
Mechanical Instrumentation, Processing, Piping and Structures	5,413,000	14.1
Electrical	21,018,000	56.0
Electrolysis Cell Modules	11,109,000	29.6
Total	37,540,000	100.0

* Hydrogen production rate: 44,000 lb/hr, or 7.8 million SCF/hr.
Electrical input: approximately 1000 MW.
Source: Reference 3.

In calculating the hydrogen production cost, we have to assign an operating efficiency for the electrolyzer, which leads in turn to an interesting observation: When hydrogen is burned, the energy released is equal to the whole of the combustion energy, or enthalpy change. However, only a portion of this, the free energy, is interchangeable with electricity, either in a fuel cell or its reverse, the electrolysis cell. The remainder, the entropy change, must be supplied or released as heat. An ideal electrolyzer cell absorbs the free energy change as electricity and requires the input of a further 20% of heat energy to maintain an overall balance. In other words, a perfect electrolysis cell would absorb heat, and the heating value of the hydrogen produced would be 120% of the electrical energy put in.

Although modern electrolyzer cells are only about 60% efficient, it seems reasonable a) to aim at a figure close to 100% in electrical efficiency as a target and b) to suppose that this could be achieved if considerable research and development is applied to electrolyzer technology in the next 2 or 3 decades. In fact, some of the Allis-Chalmers published data on its laboratory cells indicate that they were operated at electrical efficiencies exceeding 100% at elevated temperature and pressure.

Because of uncertainty over future electricity generating costs, we choose to subtract the electric power costs from all the other costs of building and operating the electrolyzer. This gives us an incremental cost for the conversion of electricity to hydrogen, which is a useful figure independent of power costs. As far as cost is concerned, we make two observations. One is that the cost of the whole electrolyzer plant is about $35/kW input, which is small — almost insignificant — in comparison with today's estimates of $400/kW or more for 1980 nuclear power plants. The other is that the extra cost of producing energy at the power station as hydrogen rather than as electricity is likely to be about $0.29-$0.57/million Btu — the higher figure being based on a 70% and the lower figure on a 100% electrical efficiency.

Hydrogen Transmission

Over 86% of the households in the U.S. are at present supplied with natural gas fuel. This ubiquitous natural gas may arrive in our homes after a transcontinental journey from a well in Texas or Louisiana, and after a temporary sojourn through the summer months of light demand in a natural underground storage system in another part of the country. This country already has an efficient and highly developed network of transmission pipelines, storage systems, and distribution pipes which are capable of moving energy around the country in enormous quantities at relatively low cost. But because the system is buried underground, most of us are unaware of its existence, or we simply take it for granted. In contrast, complaints about the obvious growth of the aboveground electricity network have presented the electricity industry with an incredibly difficult problem, both in public relations and in the sheer economics of burying the cables.

Nobody has yet constructed a 1000-mile pipeline to carry hydrogen at high pressure; however, many shorter pipelines are in use in industry[10] to carry bulk hydrogen from the production plant to the consumer. The technology exists, but the need for long-distance applications has not yet arisen.

Because of hydrogen's lower heating value (325 Btu/SCF compared to 1000+ Btu/SCF for natural gas), it might appear to require significantly larger pipelines to carry the same amount of energy. However, although we have to move about 3 times the volume of gas, the lower specific gravity of hydrogen produces a nearly compensating increase of 2.5 times the flow capacity of a given pipeline.[15] The greater volume of gas to be handled results in an increase of 3 times the pumping power needed for transmission. Experience in moving large volumes of hydrogen within chemical plants and refineries makes it appear that we can use pipelines of similar size and materials to those used for natural gas. The combination of these factors suggests that an increased capital and operating cost of about 60% will result from the long-distance transmission of hydrogen rather than natural gas, based on equivalent amounts of energy. Because the safety precautions in a hydrogen distribution system will be more demanding, we will assume a 100% increase in capital and operating costs for a local hydrogen distribution system.

Hydrogen Cost

Using statistical data published by the American Gas Association[1] and the Federal Power Commission,[13] it is possible to break down the average selling prices of gas and electricity into their production, transmission, and distribution components. Using the average production price of electric power, the cost of electrolysis referred to earlier, and the assumptions previously outlined for the increased cost of transmitting and distributing hydrogen, we arrive at the figures shown in Table 2, based on the latest available (1969) statistical information.

Table 2. RELATIVE PRICES OF DELIVERED ENERGY

	Electricity	Natural Gas	Hydrogen
	$/million Btu		
Production	2.52*	0.16	2.81-3.09*
Transmission	0.62	0.18	0.22
Distribution	1.61	0.27	0.34
Total (average selling price)	4.75	0.61	3.37-3.65

* Power purchased at 8.6 mills/kWhr.

Table 2 illustrates clearly the already recognized facts that transmission and distribution of energy in underground natural gas pipelines cost only about 20% as much as transmission and distribution of electrical energy (largely by overhead lines) and that purchase of delivered energy as natural gas is nearly 8 times cheaper than electricity. What is also apparent from these figures is that if we could build and operate an Allis-Chalmers electrolyzer today at the predicted costs, we should be able to deliver hydrogen energy to the average user more cheaply than electrical energy.

As time progresses, we expect the costs of natural gas and electricity to rise, but at different rates. Nuclear electricity costs are predicted to rise only slowly because the breeder reactor will provide energy with very little limitation in the fuel supply. In contrast, all fossil fuel prices, including natural gas, will rise more rapidly because the resources are being depleted, and future production becomes correspondingly more expensive. Ultimately, the cost of natural gas will exceed that for hydrogen. At that point, the "hydrogen economy" will be truly justified economically. Before that time, conservation of fossil fuel supplies and of a clean environment could accelerate the justification of a hydrogen system.

CONCLUSIONS

This paper has not dealt with the opportunities and the problems that would be raised by the universal availability of hydrogen as a fuel. Some of these will be obvious, and others are dealt with elsewhere.[7] The sheer magnitude of a conversion operation would be so great as to require years of planning. The benefits of such a conversion would be immense to the gas industry, which would thus have an active role in the "nuclear age"; to the electric industry, which would benefit from the improved load factors, lower transmission costs, and greater freedom in power station siting; to the waste disposal industry, which would find an abundance of by-product oxygen available at a very low price; to the chemical and metallurgical industries, which would both find expanding uses for commodity hydrogen; and to the general population, which would benefit from the almost complete elimination of atmospheric pollution. Perhaps most important of all, such a change-over does not appear to present any technical "roadblocks." Although the problems are immense, they appear to be straightforward technological problems which do not require the "technological breakthrough" that appears to be the stumbling block of so many otherwise sound concepts.

REFERENCES CITED

1. American Gas Association, 1970 Gas Facts. Arlington, Va., 1971.

2. Bacon, F. T., "The High Pressure Hydrogen-Oxygen Fuel Cell," Ind. Eng. Chem. 52, 301-03 (1960) April.

3. Costa, R. L. and Grimes, P. G., "Electrolysis as a Source of Hydrogen and Oxygen," Chem. Eng. Prog. 63, 56-58 (1967) April.

4. De Beni, G. and Marchetti, C., "Hydrogen, Key to the Energy Market," Euro Spectra 9, 46-50 (1970) June.

5. Elliott, M. A., "Energy Conversion and Fuel Reserves." Paper presented at the ASME North American Fuel Technology Conference, Ottawa, May 31-June 3, 1970.

6. Erren, R. A. and Hastings-Campbell, W., "Hydrogen From Off-Peak Power," Chem. Trade J. 92, 238-39 (1933).

7. Gregory, D. P., Ng, D.Y.C. and Long, G. M., "Electrolytic Hydrogen as a Fuel," in Bockris, J. O'M., Ed., The Electrochemistry of Cleaner Environments. New York: Plenum Press, in press.

8. Mrochek, J. E., "The Economics of Hydrogen and Oxygen Production by Water Electrolysis and Competitive Processes," in Grigorieff, W. W., Ed., Abundant Nuclear Energy, 107-22. Washington, D.C.: U.S. Atomic Energy Commission, 1969.

9. Murray, R. G. and Schoeppel, R. J., "Emission and Performance Characteristics of an Air Breathing Hydrogen-Fueled Internal Combustion Engine." Paper 719009 presented at the 1971 Intersociety Energy Conversion Engineering Conference, Boston, August 1971.

10. "Pipeline Distribution for Carbon Monoxide and Hydrogen Is Expanding," Chem. Week 108, 49 (1971) May 19.

11. Rosenberg, R. B. and Kweller, E., "Catalytic Combustion of Reformed Natural Gas," Appliance Eng. 4, 32-36 (1970) August.

12. Steinberg, M. and Holmes, J. M., "Low Cost Power and the Chemical Process Industry," Chem. Eng. Prog. 63, 35-67 (1967) April.

13. U.S. Federal Power Commission, Statistics of Privately Owned Electric Utilities in the United States, 1969. Washington, D.C.: U.S. Government Printing Office, 1970.

14. U.S. National Power Survey Transmission Technical Advisory Committee, The Transmission of Electric Power. Washington, D.C.: U.S. Federal Power Commission, 1971.

15. Von Fredersdorff, C. G., "Relative Costs of Transmission of Pipeline Gas," in American Gas Association Operating Section Proceedings — 1959, CEP-59-18.

16. Weinberg, A. M. and Young, G., "The Nuclear Energy Revolution and Chemical Processing," in Eringen, A. C., Ed., Recent Advances in Engineering Science, Vol. 2, 1-19. New York: Gordon and Breach, 1965.

17. Winsche, W. E., Sheehan, T. V. and Hoffmann, K. C., "Hydrogen — A Clean Fuel for Urban Areas." Paper 719006 presented at the 1971 Intersociety Energy Conversion Engineering Conference, Boston, August 1971.

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