fossil resources and import foreign fuels would cost about $110 billion by 1985.

In view of the enormity of the future energy problems facing the U.S., it is believed that promising options should be kept open by instituting vigorous research and development programs. A particularly important future option is believed to be in the area of nonfossil synthetic fuels.

2.3 Conclusions

The results of an assessment of the various sections of a synthetic fuel based system are summarized as follows.

Fuel Production. The process (nonfossil) most likely to be used for the large-scale production of hydrogen is water electrolysis. With further research and development, efficiency increases of 25% and plant cost reductions of 45% appear possible. Large economic improvements would also result if large markets for the by-products, oxygen and deuterium, could be found.

The thermochemical production route has not been developed past the laboratory stage but could be an attractive long-range method.

Radiolytic and direct thermal decomposition of water do not seem to offer attractive commercial possibilities. Several biological production schemes should, however, be further investigated to establish technical feasibility.

As indicated above, obtaining fuels from urban and agricultural wastes represents an attractive development area.

Production of hydrogen or methanol from coal appear to be developed processes, although no large plants have yet been built. Commercial implementation seems to be largely dependent on economic factors, but with current prices for coal, hydrogen from this source would be about one-half as costly as that from water electrolysis. Use of the western lignite deposits for hydrogen and methanol production appears to offer a number of advantages and should be further evaluated.

Table 2 summarizes current and projected production costs for the various synthetic fuels considered.

Storage and Transportation. The technology of large-scale storage and transportation of hydrogen and other synthetic fuels appears to be generally well developed. The use of underground aquifers or depleted gas wells for storage of hydrogen is, however, an area requiring further work. Small-scale storage, particularly for mobile energy, is one of the priority areas for further development. In addition to liquid hydrogen, compounds of hydrogen or hydrides offer attractive storage possibilities. Preliminary indications are that the costs for pipeline transmission and local distribution of hydrogen will be slightly more than those for natural gas; however, gas transmission and local distribution cost is less than one-third the cost of a corresponding conventional electric system. There is a need, however, to develop more precise cost estimates on a consistent basis for the transmission and distribution of electricity and hydrogen so that more definitive systems analyses can be made.

Fuels Utilization. Hydrogen appears to be readily substitutable for other fuels and in most cases yields real benefits, particularly in reduced environmental degradation and increased energy use efficiency. The need for government-supported research and development appears to be relatively small in the urban use sector, although eventual support for demonstration and conversion efforts would require significant funding levels. Industrial uses for hydrogen are growing and could expand greatly if hydrogen were available at a price suitable for new chemical and metallurgical uses. Also, hydrogen appears to be readily substitutable for other industrial fuels and would yield substantial environmental and efficiency advantages. Its use in the industrial sector does not appear to require significant, direct government support for research and development work. Adapting synthetic fuels to transportation uses, particularly hydrogen for aircraft and automobile use, represents an area where research and development is needed. Fuel logistics, on-board storage, and power conversion are specific areas requiring further work. In electrical generation, fuel cells and

Table 2. Summary of synthetic fuels production cost[a]

Fuel	Fossil-based process	Fuel cost (¢/10^6 Btu)	Electrical (or other) based processes	Fuel cost (¢/10^6 Btu)
Hydrogen	Natural gas, 40¢/10^3 ft^3	97	Water electrolysis	
	Coal, $7/ton	132	Power, 8 mills/kWhr	368
	Lignite, $2/ton	78	Advanced technology, 8 mills/kWhr	233
	(Liquefaction	150)	Advanced technology + by-product credits, 8 mills/kWhr	174
			Off-peak power, 2.5 mills/kWhr	155
Ammonia	Natural gas, 45¢/10^3 ft^3	157	H_2 via H_2O electrolysis, 8 mills/kWhr	517
			H_2 via H_2O electrolysis, 2.5 mills/kWhr	228
Hydrazine		~2100		
Methanol	Natural gas, 40¢/10^3 ft^3	158	H_2 via H_2O electrolysis, 8 mills/kWhr (CO_2 from air)	~550
	Coal, $7/ton (~27¢/$10^6$ Btu)	148		
	Lignite, $2/ton (~15¢/$10^6$ Btu)	~125		
Ethanol	Petroleum feed stocks	~460	Fermentation from corn, $1.25/bu	880
Methane	Well-head gas	15 - 40	Urban and agricultural wastes	~115
	LNG, imported	80 - 100		
	Coal	80 - 100		
Gasoline	Crude oil	105		

[a]Costs are based on 15% fixed charge rate and large plant capacities.

turbines would both benefit from the use of hydrogen, or hydrogen and oxygen, but both systems need further development.

Systems Considerations. Based on preliminary systems analyses, indications are that nonfossil synthetic fuel systems can overcome many of our long-term energy problems, although further analyses are required to establish the timing and urgency of implementation. It is likely that synthetic fuels from fossil sources (coal, oil shale, etc.) will be less expensive in the near term but, as the more attractive coal deposits are depleted, the synthetic fuels from nonfossil sources should become generally economically competitive. As indicated in Fig. 3, recent estimates[2] of the extent of the world coal resources suggest that the maximum rate of utilization of coal may occur between the years 2030 and 2070, at which point approximately 50% of the available resources will have been depleted; however, other estimates predict the peak occurs much further out in time. Obviously, the position of this peak shifts closer to the near term if coal resources are used in the manufacture of synthetic fuels. Thus, it is necessary to establish the position of this peak in order to have sufficient research and development lead time to anticipate the point of beginning the required implementation of nonfossil synthetic fuels in the energy economy. For some specialized applications or environmental advantage, electrolytic hydrogen produced via low-cost, off-peak power, or perhaps from remote hydropower, will be competitive on a near-term basis.

Systems analyses comparing an all-electric energy system and a combined electric-hydrogen supply system for residential consumption show that the combined system can be more economic. Advantages result primarily from relatively low gas transmission and distribution costs and high load factor operation of the primary nuclear power plants. The primary energy source for the combined system, however, must be about 25% larger to deliver the same total energy. Thus any costs associated with waste heat disposal or the handling of increased amounts of waste products must be weighed against the environmental and convenience advantages of synthetic fuels. As a storable energy form, hydrogen may find near-term use as an alternative to pumped-hydro storage systems.

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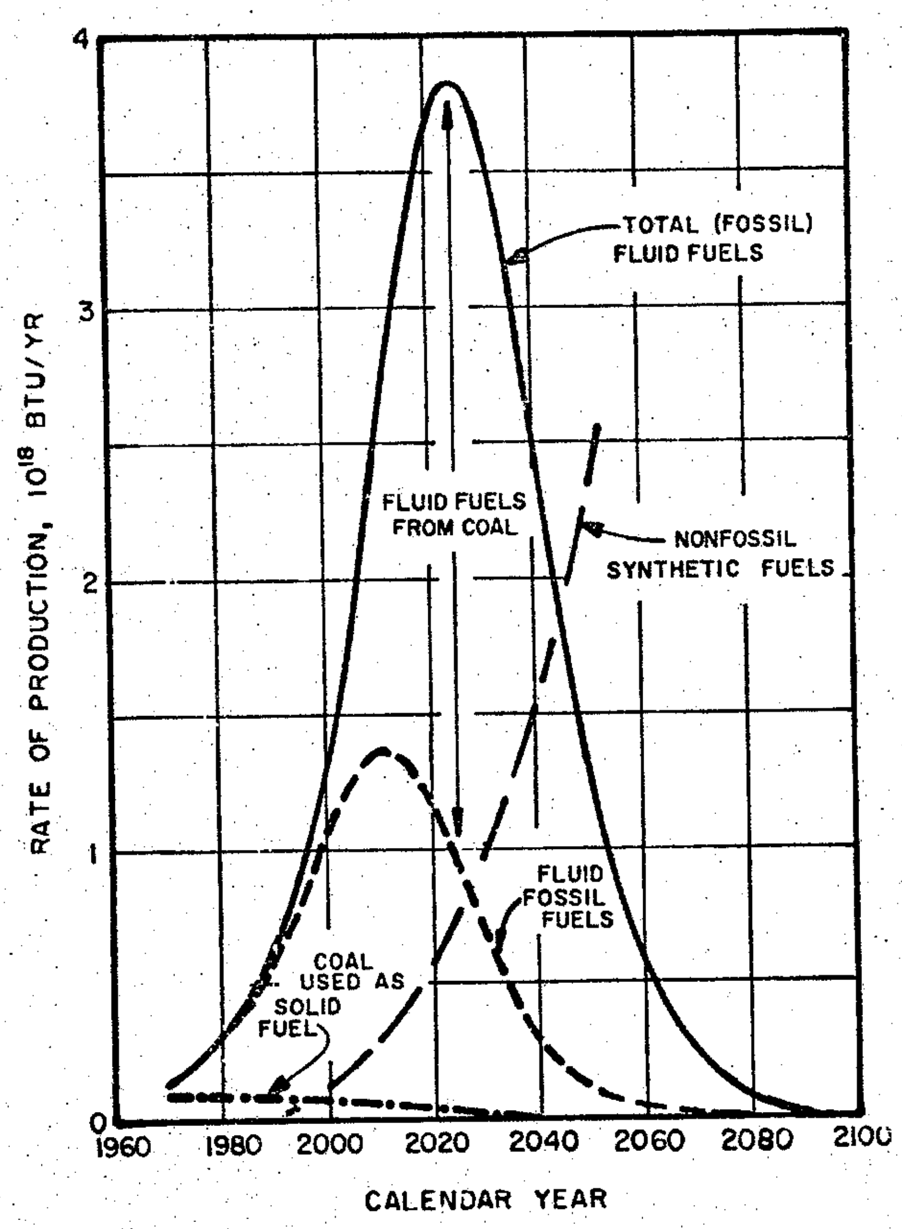


This may be especially attractive if accomplished in connection with other uses of hydrogen, for example, in the transportation sector. A power plant devoted at least partly to producing electrolytic hydrogen could also be used to provide peaking power by decreasing the rate of hydrogen production.

2.4 Summary of Recommended Research and Development

Applications of synthetic fuels and the associated research and development requirements were divided into two categories: those which can have a near-term, by 1985, impact on the nation's energy problems and those which would be of significant impact after this date. The near-term tasks which were identified are:

1. development and demonstration of methanol from coal as an automotive fuel,
2. development and demonstration of H_2 produced from coal for use in the industrial sector both as a chemical and as a fuel,
3. development and demonstration of H_2 as an energy storage medium for electric utilities use in supplying peak power demands,
4. development and demonstration of the production of gaseous and liquid fuels from urban and agricultural waste products.

Assuming a reasonable funding level, these programs are projected to require up to a five-year research and development effort. The methanol task would establish the technology and economics of both the production from coal and/or lignite as well as the end use in automobile engines. Since auto transportation represents the biggest single user of petroleum, the successful implementation of this program could have a significant impact on the oil-import and air pollution problems. Tasks 2, 3, and 4 also appear to have near-term viability and would likewise relieve the demand for natural gas and petroleum.

The research and development program identified to achieve the longer-term impact is an follows:

1. use of hydrogen as a transportation fuel, particularly for aircraft and for specialized ground vehicles;

2. hydrogen production investigations;
3. long-distance transmission and bulk storage of hydrogen;
4. public safety studies;
5. overall systems analyses.

It is estimated that a five- to ten-year research and development program would be required to establish the feasibility of using hydrogen as a transportation fuel. This program would give particular emphasis to fuel tankage and logistics and their interrelationships to engine and frame considerations.

Hydrogen production investigations to improve the water electrolysis process, as well as to investigate new methods such as thermochemical and biological, could involve a five- to ten-year program.

Long-distance transmission and bulk storage of hydrogen, including system studies, design optimizations, and component development, are estimated to require a continuing effort of at least five years.

Public safety and overall system analysis are envisaged as long-term relatively low-level efforts, but ones which are essential to a smooth implementation period as well as to form the base for a well coordinated research and development program.

It is expected that most of the long-term tasks will require concerted work well beyond the initial feasibility efforts outlined above, but will depend strongly on the results obtained by the end of the research and development period.

In general, the panel concluded that the main obstacle to the use of hydrogen as a universal fuel is an economic one, and that an extensive and long-range research and development program could do much to narrow the gap between its cost and the cost of fossil fuels. The cost of fossil fuels, because of declining resources and increasing environmental protection requirements, should increase at a higher rate than the cost of producing the synthetic fuels, and this will also contribute to improving the relative economic position and shortening the implementation period for the adoption of the hydrogen-based economy.

It is clear that our fossil fuels will ultimately be depleted and that reliance must then be placed on the nonfossil synthetic fuels. When this will take place or when a transition from coal based to nuclear- or solar-based fuels should begin is suggested as a topic for a future more detailed study. However, Fig. 3 indicates one case of assumed utilization of the U.S. coal resource[2] and a projected rate for implementing a synthetic fuel economy. If one assumes a reasonable time to complete research and development programs and then to implement a new fuels systems, it is evident that by making a strong research and development commitment now followed immediately by a concerted implementation program it should be possible to have the new system available to meet our long-term needs.

3. PRODUCTION OF SYNTHETIC FUELS

Perhaps the most critical factor influencing the viability of an energy system based on synthetic fuels resides in the production system, particularly in terms of the costs and the impact on the use of resources and on the environment. This section discusses the various options for the production of hydrogen, namely, electrolysis, thermochemical, biological, radiolytic, and various combinations, and the production of other synthetic fuels, particularly those made from hydrogen. Since the electrolysis and the thermochemical processes have received far more consideration than the other proposed production systems they are discussed in much more detail.

A section on the use of coal is included for comparison and to illustrate the most likely option to bridge the interim from the present to the time when fossil fuels become scarce. This section considers only two fuels made from coal: hydrogen and methanol. Other possible fuels, methane and a complete range of Fischer-Tropsch synthesized hydrocarbons are not discussed due to the time limitation for this study.

3.1 Hydrogen

The two principal electrolytic processes for producing hydrogen are water electrolysis and hydrogen-halide electrolysis. (Since the hydrogen-halide process is actually a two-step process involving a thermal process of reacting a halide with water to form the H-halide, this system is discussed in Section 3.1.4, Combination Production Systems.)

3.1.1 Water electrolysis

Physical principles and theory. Water electrolysis is accomplished by passing a direct current between two electrodes immersed in an electrolyte (usually potassium hydroxide solution); hydrogen is formed at the cathode and oxygen is formed at the anode. The rate of hydrogen production is directly proportional to the current passing between the electrodes and is given by Faraday's Law as 1 lb of H_2 per 12,060 A-hr.

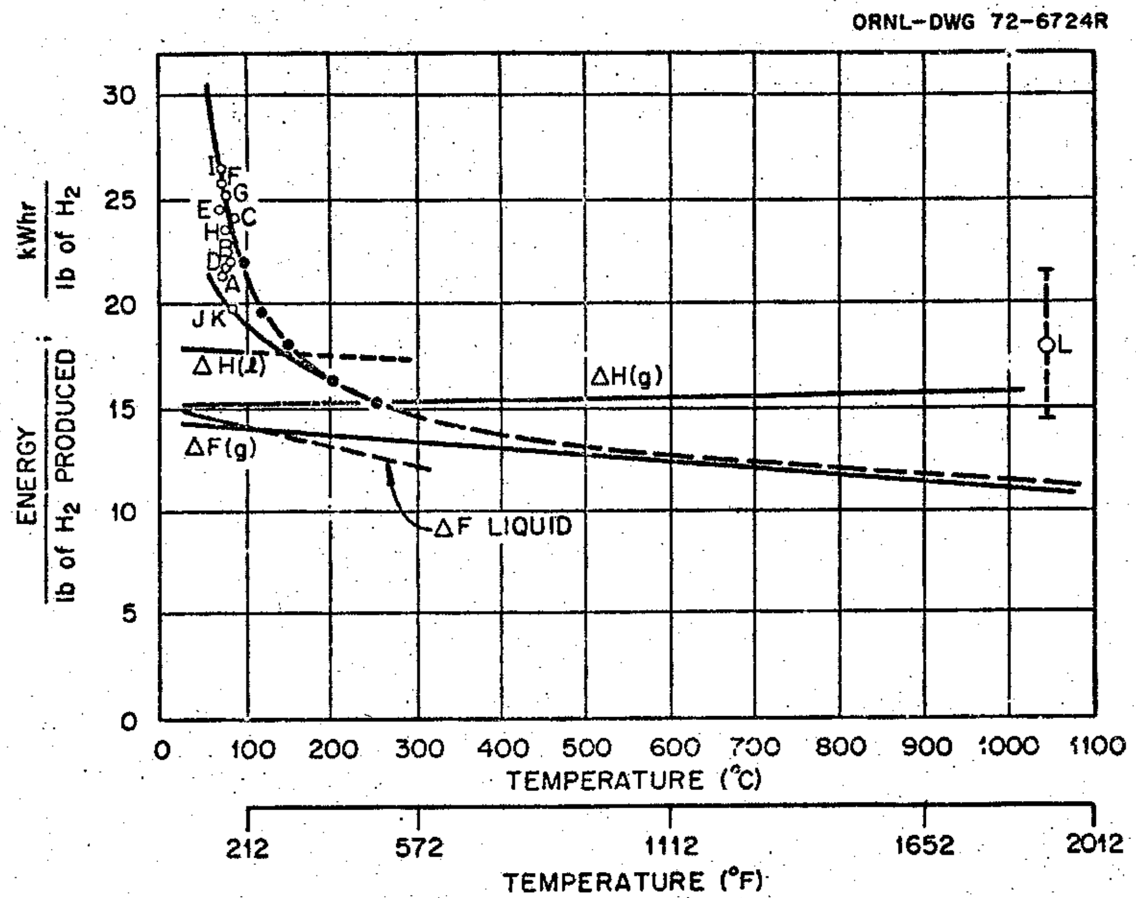
The energy that must be supplied to the cell, to cause the reaction H_2O (liquid) $\rightarrow$ H_2 (gas) + $1/2O_2$ (gas) to proceed is the enthalpy of formation of water, ΔH, and is equal to 68.32 kcal/mole at 25°C and 1 atmosphere. However, only the free energy of this reaction, ΔF, equal to 56.69 kcal/mole, has to be supplied to the electrodes as electrical energy. The remainder is required as heat, and this can theoretically be provided as thermal energy from the surroundings, or from electrical losses within the cell.

According to a basic law of thermodynamics, the electrical work ΔF, done on or by a cell is equal to the free energy change occurring, or

$$\Delta F = -nFE$$

where n is the number of electrons passing, E is the reversible voltage of the cell, and F is Faraday's constant. By the use of this law, the minimum theoretical electrical energy requirement can be measured in terms of an applied voltage, and for the electrolysis of liquid water solutions at 25°C it is 1.229 V, or 14.9 kWhr/lb H_2. A perfect cell would operate at this voltage and energy input but would require the additional input of thermal energy equivalent to another 3.1 kWhr/lb H_2. In order to provide all the necessary energy as electrical energy, the corresponding voltage is 1.482 V (18.0 kWhr/lb). A practical cell can approximate this voltage at low output rates, since it is still experiencing a 20% low of efficiency from an "ideal" situation. Under usual operating conditions, commercial electrolysis plants require much higher power levels, due to even greater than 20% power losses in electrolyte or in the electrodes themselves.

The theoretical reversible voltage (defined by the free energy change) decreases with temperature, while the "thermoneutral" voltage (defined by the enthalpy change) increases slightly with increasing temperature. The theoretical energy requirements are shown in Fig. 4 along with the actual performance of selected cells. The actual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ENERGY / lb of H2 PRODUCED ; kWhr / lb of H2
0
5
10
15
20
25
30
0
100
200
300
400
500
600
700
800
900
1000
1100
TEMPERATURE (°C)
212
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performance is improved at elevated temperatures due to changes in the conductivity of the electrolyte and in the activity of the electrodes. Note that the apparent advantage of very high temperature (∿1100°C) vapor cells using a solid electrolyte is not currently realized. This is apparently due to the necessity of operating such cells at a rate that results in sufficient waste heat to maintain cell operating temperature. A nearly equal energy requirement is obtained with alkaline electrolyte electrolyzers operating at temperatures of 150°C (302°F).

Efficiency of water electrolysis should be defined as the energy stored as chemical energy in the hydrogen (ΔH) divided by the electrical energy required to produce hydrogen. There are two values of the chemical energy, i.e., the "high" heating value (HHV) and the "low" heating value (LHV) - the difference, ∿20%, is the heat available as latent heat of condensation. Throughout this report the LHV is used, since in most end uses the latent heat is not productive. Commercially available electrolysis plants operate at electrical efficiencies between 57% and 72%. The best demonstrated efficiency for advanced electrolysis cells is approximately 80%. Note that once the cell performance reaches the "ΔH" line on Fig. 4, operation below this voltage is theoretically possible and represents an apparent efficiency greater than 100% efficiency if only the electrical input is considered. As stated earlier, operation within the bounds of the ΔH and ΔF lines of Fig. 4 is quite possible, results in an "endothermic" cell, and thus requires the input of thermal energy at the cell's operating temperature.

Current commercial electrolysis plants. Current installed electrolysis plant capacity throughout the world is estimated to be 3 x 10^6 lb of H_2 per day. Primary use of this hydrogen is in the production of ammonia. Hydrogen is predominantly produced from fossil fuels by catalytic steam reforming or partial oxidation, so that the percentage of hydrogen produced by electrolysis throughout the world is only 3% of the total hydrogen used in the U.S. The reason for this low percentage is the current low cost of hydrocarbon fuel compared with the cost of electricity.

The electrolysis plants that have been installed are located in areas where there is a significant demand for fertilizer (NH_3), plentiful low-cost electricity, and no low-cost hydrocarbon fuel supply. Areas in which this has been true include India, Egypt, Chile, and Norway.

Table 3 lists a number of major electrolytic hydrogen plants, their operating parameters, and capacity. As can be seen, some of the plants have been installed and operated for a considerable number of years.

Economics of hydrogen production by electrolysis. In the design of an electrolysis plant, two factors predominate in the determination of the cost of the hydrogen produced: (1) the capital cost of the electrolysis plant, the cost of money, and the life of the equipment; and (2) the cost of electrical power. The desire for low capital cost tends to push the design operating current density to the highest level possible, but this, in turn, results in lower efficiency, hence increased power consumption, so that a trade-off between capital and operating cost must be considered to arrive at the optimum plant design. This is the major reason for the large variation of plant operating parameters reported in Table 3. Today's capital cost of large-scale electrolysis plants is approximately \$95/lb H_2 per day or approximately \$95/kW(e) based on input power (using 24 kWhr/lb H_2). At a fixed charge rate of 15% and a 90% plant factor, the capital charges would be equivalent to 4.3¢/lb H_2, or 84¢/10^6 Btu.

An advanced electrolysis plant has been estimated to cost less than \$40/lb H_2 per day or, using 20 kWhr/lb H_2, \$48/kW(e) (equivalent to about 2¢/lb H_2). The major components of system costs of an advanced electrolysis plant are shown as a percentage of total plant cost in Table 4. The components of this plant were optimized for operation at a power cost of 5 mills/kWhr. The major cost item is the power supply which is assumed to be a transformer/silicon-controlled-rectifier (SCR) type. The second largest cost item is the electrolysis module, which is assumed to be a filter press type. The cost percentages would not be expected to vary appreciably if a tank-type electrolysis module were used.

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Table 3. Summary of electrolytic hydrogen plant equipment

Company/location	Cell name	Cell Design: Type	Current density (A/ft²)	Operating voltage (V/cell)	Module size (lb H_2/day)	Pressure (psig)	Number of plants	Experience: Largest size plant (lb H_2/day)	Earliest plant (year)	Best known plant (year)
A. Norsk Hydro Notodden, Norway	Hydro-Pechkranz	Filter press	140	1.778	1880	1	3	284,000	1927	Rjukon, Norway 1965
B. Lurgi Frankfurt, Germany	Zdansky-Lonza	Filter press	200	1.832	4200	440	32	22,000	1955[a]	Cusco, Peru 1958
C. DeNora Italy	DeNora	Filter press	280	2.00[b]	4100	1	2	110,600	1958	Nangal, India 1958
D. Pintsch-Bamag Germany	Bamag	Filter press	230	1.788	2600	13.5	200	UNK	1935	UNK
E. Electrolyser Corp. Canada	Stuart	Tank	200	2.04	40	0.03	1000	1,130	1930	Teledyne Wah Chang, Alabama, USA, 1971
F. Cominco Canada	Trail	Tank	80	2.142	38	0.1	1	77,000	1939	Trail, Canada 1939
G. Teledyne Isotopes USA	EGGS	Filter press	400	2.1	65	70	2	50	1968	Teledyne Isotopes, USA, 1972
H. Demag Elektro-metallurgie GMBH Duisburg, Germany	Demag	Filter press	92 to 280	1.75-1.95	900	1	57	177,000	1945	Aswan Dam, Egypt 1960
I. Electric Heating Equipment Co. USA	Kent	Tank	115	2.2	28	0.1	100	1,610	1920	Hobart, Tasmania 1949
		Cells being developed								
J. Teledyne Isotopes USA		Filter press	400	1.65	13	2000		Designed for military aircraft application		
K. Teledyne Isotopes		Filter press	250	1.64	94	3000		Designed for nuclear submarine application		
L. General Electric		Solid electrolyte	3260	1.2-1.8		1		2000°F, not now under development		
M. Westinghouse		Solid electrolyte	900	0.5[c]		1		Used for CO_2 electrolysis in spacecraft atmosphere control system		

[a] First Zdansky-Lonza plant.

[b] DeNora has indicated an ability to achieve 1.61 V on new cells.

[c] Assumes a fuel depolarized mode of operation, i.e., coal. Does not expect cell to be used as water electrolyzer.

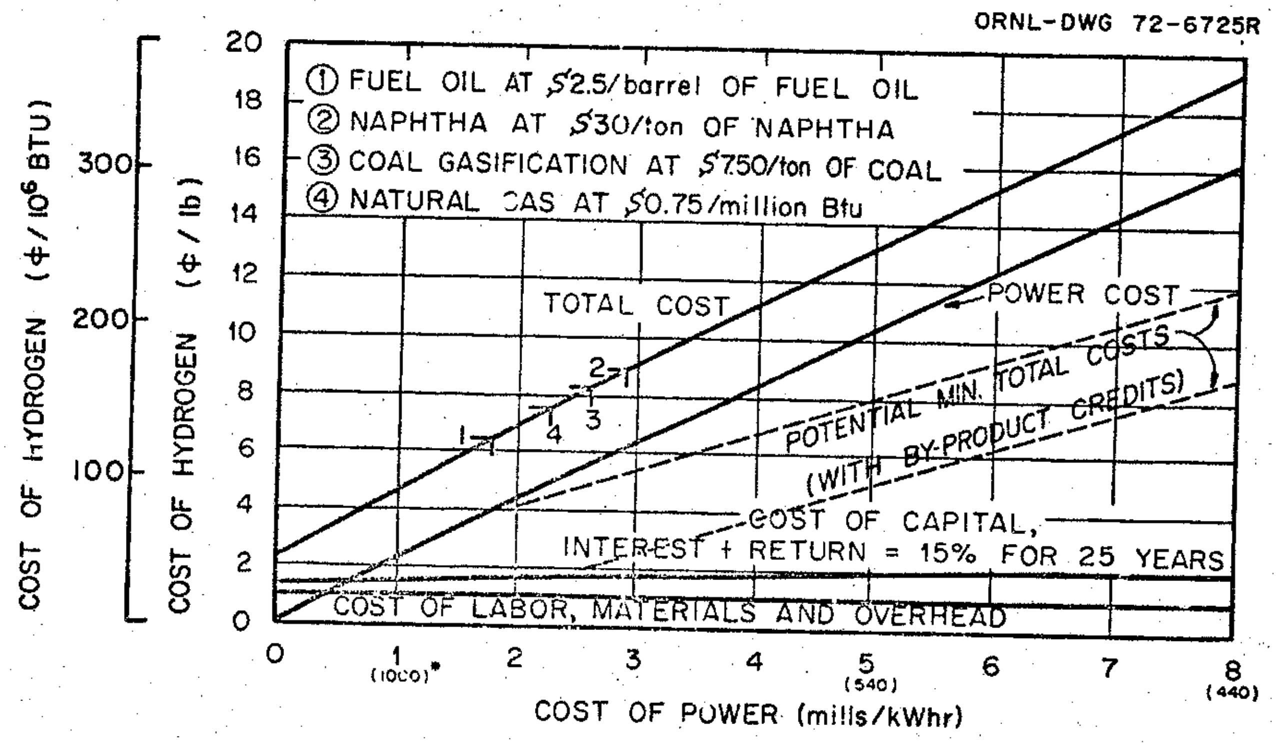
The total hydrogen production cost for advanced electrolysis plants, including electricity cost is plotted in Fig. 5. The cost of producing hydrogen has been minimized at each power cost. The importance of the cost of electricity is readily evident, representing 84% of the production cost at 6 mills/kWhr and 73% at 3 mills/kWhr. An allowance has been made for a power conversion efficiency of 95%, the approximate efficiency currently obtained by transformer/SCR power supply. An efficiency of 97% might be obtained with acyclic dc generators.

Table 4. Plant cost breakdown by major cost element of an electrolysis plant, excluding energy costs

Major cost element	Approximate percentage of total cost
Parts, materials, and equipment	
Power supply	36
Electrolysis module	33
Plumbing	8
Spares and miscellaneous	3
Labor and overhead	20

Plant supervision, operators, maintenance labor and materials, and overhead all contribute to the cost of hydrogen. This is estimated to be 0.96¢/lb H_2, or about 19¢/10^6 Btu.

A cost credit for the sale of oxygen may be possible. Current price of oxygen is approximately $8/ton. Since about 8 lb of oxygen is produced per pound of hydrogen, this represents a credit of 3.2¢/lb H_2. It is not likely that this total credit can be obtained because of the high relative cost of transporting the oxygen to the market. The actual credit is estimated to be between 1.6¢/lb H_2 ($4/ton) and zero. In some cases it may be possible to co-produce deuterium (heavy water) and



*Cell current density, amps/ft^2

Fig. 5. Total cost of hydrogen production.

receive some credit against the cost of producing hydrogen. In two recent analyses[3] of this possibility, a credit range of from 0.8¢ to 1.6¢/lb H_2 was computed. Also shown in Fig. 5 are the estimates of H_2 production costs for various processes using fossil fuels. It is of interest to note that at the projected price for natural gas of 75¢/10^6 Btu, hydrogen could be produced for 10¢/lb, or 194¢/10^6 Btu. This is equivalent to the water electrolysis process with a power cost of 3.5 mills/kWhr. Off-peak power from nuclear power plants could be priced at about 2.5 mills/kWhr if no capital charges are included. At this power cost hydrogen could be produced for \$1.17/10^6 Btu.

Ultimate potential. Although water electrolysis is already a relatively efficient process, it does appear to be susceptible to further improvement. In particular, increasing the operating temperature and reducing some of the internal IR losses appear possible. As implied by Fig. 4, it may be possible to attain a performance level where only 13 to 15 kWhr/lb H_2 is required. (At this low power level, heat addition is required to maintain the cell operating temperature.) This represents a 25 to 35% reduction in power requirement which could be supplemented by an additional 2 to 3% by improvements in the power conditioning system. This would mean a production cost reduction of as much as 5¢/lb H_2 (from 14¢/lb) at a power cost of 6 mills/kWhr, but, more importantly, it means that the power plant capacity and the corresponding capital investment required for a given hydrogen capacity could be decreased by over 30%. Credits available from by-products, oxygen and deuterium, could give an additional 2¢ to 4¢/lb cost reduction as indicated in Fig. 5.

With an electricity-intensive process such as electrolysis, considerable leverage exists in decreasing the amount of power required per unit of production or in decreasing the cost of the power. Low-cost power as may be available from some few remaining remote hydroelectric sites would seem to be ideal for this use. Also, the use of off-peak power, particularly from a future essentially all-nuclear system, would also be an attractive power source. The advanced cells seem to be readily adaptable to operating with large power swings (variable cell current density) and can make use of the power when it is available or dispense with it when the electrical system requires it.[4,5] This latter characteristic could eliminate the need for a separate low-use factor system for generating power to meet the peak demands. This characteristic also allows electrolysis plants to be coupled with intermittent energy sources such as solar, winds, tides, etc.

Although investment costs normally contribute relatively little to the total production cost of electrolytic hydrogen, with the extremely large plants that may some day be required, the benefits of decreasing the demands for limited capital resources could be an important factor. As indicated in Table 4, over one-third of the plant cost is in the power-conditioning system, and several possibilities seem to be available for decreasing this component, particularly with the concept of a dual-purpose electricity/hydrogen installation. Examples of these are: (1) direct generation of direct current with acyclic generators, perhaps with cryogenic machines using some of the LH_2 (liquid hydrogen) produced, and (2) using direct current as produced from some advanced generating systems, magnetohydrodynamic (MHD), thermo-electric, thermo-ionic, etc., or using a portion of the power from a dc long-distance transmission line.

It should be emphasized that the overall process efficiency and cost of producing hydrogen by water electrolysis is closely related to the electricity production technology. Recognition should therefore be given to potential improvements in the generation of electricity which are currently under development, e.g., higher temperature operation, combined cycles (both topping and bottoming), and MHD. Some of these developments may raise the conversion of heat to electricity to a level of 50-55% and thus yield an overall hydrogen production efficiency of as much as 50%.

<u>Environmental and resource effects.</u> The main effects of the electrolytic production of hydrogen on the environment are those associated with the production of the electricity required. With nuclear electricity these are primarily disposal of waste heat and the waste fission products and the mining and preparation of the uranium

feed material. If the ultimate system resolves down to a choice between all-electric and electric-hydrogen systems, the above-mentioned environment and resource effects will not be greatly different (see Sec. 6, Systems Analysis). The production process itself would most likely reject some waste heat and perhaps some by-product oxygen, which is not normally considered a pollutant, in fact, it has many pollution abatement uses.

The primary metal used in the construction of electrolysis plants which might become of resource concern is nickel. It is estimated that the maximum nickel requirement would be 1×10^{-5} lb/lb H_2 (as plant capacity). If the natural gas deficit of 1985 of 15×10^{18} ft^3 were met with hydrogen, the amount of nickel required would be about 3×10^6 lb. This may be compared with the 1966 U.S. production of 92×10^6 lb and a world production of over 700×10^6 lb.

Platinum or palladium would most likely not be required for this application.

Safety and reliability. The gases produced, the chemicals used, and the voltages associated with electrolytic hydrogen production plants require attention to well defined engineering and safety practices. The record of the industry, with a historical background of over 50 years, has been excellent. More recently the ability to safely handle large volumes of liquid and high-pressure hydrogen and oxygen has been demonstrated by the space program.

The record attained by installed electrolytic plants has been very good. In many instances the operating time per year has approached 95% of the available (or desired) time. The operating lifetime of a properly maintained plant is greater than 20 years.

Research and development. Relatively little research and development on the water electrolysis process is currently in progress. Teledyne Isotopes* has research and development work in progress to lower cell fabrication costs and to improve cell performance and service lifetime. Some work on specialized systems for space and submarine applications is also being done although it seems unlikely that much of

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*Formerly the Allis Chalmers Advanced Electrochemical Products Department — acquired by T. I. in March 1971.