

HYDROGEN AND SYNTHETIC FUELS FOR THE FUTURE*

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INTRODUCTION

Early in 1972 the Energy R&D Goals Committee of the Federal Council on Science and Technology organized a study to assess a number of basic energy technologies which could favorably influence the U.S. future energy supplies. Various federal agencies sponsored eleven technical panels to perform this assessment and to prepare R&D plans for developing the priority technologies. The findings of one of these panels, "Hydrogen and Synthetic Fuels," sponsored by the USAEC, is the primary subject of this paper.

While there are currently serious problems in providing adequate electricity, the longer-term energy problems seem to be more associated with providing an assured supply of environmentally acceptable portable fuels. The importance of this supply is apparent when it is realized that electrical energy only meets about one-tenth of our end-energy needs today - the remainder is supplied from fossil fuels, mainly petroleum and natural gas.

While production of synthetic fuels requires thermal or electrical energy and thus may appear to complicate an already difficult problem, this energy can be obtained from domestic and, for the most part, clean sources, e.g., nuclear or solar. Further, because of low transport costs, synthetic fuels can be produced at remote, well-regulated plants and thus would not contribute to the primary pollution problems that exist in our urban centers. An additional consequence of such a system is that of conservation of our limited fossil fuel resources, particularly petroleum, so that they may be used as valuable chemical product feedstocks and in metallurgical processes. The synthetic fuels, especially hydrogen, may be consumed with very little or no air pollution as well as with higher conversion efficiencies and thus could be more attractive for urban uses than the fossil fuels in current use.

The intent of this paper is to summarize the findings⁽¹⁾ of the Synthetic Fuels Panel which evaluated the major aspects of new fuels systems, i.e., production, storage and transportation, end uses and an overall systems analysis. While the emphasis was on hydrogen and other fuels from nonfossil sources, a section on the use of coal to produce hydrogen and methanol is also included to help define the interim time period before our dependency on nonfossil fuels occurs.

The organization of the panel and the main contributors to the effort are given in the Appendix. The primary fuels considered, along with a listing of their significant characteristics, are given in Table 1.

PRODUCTION OF 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. In considering the production of hydrogen from nonfossil primary energy sources four main processes are available - water electrolysis, thermal-chemical, biological, and radiolytic. Most current hydrogen production facilities are based on the use of fossil fuels, mainly natural gas and various petroleum fractions wherein the hydrogen source is partly from the hydrocarbon and partly from

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Table 1. Comparative characteristics of synthetic fuels

Fuel	Heat of combustion, low heating value (Btu/lb)	Heat of vaporization at b.p. (Btu/lb)	Relative fuel required to equal H ₂ heat content		Density		Boiling point (°F)	Ease of storage ^d	Toxicity ^b	
			By wt	By vol	Liquid (lb/ft ³)	H ₂ ^a (lb/ft ³)				Gas, STP (lb/ft ³)
Hydrogen (H ₂)	51,600	194	1.0	1.0 (liq.)	4.4	4.4	0.005	-423	6 (liq.)	1
Ammonia (NH ₃)	8,000	590	6.4	0.6	42.6	7.8	0.043	-28	4	5
Hydrazine (H ₂ H ₄)	7,200	540	7.2	0.5	62.4	8.9		236	3	6
Methanol (CH ₃ OH)	8,600	474	6.0	0.5	49.7	7.1		149	2	4
Methane (CH ₄)	21,500	220	2.4	0.4	25.9	6.5	0.041	-259	5 (liq.)	2
Ethanol (C ₂ H ₅ OH)	11,600	360	4.4	0.4	49.7	6.5		173	1	3
Gasoline ^c (C ₈ H ₁₈)	19,100	140	2.7	0.3	43.8	7.0		257	(1)	(4)

^aDensity of hydrogen in the fuel.

^bRelative ranking.

^cIncluded for reference only.

water. As these fossil fuels become more expensive and less available, H_2 can be made from coal in which carbon is used to reduce water. As coal becomes more expensive, hydrogen could be produced on a massive scale by water electrolysis using nuclear, solar, or geothermal primary energy sources.

Water Electrolysis

Water electrolysis is a well established commercial process in which hydrogen and oxygen are produced by the passage of electricity through a conducting water medium. Figure 1, along with Table 2, gives a comparison of the actual performance of electrolysis cells to the theoretical energy requirements as a function of cell operating temperature.

The energy that must be supplied to the cell to cause the reaction H_2 (liquid) + H_2 (gas) + $1/2O_2$ (gas) to proceed is the enthalpy of formation of water, $\Delta H_{(g)}$, and is equal to 68.32 kcal/mole at 25°C and 1 atmosphere. However, only the free energy of this reaction, $\Delta F_{(g)}$, 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.

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 actual performance is improved at elevated temperatures due to changes in the conductivity of the electrolyte and in the activity of the electrodes.

Efficiency of water electrolysis may be defined as the energy stored as chemical energy in the hydrogen (ΔH) divided by the electrical energy required to produce hydrogen. Throughout this report the LHV is used for ΔH , 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. 1, operation below this voltage is theoretically possible and represents an apparent efficiency greater than 100% if only the electrical input is considered. As stated earlier, operation within the bounds of the ΔH and ΔF lines of Fig. 1 is quite possible, results in an "endothermic" cell, and thus requires the input of thermal energy at the cell's operating temperature.

The economic factors involved in the electrolytic production of H_2 are illustrated in Fig. 2 and show the strong influence of the cost of the electricity used. The improvements in the cell efficiency that appear achievable, together with partial credit for the by-products, oxygen and deuterium, could allow a factor of two decrease in the production cost.

With such an electricity-intensive process 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 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 shed it when the electrical system requires it.^(2,3) 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.

Thermochemical Processes

Electrolysis of water suffers from inherent thermodynamic limitations on the efficiency of initial conversion of thermal to electrical energy (currently ~30-40%) in addition to an expected maximum realizable electrolytic efficiency of about 80-90%. The large-scale needs for fuel therefore justify attempts to find processes that may exceed

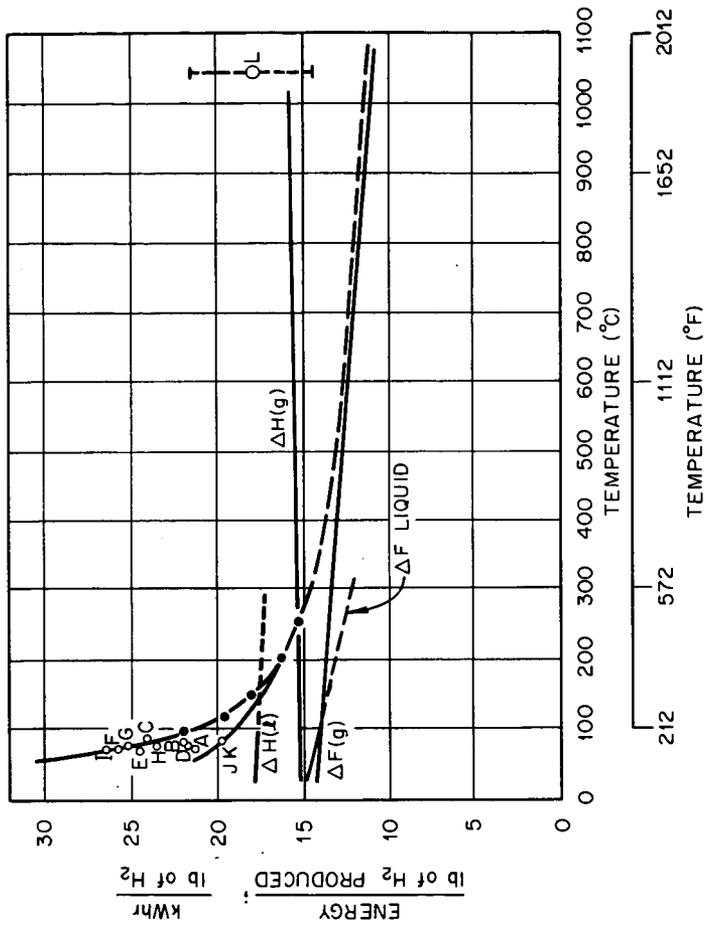


Fig. 1. Performance of water electrolysis cells compared to theoretical relationships. (See Table 2 for identification of A to L.)

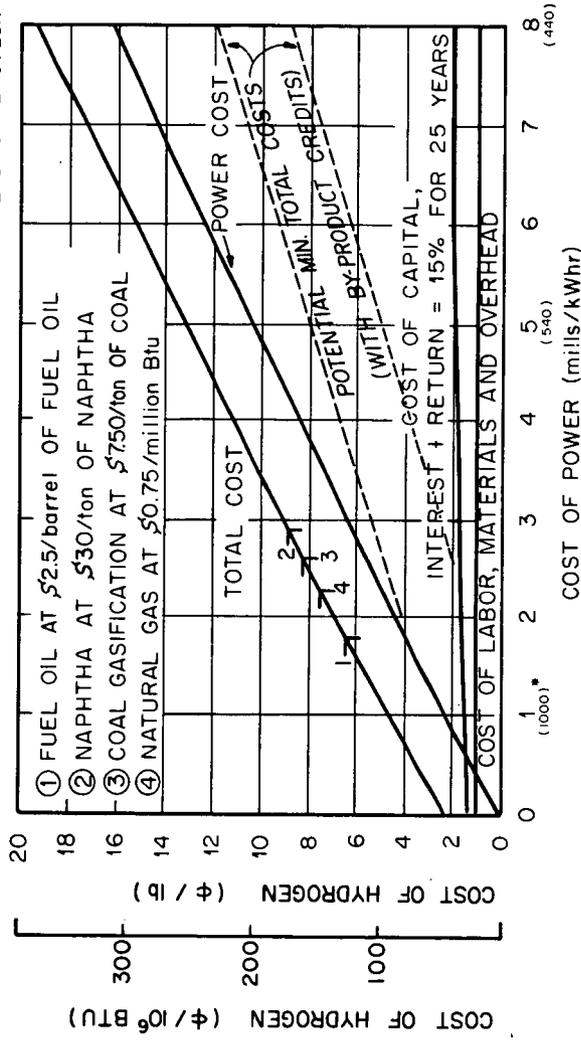
Table 2. Summary of electrolytic hydrogen plant equipment

Company/location	Cell name	Type	Cell Design				Experience			
			Current (A/cell)	Operating Voltage (V/cell)	Module (lb H ₂ /day)	Pipework (ft)	Number of plants	Largest plant (lb H ₂ /day)	Earliest plant (year)	Best known plant (year)
A. Norsk Hydro Bodden, Norway	Hydro-Fuehranz	Filter press	140	1.778	1880	1	3	284,000	1927	Rjukan, Norway 1965
B. Lurgi Frankfurt, Germany	Zdaneky-Loma	Filter press	200	1.832	4200	440	32	22,000	1955 ^a	Cuzco, Peru 1958
C. DeSore Italy	DeSore	Filter press	280	2.00 ^b	4100	1	2	110,600	1958	Madag, India 1958
D. Pilsch-Baum Germany	Baum	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	Teleyne Wash 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 ORH Duisburg, Germany	Demag	Filter press	82 to 175- 280	1.75- 1.95	900	1	57	177,000	1945	Awana Dm, Egypt 1960
I. Electric Heating Equipment Co. USA	Kent	Tank	115	2.2	28	0.1	100	1,610	1920	Hobart, Tasmania 1940
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 electro- lysis	360	1.2- 1.8		1				2000 ^o F, not now under development
M. Westinghouse		Solid electro- lysis	900	0.5 ^c		1				Used for CO ₂ electrolysis in spacecraft atmosphere control system

^aFirst Zdaneky-Loma plant.

^bBefore has indicated an ability to achieve 1.61 V on new cells.

^cAssumes a fuel depolarized mode of operation, i.e., coal. Does not expect cell to be used as water electrolyser.



* Cell current density, amps/ft²

Fig. 2. Production cost of hydrogen via water electrolysis.

the 25-35% overall thermal efficiency of electrolysis for hydrogen production. With the development of high-temperature nuclear fission reactors (and the potential development of fusion reactors), two conceivable processes for the production of hydrogen from water are: (1) thermochemical and (2) radiolytic. Solar or geothermal energy also are potential alternative heat sources for the thermochemical route. It should be recognized, however, that these high-temperature heat sources are also capable of more efficient conversion of heat to electricity so the ultimate overall electrolytic efficiency might approach 50%. Further, efficiency must be tempered with economics, reliability, safety, etc. to make meaningful comparisons between processes.

Various thermochemical hydrogen production routes have been investigated from the direct (high-temperature) dissociation of water to four- and five-step chemical reaction sequences, but none have been developed to the point of commercial utilization. In one set of reactions involving the reverse Deacon reaction followed by three sequential reactions of various vanadium chlorides, thermal efficiencies of 6 to 18% were computed⁽⁴⁾ after allowing for all process energy requirements and losses. Higher efficiencies have been claimed by other investigators using different reaction sequences.⁽⁵⁾

Biological and Other Processes

Biological processes have been in use for the production of synthetic fuels in a limited manner for many years. Primary examples are the generation of methane from sewage and fermentation of grains and sugars to produce alcohol. In most cases, such systems are dependent on the diffuse solar energy input or the relatively slow processes of bacterial action and therefore may be difficult to scale up economically to the very large sizes required to meet a significant share of the future demand for fuels. A system for producing hydrogen via an interrupted photosynthesis process has been proposed and is currently being investigated. Based on preliminary estimates, a 500-tons-per-day hydrogen plant would require the solar input collected over an area of 22 square miles.

A number of other production possibilities were recognized, e.g., multistep chemical reaction followed by electrolysis, combined water electrolysis with coal gasification, using by-product oxygen, and radiolytic decomposition of water. Insufficient existing data were available to make comprehensive analyses of these processes.

The technologies and costs for the production of other synthetic fuels, specifically NH_3 , CH_3OH , and N_2H_4 , were shown to be well developed commercial processes. The long-range potential problem of a source of carbon (as CO or CO_2) for methanol synthesis was believed to be available from the atmosphere, limestone, seawater or combustion of waste organic matter.

Waste Processes

Obtaining fuels from urban and agricultural wastes was briefly examined. Of the 3×10^9 tons of solid organic wastes generated yearly in the U.S., about two-thirds are manure and over 80% are of agricultural origin. Total municipal and industrial wastes are about 0.4×10^9 tons, half of which are currently collected for disposal by municipal agencies.⁽⁶⁾

A study prepared for the U.S. Department of the Interior's Bureau of Mines (BuMines)⁽⁷⁾ indicates that more than half the total weight of these wastes is actually water. In 1971, the total amount of dry, ash-free organic waste produced in this country was only 880 million tons with about 136 million tons of dry organic wastes being readily collectable for conversion. This amount would have produced 170 million barrels of oil - roughly 3% of 1971 consumption of crude oil or 12% of imported crude. Alternatively, this amount of waste could have produced 1.36 trillion scf of methane, about 6% of 1971 consumption of natural gas. If all the wastes could be collected for this purpose, nearly 40% of our natural gas use could come from this source.

Among the problem areas which must be considered in developing synthetic fuels from wastes is the cleanliness of the fuels, i.e., the suitability of the fuels to unrestricted use as pipeline gas and the economic collection and storage of diffuse wastes sources, particularly agricultural wastes.

Agricultural Processes

Related to the use of waste processing is the production of fuels via intensive agriculture. The fuels that may be produced in this manner are ethanol from fermentation of grains, sugars, or starches, methanol from waste products, and wood from tree farms. The crop processing technology seems to be well developed, but the overall economics have been unfavorable due to the low cost of competing fossil fuels. The application of intensive agricultural methods (i.e., use of optimized nutrients, soil moisture levels, etc., coupled with a multiple crop climate), and the rising price of fossil fuels work toward making this scheme profitable. However, the relatively large amounts of land required to produce a significant fraction of our fuel requirements seem to preclude the use of this concept to areas of very specialized application, e.g., ethanol as a replacement for tetraethyl lead (10% in gasoline).*

The use of wood obtained from a tree farm has been proposed⁽⁸⁾ as a fuel for a conventional steam-electric power station. Preliminary computations indicate that an intensively farmed area of 400-600 sq mi would be required to continuously supply a 1000-MW(e) power station with wood fuel.

Although not usually considered agriculture, growing algae for fuel has often been proposed.⁽⁹⁾ Here the fuel could be methane, but again the large land areas required suggest that such a system is not likely to meet a significant fraction of our total energy needs.

USE OF COAL

While the emphasis of the Synthetic Fuels Panel was directed toward nonfossil sources of portable fuels, some effort was devoted to the use of coal and lignite for the production of hydrogen and methanol. Many other studies and demonstrations are in progress to produce more conventional hydrocarbon fuels from coal which could be used for a comparative analysis.

The U.S. has been estimated to have had 3.21×10^{12} tons of coal at the end of 1969⁽¹⁰⁾ or the equivalent of 64.4×10^{18} Btu of energy. Only one-half of this coal is believed to be recoverable; however, the U.S. total consumption of nonnuclear energy in 2000 has been estimated to be about 131×10^{15} Btu. A rough conservative assumption can be made that one-half of the energy in the coal could be delivered to end uses in the form of hydrogen and methanol. Thus, even if all nonnuclear energy were to be provided by hydrogen and methanol, coal could be the source of these two synthetic fuels for 120 years at the year 2000 consumption rate.

Two methods for producing hydrogen from coal were reviewed: steam-oxygen (Synthane) and CO₂-acceptor. These processes give similar production costs; those for the CO₂-acceptor process are shown in Fig. 3 as a function of the cost of the raw material. While these processes appear to be commercially viable, they have not been used in the U.S. due to the relatively lower cost of hydrogen available from natural gas and various petroleum fractions. In comparison to the production of methane from coal, hydrogen appears to offer a simplified flow sheet since no methanation step is required.

Methanol has been produced from coal in some parts of the world but not in the U.S. A two-step analysis of the manufacturing costs of (1) coal gasification and synthesis gas (H₂, CO) purification and (2) methanol synthesis is summarized in Table 3. The cost of

* This requires 8.8×10^9 gal of alcohol/yr or 3.3×10^9 bushels of grain or about 40×10^6 acres of land.

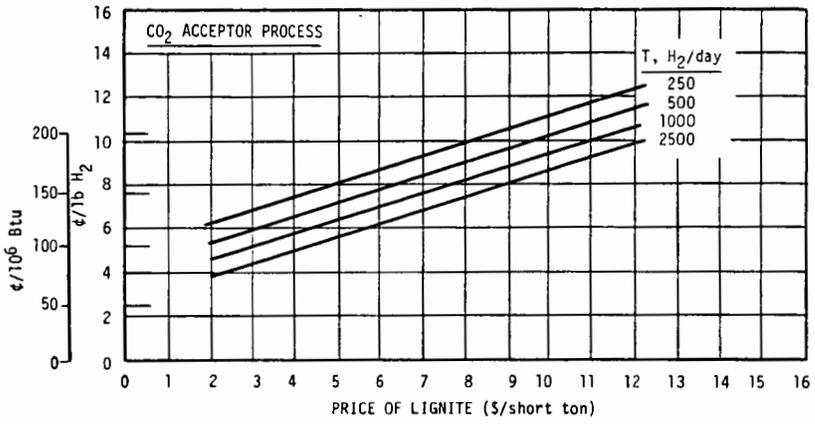


Fig. 3. Cost of producing hydrogen from coal.

Table 3. Economics of synthesis of 20,000 tons/day of methanol (MeOH) from coal

Item	Unit	Units /day	Cost		
			\$/unit	\$/day	¢/gal MeOH
Synthesis gas manufacture (Capital for plant: \$260 x 10 ⁶)					
Coal ^a	Ton	26,000	7.00	182,000	3.02
Chemicals				1,000	0.02
Process water	10 ³ gal	6,250	0.20	1,250	0.02
Cooling water	10 ³ gal	346,000	0.02	6,920	0.11
Operating labor	Man-hr	960	4.00	3,840	0.06
Supervision				380	0.01
Maintenance				35,600	0.59
Overhead				<u>4,220</u>	<u>0.07</u>
Precapital manufacturing cost				235,110	3.90
Capital charges at 15%/year				<u>106,800</u>	<u>1.77</u>
Total cost				341,910	5.67 (99¢/10 ⁶ Btu)
Methanol synthesis from provided Syngas (Capital for plant: \$135 x 10 ⁶)					
Steam	10 ³ lb	38,200	0.65	24,800	0.41
Fuel	10 ⁶ Btu	21,600	0 ^b		
Electricity	kWhr	100,000	0.01	1,000	0.02
Cooling water	10 ³ gal	540,000	0.02	10,800	0.18
Catalyst and chemicals				15,000	0.25
O&M labor and supervision				50,000	0.83
Overhead				<u>14,000</u>	<u>0.23</u>
Precapital manufacturing cost				115,600	1.92
Capital charges at 15%/year				<u>55,400</u>	<u>0.92</u>
Subtotal				171,000	2.84
Total cost				512,910	8.51 (148¢/10 ⁶ Btu)

^aCombined raw material and fuel.

^bPurge gas from synthesis gas plant.

producing the synthesis gas is seen to be the dominant cost and this, in turn, is largely dependent on the cost of coal. If lignite at \$2/ton were used, the total cost would decrease to 6.4¢/lb (\$110/10⁶ Btu). The costs of the various fuels are summarized in Table 4.

STORAGE AND TRANSPORTATION OF SYNTHETIC FUELS

The technology and practice of storage and transportation of most of the fuels considered in this paper have been extensively developed and demonstrated on a significant scale. Hydrogen gas is being produced and distributed in and among refineries under conditions that would simulate a fuel gas production and distribution system. There are, however, no existing hydrogen transmission or distribution systems in which booster compressors are utilized. Liquid hydrogen equivalent to over 100 billion cu ft (STP) has been produced and distributed in support of the space program. Production of ammonia for fertilizer has reached a scale of distribution in which large interstate pipelines are now operating in addition to the extensive barge, rail, and truck systems that have been built to achieve economical distribution. Because of the seasonal nature of agricultural chemicals supply, large storage complexes have also been developed. Methanol has long been a basic tonnage petrochemical, and distribution by all means has been fully developed.

Storage of Fuels

The estimated investment for storing energy in the form of a synthetic fuel is illustrated in Fig. 4. The storage of gaseous hydrogen in pressure vessels appears to be non-competitive for the full range of storage capacity. This is due to the combination of low specific volume of the gas and high cost of the pressure vessel. The adaptation of gaseous storage might be enhanced by using the transmission line as an inventory device (line packing) — e.g., a pressure change from 750 to 1000 psia in 300 miles of 3 ft dia pipe can store the equivalent of 5.2×10^4 million Btu. The volume and weight of a fuel storage tank containing 2×10^6 Btu, the approximate size of an average automobile fuel tank, are given in Fig. 4. A tank of liquid (cryogenic) hydrogen would be twice as heavy, seven times greater in volume, and of much higher cost than an equivalent tank of gasoline.

It should be recognized that the storage costs shown are based on present technology and production techniques. With further development and use of mass production systems it is expected that the values shown for the unconventional types should decrease by as much as a factor of two.

The cost of a compression and/or liquefaction system should be added to the cost of storage in assessing the utility of hydrogen energy systems. The cost of hydrogen gas compression might typically be 15 to 50¢ per 10⁶ Btu (.8 to 2.6¢/lb) for a wide range of delivery pressures and equipment utilization factors. The cost of hydrogen liquefaction might typically be \$1 to \$2 per 10⁶ Btu (5.2 to 10.4¢/lb) for a wide range of system capacities and utilization factors. The electrical power requirement alone is about 5 kWhr/lb H₂. These costs are usually more significant than tankage costs and must be considered in the design and evaluation of liquid H₂ storage systems.

Evaporation losses from large LH₂ tanks (~10⁶ gal) are typically 0.03%/day while small mobile tanks may be from 1 to 10%/day. A possibility for circumventing some of the above costs and storage losses is the use of hydrides or compounds of hydrogen. Several hydride storage systems have been investigated and indicate that a large number of binary and tertiary metal systems are available for this use. Magnesium and alloys of Mg and Cu or Ni⁽¹¹⁾ will release H₂ at 1 atm at temperatures of from 440°F to 540°F. Also some intermetallic compounds of the composition AB₅,⁽¹²⁾ where A is a rare-earth metal and B is nickel or cobalt, are reported to absorb and desorb large quantities of hydrogen at near room temperature. Some compounds such as ammonia and hydrazine can be readily decomposed to yield H₂. The hydrogen density in these compounds is from 1.5 to 2.0 times that of liquid hydrogen. Still lower effective heating values would, however, result since the heat of dissociation must be supplied, although in some applications waste heat may be utilized for this purpose.

Table 4. 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
Ammonia	Natural gas, 45¢/10 ³ ft ³	157	Off-peak power, 2.5 mills/kWhr, adv. tech.	195 ^b
			H ₂ via H ₂ O electrolysis, 8 mills/kWhr	517
Hydrazine		~2100	H ₂ via H ₂ O electrolysis, 2.5 mills/kWhr	228
Methanol	Natural gas, 40¢/10 ³ ft ³	158	H ₂ via H ₂ O 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
	Well-head gas	15 - 40	Urban and agricultural wastes	~115
Methane	LNG, imported	80 - 100		
	Coal	80 - 100		
Gasoline	Crude oil	105		

^aCosts are based on 15% fixed charge rate and large plant capacities.

^bWater electrolysis plant operated at a 0.3 load factor.

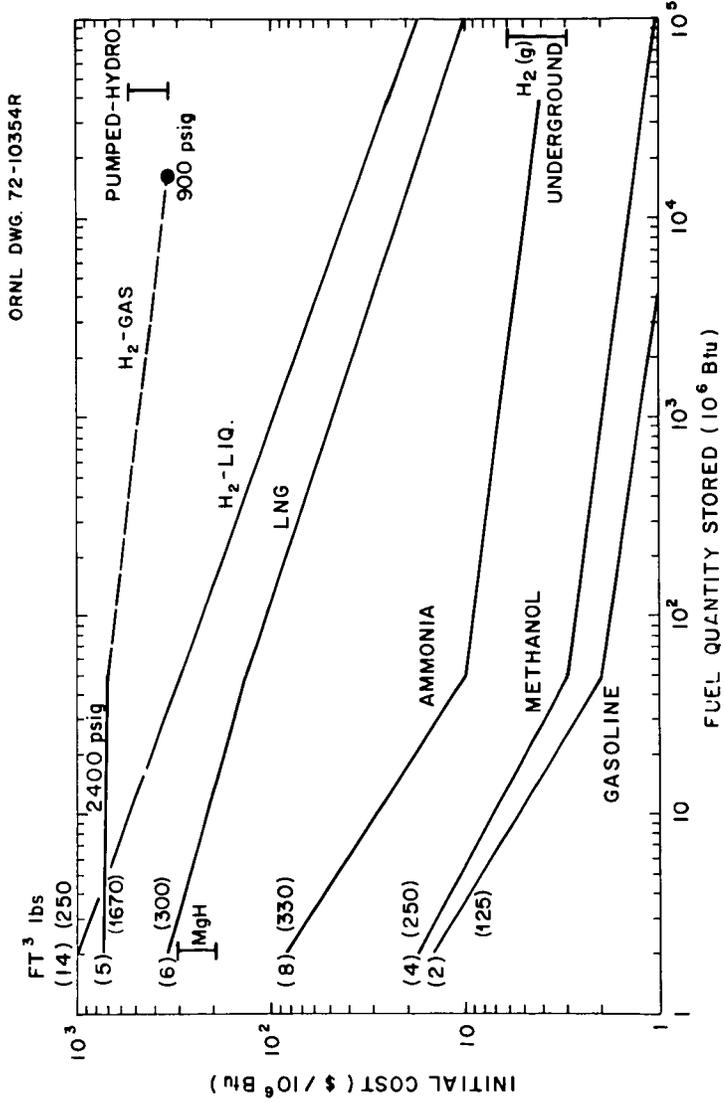


Fig. 4. Investments costs for storage of energy.

Fuels Transportation

The costs of transporting various forms of energy in a near-urban environment are summarized in Table 5. An average cross-country cost for natural gas transmission today is reported to be 1.5 to 1.7¢/10⁶ Btu per 100 miles.⁽¹³⁾ Hydrogen transmission cost would be 2.6 times this cost since compressor size and horsepower must be considerably increased and a more expensive fuel (hydrogen) used to power the compressors. By increasing the pipeline operating pressure from the "usual" 750 psia to 2000 psia, this factor could be reduced to about 1.5. Further, the average pipeline distance for hydrogen is likely to be less than for natural gas so that the total costs of delivery may be nearly equal.

The advantage in pipelining fuels is the ability to scale this type of system up to very large capacities with the resultant effect of the economy of scale being to lower unit-energy transfer cost. The use of pipeline transport of thermal energy will therefore be superior for the transmission of energy over long distances and/or transmission of very large blocks of energy. Relative to natural gas, the volumetric flow of hydrogen must be quite high because of its low specific heat content, although the low molecular weight compensates considerably, resulting in similar system performance. The primary penalty in transmitting hydrogen over methane is the increased cost of recompression which amounts to a relatively small fraction of the cost of a transmission system in a near-urban environment. This penalty may be offset by the potential efficiency gain of hydrogen energy conversion devices and the resultant flow decreases in the hydrogen energy transmission system. An area of concern in the transmission of hydrogen, however, is in the admission of this gas into older existing mains since the leakage coefficient is three to six times that of methane. Techniques of sealing older natural gas systems would therefore have to be developed to avoid their total replacement in transition to use by hydrogen.

USE OF SYNTHETIC FUELS

End uses for hydrogen and other synthetic fuels were examined for the major energy use sectors, i.e., industrial, urban, transportation and electricity generation.

Industrial

Industrial uses for H₂ are mainly as a chemical as in ammonia production and in petroleum refining. Iron ore reduction could potentially require large amounts of hydrogen as will most coal processing schemes. Its use as an industrial fuel appears, technically, to be unlimited. Further, if a dual pipe (hydrogen and oxygen) system were available, or as dictated by economic tradeoffs, with oxygen from an air liquefaction plant, process steam could be produced directly. With this arrangement, a simple pipe-combustor-attenuator (as a closed system) would be substituted for the current massive water tube steam generators.

Of the other synthetic fuels methanol appears the easiest to adapt to industrial fuel uses - in fact, is already (as "methyl-fuel")⁽¹⁴⁾ being evaluated as a boiler fuel. Because of its toxicity and poor combustion properties, ammonia would be less suitable for this use. It may, however, be readily dissociated to H₂ and N₂ which for many applications would be an attractive fuel.

Urban

Although some system revisions would be required, hydrogen appears to be substitutable for any natural gas use and, at the same time, with improvements in use efficiency. Conversion to a hydrogen system should be possible with only a minor amount of capital expenditure. Although gas distribution systems already exist, they may require some upgrading to meet leakage and increased flow requirements, and gas burners would require modification. Safety problems associated with the use of hydrogen are comparable with those associated with the use of natural gas. An education program will be required to familiarize the public with the use of hydrogen.

Table 5. Energy transmission - relative transportation costs
(near-urban environment)

	Volume (10 ⁶ Btu/hr)	Size	Investment per 100 miles (10 ⁶ \$)	Total cost, operating plus investment ^d per 100 miles (¢/10 ⁶ Btu)
H ₂ gas	21,000	36-in. pipe	68 ^{b,c}	5.7 ^c
NH ₃	21,000	36-in. pipe	62 ^{b,c}	5.0 ^c
CH ₃ OH	21,000	30-in. pipe	52 ^{b,c}	4.2 ^c
Natural gas	21,000	36-in. pipe	62 ^{b,c}	5.1 ^c
H ₂ Liquid	550	3-in. pipe	79 ^d	250.0
H ₂ Liquid	1,800	1,100,000-gal barge	2.4	6.9
H ₂ Liquid	62	13,000-gal trailer	0.15	34.0
Electric (superconducting line)	13,600	4,000-MVA line	140	19.3
Electric (aboveground)	8,500	2500 MW, 750 kV	30	8.3
Electric (belowground)	8,500	2500 MW, 345 kV	~300	~100

^aUnit cost assumption: 100% utilization of facility, 15% = fixed charge rate (depreciation, interest, return on investment), operating power 6 mills/kWhr.

^bReported pipeline costs can vary by as much as a factor of 4, depending on terrain, congestion, etc.

^cFor cross-country straight lines, 50% reduction is likely.

^dNo reliquefaction included.

As for the industrial sector, methanol could readily find use as a residential/commercial fuel, but ammonia use would probably be more difficult.

Transportation

Hydrogen, with air from the atmosphere or with oxygen supplied on board, offers an impressive potential for fueling future transportation systems. Due to hydrogen's high gravimetric heat of combustion, $\sim 2\ 1/2$ times greater than conventional hydrocarbon fuels, it is an attractive fuel for aircraft. As a liquid, its low density ($\sim 1/10$ that of jet fuel) and low temperature (-423°F) do, however, present some design and operating problems. Improvements in air transport efficiency are potentially great, e.g., a recent analysis⁽¹⁾ of a hydrogen-fueled subsonic commercial transport showed that a 30% decrease in takeoff weight is possible. With high-speed aircraft substituting hydrogen for jet propulsion fuel could give a 45% increase in payload at a Mach 3 cruise condition. For hypersonic aircraft ($>\text{Mach } 4$) the use of liquid hydrogen is probably mandatory due to its unique cooling capabilities and attractive chemical properties, e.g., noncoking.

For ground transport hydrogen appears to be substitutable for existing fossil fuels, but sizable problems are evident relative to fuel tankage and logistics. Large fleet-operated trucks or buses or high-speed trains appear to be the easiest to adapt to hydrogen fuel. The clean-burning characteristics of hydrogen offer an additional option to overcoming the polluting effects of internal combustion engines.

Hydrogen-oxygen fired steam cycle power plants may be of special interest to nuclear-powered ships, to provide large amounts of reserve speed, for example. For submersibles this power plant's completely condensible exhaust (water) offers a number of system advantages.

Of the other synthetic fuels, methanol and ammonia show some promise for the ground transport sector with methanol the more attractive fuel. Its main advantages are that it shows promise as a long-term, high quality, domestically produced, portable fuel, particularly as a replacement for gasoline. Since it is basically a high-octane, clean-burning fuel (without additives), it can be used in high-performance engines with apparently relatively simple exhaust treatment and thus compensate, in part, for its low heating value. Its current relatively higher cost, low heat of combustion and higher volatility appear to be the primary obstacles to its widespread use today.

Electricity Generation

The use of nonfossil synthetic fuels for electricity generation would seem to apply only in special situations such as to meet a relatively remote small requirement or as a part of an energy storage power peaking system.

One possibility is that electricity will be generated near the load center from hydrogen fuel or hydrogen-oxygen taken from pipelines as it is transmitted long distances from remote production sites. Both thermomechanical systems and nonthermomechanical systems appear plausible for converting hydrogen energy into electrical form. Examples are gas turbines, magnetohydrodynamic generators, and fuel cells.

Hydrogen is expected to be a very favorable fuel for gas turbine operation, permitting increased turbine inlet temperatures to be reached, provided that the excellent cooling virtues of hydrogen can be used to keep metal temperatures under control. If cryogenic hydrogen is used, precooling of inlet air and/or compressor intercooling might be advantageous in increasing efficiency and/or output. Efficiencies of 35% are anticipated for the hydrogen-air turbines. The hydrogen-oxygen turbine offers the ultimate in cycle efficiency and may exceed 60% with several generations of development. The hydrogen-oxygen turbine also prevents any air pollution since the exhaust is pure water and may be condensed, i.e., since air is not used in the combustion process, no NO_x can be formed.

Primarily in the space program, hydrogen has found limited use in fuel cells with either air or oxygen to produce electricity. Commercial fuel cells are being developed by Pratt & Whitney as part of the TARGET* program using air and hydrogen derived from natural gas. With a pipeline source of hydrogen, this technology could be readily adapted for its direct use and would in the process realize significant improvements in cell efficiency and in lower operating costs. Efficiencies of the prototype units using reformed natural gas and air are 35 to 40%. Using hydrogen with large units, efficiencies up to 55% are projected and using hydrogen and oxygen a 60% efficiency (AC power out/heat energy in) should be realized. Fuel cells fueled with hydrogen should produce electricity with only minimal air pollution, since the main waste product is water vapor. Waste heat would be rejected to air and with few moving parts (cooling fan and pump) their operation is quiet; further, they exhibit a characteristic of maintaining high efficiency at part load, i.e., down to ~25% of design load.

Fuel cells have also been proposed for supplying utility peak power needs using hydrogen fuel (and oxygen) produced electrolytically during low demand periods. Overall efficiencies (electricity in/electricity out) with today's technologies will probably be under 30%, but with possible future technologies the efficiency could approach 50%. As an alternative to pumped hydro storage, it does offer a flexibility of location and a compact plant which may become an important consideration for peaking facilities. Other fuels, e.g., NH_3 , N_2H_4 , CH_3OH , have been used to a limited extent in fuel cells, both directly and after dissociation.

SYSTEMS ANALYSIS

The purpose of the systems analysis effort⁽¹⁶⁾ in this short-term study was to identify system concepts which would show the typical resource, economic, and environmental impact of implementing hydrogen in selected sectors of the energy system. The concepts evaluated are listed below:

1. The use of hydrogen, generated with available off-peak electricity, as a clean fuel in the transportation sector (auto, diesel, or aircraft).
2. The use of hydrogen produced from coal, as an alternate clean fuel in the transportation sector.
3. Energy transport and distribution from remote central station sites to urban areas via hydrogen in pipelines.

It was estimated that the amount of available off-peak power in the year 2000 could satisfy: (a) 50% of the automotive, (b) 50% of the aircraft, or (c) all of the diesel fuel requirements. In one case where the off-peak fossil-generated power (for the production of H_2) was shifted to nuclear (part base load), a decrease of over 20% in petroleum imports was projected. The impact of this change on environmental factors is illustrated in Fig. 5 showing a decrease in chemical pollutants with an increase in radioactive wastes.

Another systems analysis example computation shown in Fig. 6 compares the cost of delivering hydrogen for residential energy needs to an all-electric case. As thermal energy hydrogen is less expensive than electricity due to lower transmission and distribution costs as well as savings resulting from a better utilization of the primary energy plant. If all of the hydrogen were converted back to electricity in fuel cells, the total costs would exceed the all-electrical case. If, however, an energy mix of four parts thermal to one part electrical were used to meet residential needs, hydrogen would become an attractive energy source. Also shown in this figure are the estimated costs for producing hydrogen with off-peak nuclear power and from coal at both \$7/ton and \$17/ton.

* Team to Advance Research for Gas Energy Transformation.

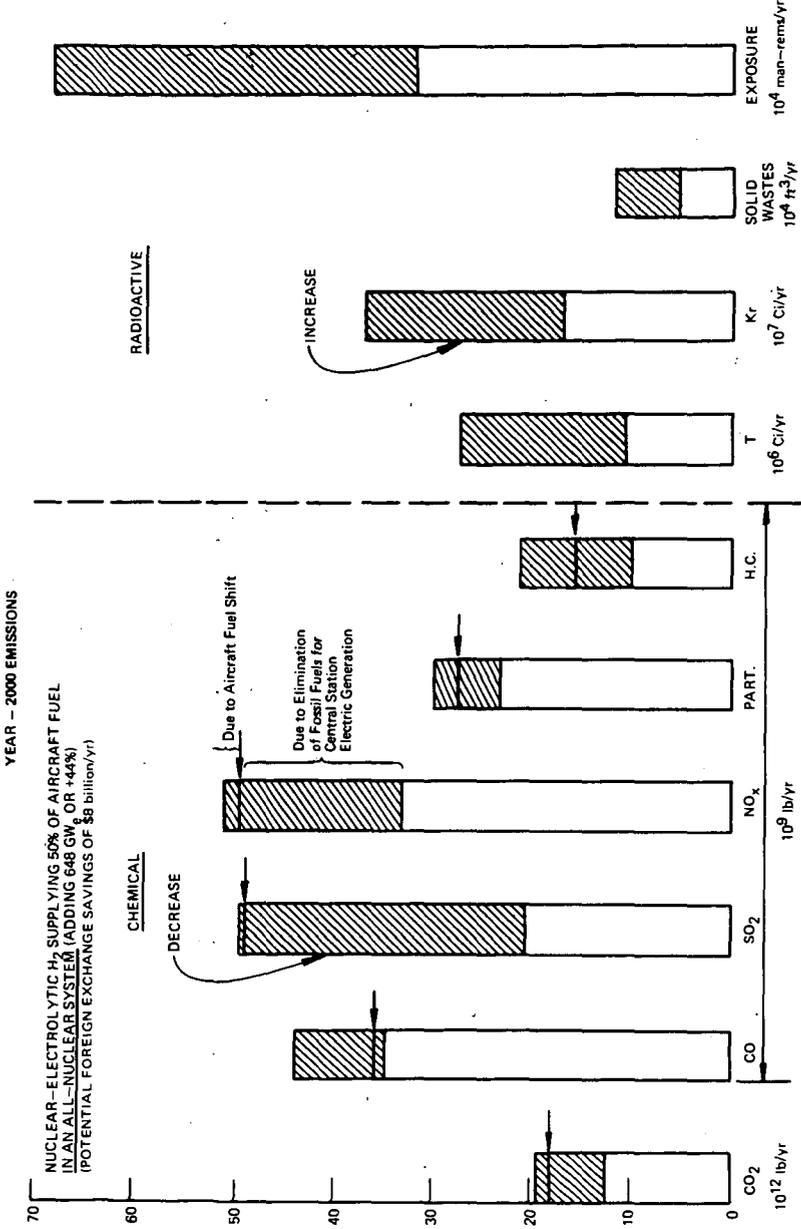


Fig. 5. Systems analysis - emission tradeoffs.

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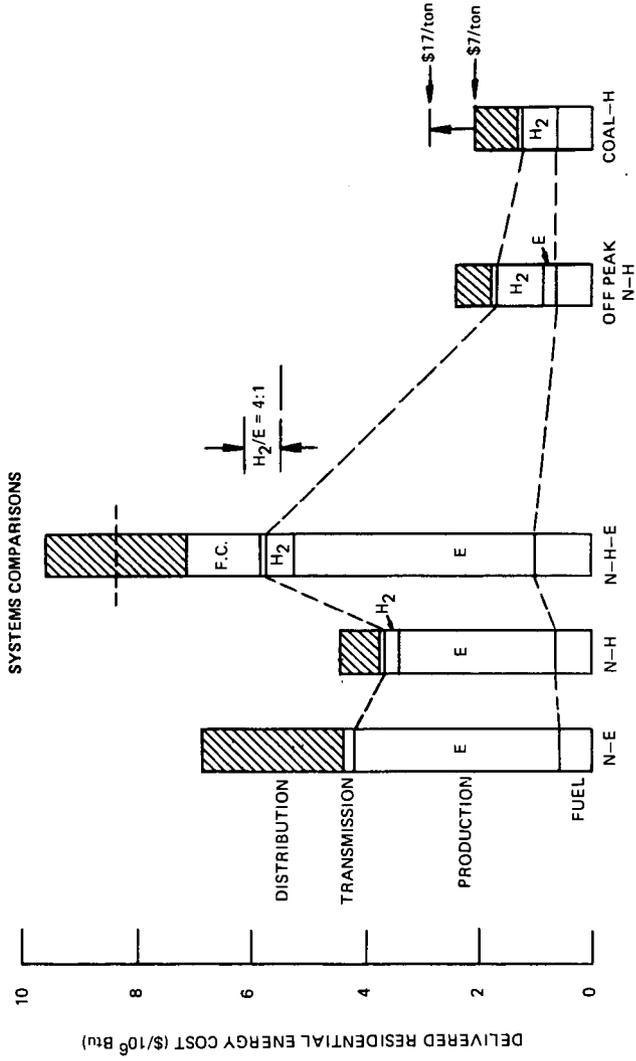


Fig. 6. Cost of delivered energy.

CONCLUSIONS AND RECOMMENDATIONS

The primary sectors of an energy system based on nonfossil synthetic fuels were examined on the basis of readily available information. The main overall conclusion reached was that these fuels can have a significant beneficial long-term impact on the energy problems facing the U.S. Hydrogen is a particularly attractive synthetic fuel for the following reasons:

1. It is essentially clean burning, the main combustion product being water.
2. It may be substituted for nearly all fuel uses.
3. It can be produced from domestic resources.
4. It is available from a renewable and universal raw material -- water.
5. Nearly all primary energy sources, nuclear, solar, etc., may be used in its production.

The main obstacles to its use as a universal fuel are its high cost relative to the current low prices for fossil fuels and, for some applications, the unresolved problems of handling a low density or a cryogenic fluid. Safety considerations, while important, are not believed to present a serious technical obstacle to its widespread use.

The panel believed that most of these economic problems could be resolved by appropriate R&D programs. The recommended R&D programs were divided into two categories: those which could 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 H₂ 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 as 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.

* The panel developed recommended R&D funding levels, but these are not yet available for publication.

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 fuel should begin is suggested as a critically important topic for a future, more detailed study.

APPENDIX

The following members of the study panel on nonfossil synthetic fuels and fuel cells, together with other contributors listed below, were responsible for the preparation of this report. The work was sponsored by the AEC under the cognizance of the Division of Reactor Development and Technology.

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REFERENCES

1. Hydrogen and Other Synthetic Fuels - A Summary of the Work of the Synthetic Fuels Panel, USAEC Report TID 26136 (Sept. 1972).
2. J. E. Mrochek, J. M. Holmes, and J. W. Michel, "The Role of Electricity-Intensive Industries in the Economics of Nuclear Power," pp. 639-52 in Proceedings of Symposium on Nuclear Energy Costs and Economic Development, Istanbul, Turkey, Oct. 20-24, 1969, IAEA, Vienna (1970).
3. J. W. Michel, Status and Recent Developments in Agro-Industrial Complex Studies, ORNL-TM-3019 (June 1, 1970).
4. J. E. Funk, "Thermodynamics of Multistep Water Decomposition Processes," paper presented at the 163d National Meeting of the American Chemical Society, Boston, Mass., Apr. 9-14, 1972.
5. G. DeBenedi and C. Marchetti, "A Chemical Process to Decompose Water Using Nuclear Heat," paper presented at the 163d National Meeting of the American Chemical Society, Boston, Mass., Apr. 9-14, 1972.
6. H. F. Feldmann, "Pipeline Gas from Solid Wastes," paper presented at AIChE 69th Annual Meeting, Cincinnati, Ohio, 1971.
7. G. E. Johnson et al., "The Production of Methane by the Anaerobic Decomposition of Garbage and Waste Materials," Pittsburgh Energy Research Center, Bureau of Mines, USDI, presented at the 163d National Meeting of the American Chemical Society, Boston, Mass., Apr. 9-14, 1972.
8. G. A. Azego, A. A. Fox, and D. R. Eaton, "The Energy Plantation," pp. 1131-34 in Proceedings of 1972 Intersociety Energy Conversion Engineering Conference, San Diego, Calif., Sept. 25-29, 1972.
9. C. G. Golueke and W. J. Oswald, "Power from Solar Energy - via Algae-Produced Methane," Solar Energy 7(3) (1963).
10. Paul Averitt, "Coal Resources of the United States, Jan. 1, 1967," U.S. Geological Survey Bull. 1275.
11. K. C. Hoffman et al., "Metal Hydrides as a Source of Fuel for Vehicular Propulsion," SAE International Auto Engineering Conference, Detroit, Mich., Jan. 13-17, 1969.
12. J.H.N. van Vucht, F. A. Kuijpers, and H.C.A.M. Bruning, "Reversible Room Temperature Absorption of Large Quantities of Hydrogen by Intermetallic Compounds," Phillips Res. Rep. 25, 133-40 (1970).
13. D. P. Gregory and J. Wurm, "Production and Distribution of Hydrogen as a Universal Fuel," pp. 1329-34 in Proceedings of 1972 Intersociety Energy Conversion Engineering Conference, San Diego, Calif., Sept. 25-29, 1972.
14. Letter of Apr. 3, 1972, from David Garrett, Vulcan Cincinnati, Inc., to T. S. Mackey, ORNL.
15. A. M. Squires, I. Steelmaking in an Industrial Complex, ORNL-4294 (November 1968).
16. W. A. Sevian, F. J. Salzano and K. C. Hoffman, Analysis of Hydrogen Energy Systems (to be published).