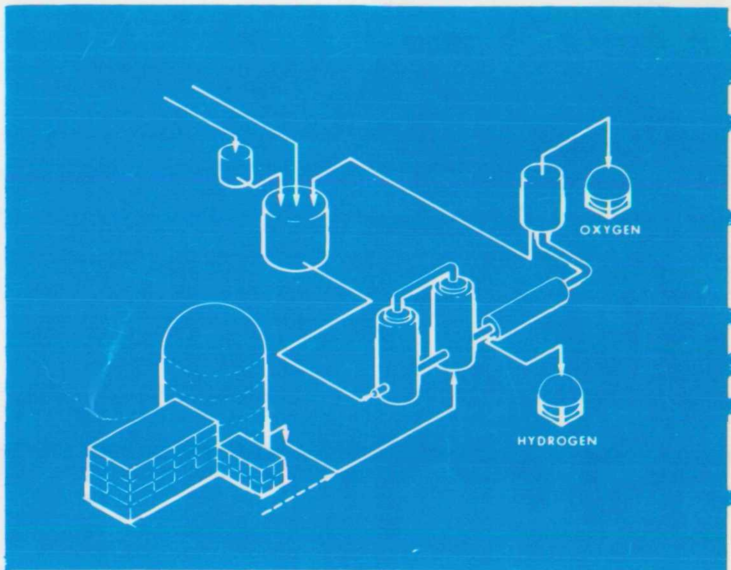
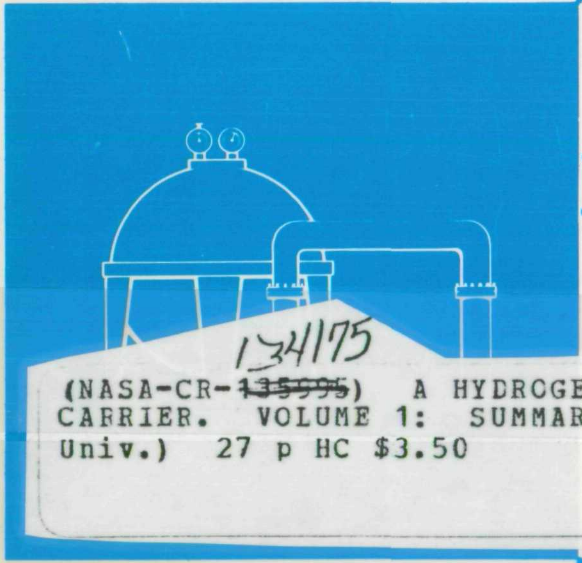
SYSTEMS DESIGN INSTITUTE

NASA GRANT NGT 44-005-114



N74-11727

A HYDROGENERGY CARRIER



134175

(NASA-CR-~~135595~~) A HYDROGEN ENERGY CARRIER. VOLUME 1: SUMMARY (Houston Univ.) 27 p HC $3.50 CSCL 20M

N74-11727

Unclas

G3/33 [illegible] 21143

VOLUME I

SUMMARY

1973

NASA [illegible]

UNIVERSITY OF HOUSTON • JOHNSON SPACE CENTER • RICE UNIVERSITY

A HYDROGEN ENERGY CARRIER
Vol. I - Summary

SEPTEMBER, 1973

Editors:

Robert L. Savage
Lee Blank
Tom Cady
Kenneth Cox
Richard Murray
Richard Dee Williams

C. J. Huang
C. J. Huang, Co-Director
University of Houston

John R. Howell
John R. Howell, Associate Director
University of Houston

Joel J. Hebert
Joel J. Hebert, Assistant Director
Rice University

Barbara K. Eandi
Barbara K. Eandi, Co-Director
NASA-Johnson Space Center

W. Richard Downs, Technical Director
NASA-Johnson Space Center

SUMMARY

Hydrogen as an energy carrier is almost ideal from an environmental viewpoint. It is made from water and its product of combustion is water. Hydrogen can be used as a fuel in all conventional areas of energy use, including industrial chemical, industrial fuel, electric power generation, residential and commercial, and transportation. A primary source of energy such as fossil fuel, nuclear energy or solar energy must be used to produce hydrogen. The cost of hydrogen will depend on the cost of the primary source of energy and the efficiency of the process used to produce the hydrogen. Projected costs of gaseous hydrogen at the producing plant range from $1.00 to $3.00 per million Btu. Pipeline transmission of gaseous hydrogen will add only a few cents per million Btu to the cost of hydrogen fuel delivered to the customer.

Initial large scale methods of production of hydrogen will be from the gasification of coal with costs forecast to drop from over $1.50 per million Btu to as low as $1.00 as the technology develops. Coal, by far the greatest domestic energy reserve, can be gasified to produce substantial amounts of hydrogen for many years. Coal will also be used to produce synthetic natural gas and synthetic crude oil. Because of the potentially high demand for coal by these competing forms of fuel, nuclear energy will also be used to produce hydrogen. The established process is by electrolysis of water but the overall efficiency is low. Depending on the cost of electric power, the cost of hydrogen gas produced by electrolysis will range from $1.00 to $5.00 per million Btu. There is very little cheap power available, even at off-peak periods and the cost of most of the hydrogen produced by electrolysis will be from $3.00 to $5.00 per million Btu.

If the needed technology is developed, direct thermal decomposition of water or thermo-chemical decomposition of water to produce hydrogen, using nuclear heat rather than electricity, will produce hydrogen at a cost of $1.00 to $1.50 per million Btu. These processes are not expected to be operational before 1985. For the period after the year 2000, solar energy may replace nuclear energy for the production of hydrogen from water, but the cost is forecast to be in the range of $2.00 to $3.00 per million Btu.

Hydrogen can be transported most economically by pipeline. Special attention must be directed to designing the pipeline to avoid conditions which may cause hydrogen environment embrittlement. This can be done.

There are no non-technical aspects of the hydrogen economy which cannot be met. Safety problems with hydrogen are similar to and probably no worse than safety problems with other hazardous fuels. Environmental, social, legal, economic and political factors have been examined. No insurmountable problems are anticipated in converting to a hydrogen economy.

Implementation of hydrogen as an energy carrier into our energy system must be by integrated steps. Although large tonnages of hydrogen are used in the chemical industry, there is no established market for hydrogen as a fuel, except in the space program. We believe that direct experience in the production, pipeline transportation, and use of hydrogen as an energy carrier is needed to demonstrate its feasibility for use in the nation's energy system. Our concept is that a demonstration project is needed to establish the technology of producing hydrogen by one of the proposed methods and transporting it by pipeline to a consumer located in a high pollution area where it would be advantageous to burn a clean fuel. A Ford foundation grant or government subsidy to pay the difference between the cost of hydrogen as a fuel and the cost of a conventional fuel would be needed to give the successful bidder a guaranteed market for several years. During this time he would be permitted and encouraged to develop other markets. In order to get maximum involvement by industry, no other government participation would be needed for this 'Hyplex' project.

Subsequent projects might be a new city (Hycity), operation on hydrogen fuel, or even an entire island such as Hawaii. Final integration of hydrogen fuel into the energy system would be the result of economic and environmental advantages.

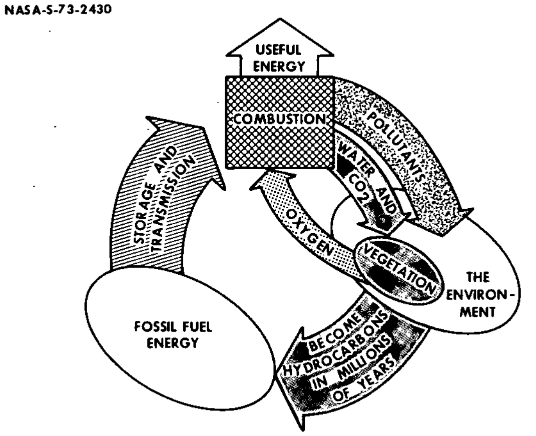
The authors of this report were under no commitment or incentive to present a particular point of view. They were assembled as Summer Faculty Fellows to do a systems analysis study. This report is the result of their work during the summer. Some positions or conclusions reported by other authors have been supported whereas other positions or conclusions have been critically questioned. This summary report may be utilized as an overview document by the decision makers who must deal with the energy problem. Complete details of results presented here may be obtained in Volume II - Systems Analysis.

OVERALL ENERGY PICTURE

This work is related to the current energy shortage in the United States. Inadequate supplies of oil and gas, coal in the wrong form or restricted in use and delayed nuclear energy projects contribute to this shortage. A lasting shortage or even a temporarily interrupted supply will have a devastating impact upon the nation's economy, its standard of living, and its defense posture. These are large stakes which must be preserved by positive corrective actions. It is this demonstrated need for energy which provides justification for this report; an independent report on hydrogen as an energy carrier.

The Fossil Fuel Cycle

The present energy shortage is the result of a combination of economic, environmental and political factors which are affecting the supply and use of fossil fuels as a source of energy. In the fossil fuel cycle (Figure 1), two aspects should be noted; the time scale, and the environmental impact. It takes millions of years for the vegetation to be converted to fossil fuel, which results in depletion of the fuel at the rate we now use it.



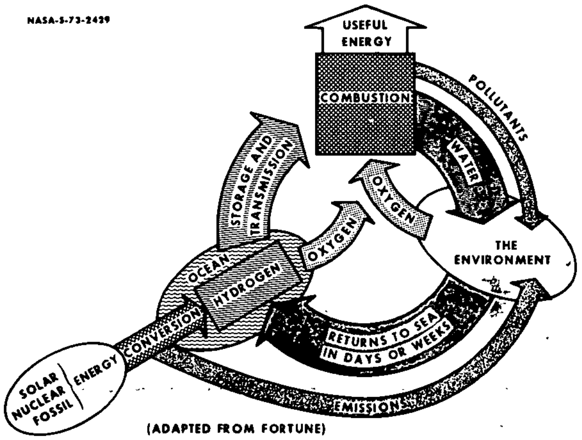
(ADAPTED FROM FORTUNE)

Figure 1. Fossil Fuel Cycle

Undesirable environmental effects occur at most points in the cycle. In the fossil fuel cycle, coal, oil or gas is burned at the point of use to produce heat energy which may be converted to useful mechanical energy or electrical energy. Air is used to supply the oxygen needed for combustion of the fuel and the products of combustion (carbon dioxide, carbon monoxide, water, sulfur oxides, nitrogen oxides, hydrocarbon emissions and/or particulate matter) are returned to the atmosphere at the point of use. The undesirable materials become pollutants and, depending on the concentrations, may cause minor or major problems.

A Hydrogen Fuel Cycle

In the hydrogen fuel cycle (Figure 2) the main product of combustion, water, returns to the sea in a relatively short time. The conversion process may have some undesirable emissions, but their impact can be minimized by locating the conversion plant in a remote area. If air is used instead of oxygen for the combustion of hydrogen, some minor amounts of nitrogen oxides may be formed as pollutants, but even in this case the total pollution would be greatly reduced compared to that from fossil fuels.



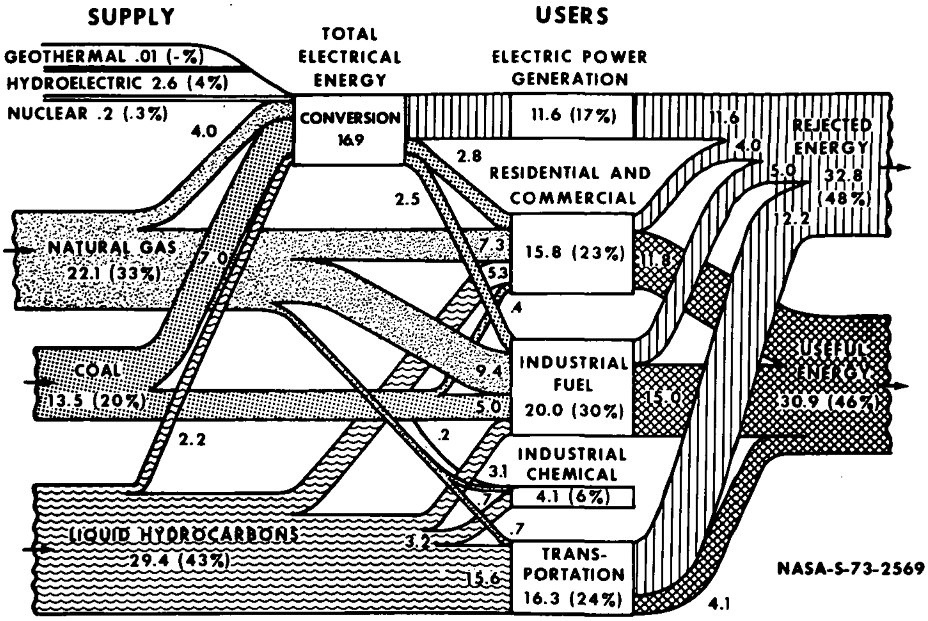
(ADAPTED FROM FORTUNE)

Figure 2. Hydrogen Fuel Cycle

Figure 2 illustrates a significant concept which must be emphasized. Hydrogen is not a primary source of energy. It can be formed from water only if one of the primary sources of energy—fossil, nuclear, or solar—is used in the process.

The Demand for Energy

A great portion of the energy used in the United States is obtained from the fossil fuel sources of coal, natural gas or liquid hydrocarbons. Historically, these fuels have been cheap, because, in relation to some other sources of energy, they are easy to obtain. Cheap, not so much because you can pick them up off the ground, but, because technology has been directed at their recovery and use. However, our supply of these fuels is waning since their formation rates are so very slow in comparison to our usage rates. Because there are several forms of fossil fuels and because we use them for so many different purposes, the energy system becomes complex (Figure 3).



(ALL VALUES ARE × 10^{15} BTU - TOTAL U.S. DEMAND 67.8 × 10^{15} BTU)

Figure 3. U. S. Energy Demand Patterns, 1970

The 68 quadrillion (68 Q) Btu expended in 1970 is an astronomical amount which, if considered in the oil equivalent of 33 million barrels per day, is equal to the flow over Niagara Falls every 15 minutes. Not very impressive? Well, remember, this oil equivalent must be mined or drilled for, shipped, refined, distributed and be supplied a place to burn. Most of these intermediate processes pollute in some way, thus adding to the complication. Even with all of this complication the costs of these polluting fuels has been low, thus allowing the development of convenience devices now considered essential to our way of life.

Previous authors have used a variety of techniques to forecast the future of the energy demand picture. Many of these, following the historical growth patterns of the past, have projected with no allowance for the now obvious limit which must exist for the individual energy consumer. This limit does exist due to the time and spatial constraints placed on each of these energy consumers. We refer to this limit as saturation. The time restraint component of saturation implies that, even though each person may perform many activities each day, only a few may be engaged in at one time. Thus, the energy expended in a day has some average upper limit. The spatial constraint restricts the use of energy per capita, since only so much space is needed to perform any of these many activities. Even if conditions were such that the use of energy was maximized, only this limited amount can be expended. By the forecasting of the time and space required for activities, a maximum energy use per capita (saturation) may be established and utilized for demand forecasting.

When the saturation concept was not applicable for per capita projection, we used the forecasts of energy demand indicators such as gross national product and adjusted historical growth rates. In all these forecasts the effects of population growth are evident. The population growth rate is projected at one percent, resulting in a total population in the United States of 270 million in 2000 and 328 million in 2020.

Total demand forecast was obtained by the composition forecasting method in which each energy use area was forecast separately then summed. Areas for the study reviewed below are:

- residential and commercial
- industrial-fuel
- transportation
- electric power generation
- industrial-chemical

The future of the saturation energy picture is a definite indicator that conservation is not only necessary, but that it will be practiced—whether we like it or not. Consequently, in each use area a conservation picture is presented. These conservation measures are not the result of doing without energy, rather the wiser use of energy. We believe these conservation demand projections to be the future of energy demand, since they represent reasonable, livable efforts to conserve the energy we are able to obtain for this country.

FUTURE DEMAND BY USE AREAS

Residential and Commercial

The residential and commercial use area represents 23 percent of the 1970 energy market. Over three-fourths of this amount is used for space heating, water heating, cooking and refrigeration. Most of the energy is obtained from fossil fuels (85 percent in residential and 65 percent in commercial) and the balance from electricity. Due to recent upsurges in air conditioning and other comfort items, the yearly growth rates of this area have been high; 2.7 percent for residential and 3.7 percent for commercial.

A saturation limit of 400 million Btu per year per household is expected to be reached by 1985. This will allow complete space conditioning and a proliferation of appliances in all households. Due to the increased services needed for the populace and a vigorous competitive market, commercial energy use is expected to grow at 3.5 percent per year.

Conservation in residential and commercial will be practiced by increased use of insulation and improved design, all of which will reduce thermal losses of the structure, resulting in an eventual 25 percent savings in energy. The major energy using devices in this area can be expected to be improved so that, by 1985 their efficiency will be from 10 percent to 25 percent greater. The saturation and conservation forecasts for the individual areas of residential and commercial are depicted in Figure 4. Note that, even though most of the conservation measures are long term, an approximate 25 percent savings of energy is possible by the year 2000.

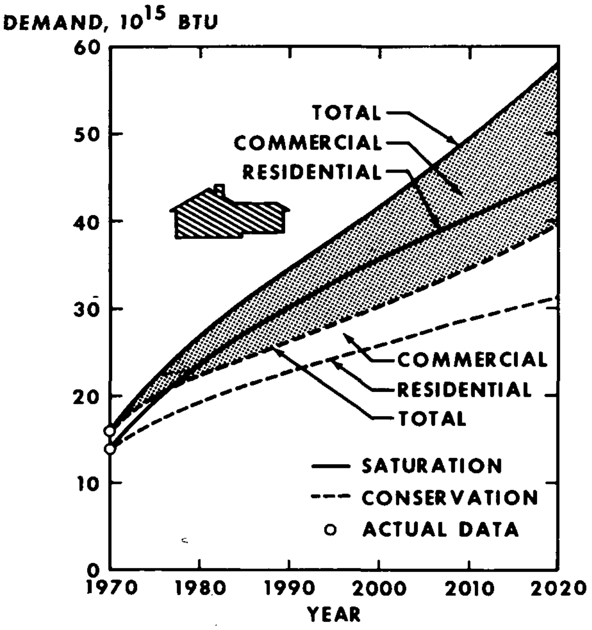


Figure 4.
Residential and Commercial Demand, 1970-2020

Industrial - Fuel

The use of fossil fuels for direct heating and steam generation and the use of electricity for heating and mechanical drive is the energy use area of industrial-fuel. Some of the principal sectors of this largest user of energy (30 percent of total) are listed below:

primary metal industries
chemicals and allied products
petroleum refining and related industries.

The common fossil fuels, plus electricity, are the energy suppliers for the area, however, almost one-half (47 percent) of the energy is supplied by natural gas. Due to the environmental restrictions and greater effort to obtain raw materials, the historic decrease in energy input per unit output has seen a reversal in trend. It is anticipated that future increases in efficiency will overtake this short, present-term trend toward increased energy per unit output.

If allowed to, the uses of energy in this area are expected to grow at a rate of 3 percent per year. The higher-than-saturation growth rate is anticipated due to the need for new products, population growth and necessary replacement of presently owned goods. However, conservation will result from more efficient equipment, better maintenance policies and early replacement of old equipment. Overall, a 10 percent savings is anticipated in the industrial-fuel area. Total saturation and conservation projections are presented in Figure 5.

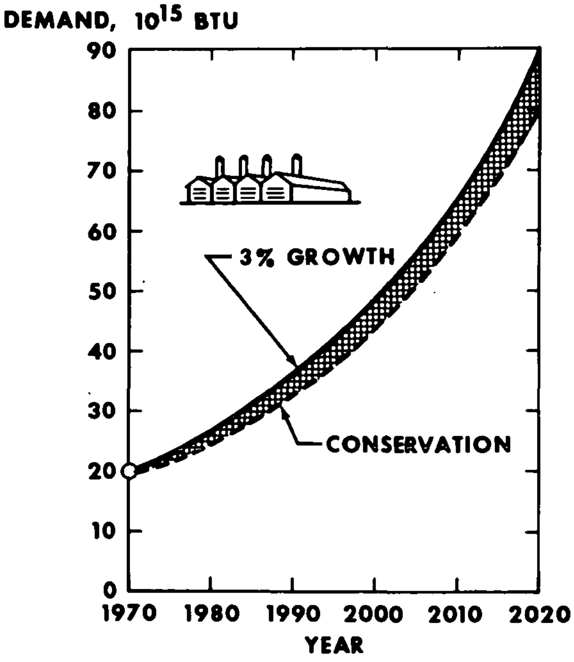


Figure 5. Industrial - Fuel Demand, 1970-2020

Transportation

Although the transportation area is the most visible of all energy users, it is not the largest. Twenty-four percent of all the energy is spent in the operation of private and commercial passenger traffic, commercial freight systems and other transport facilities such as agricultural, construction and recreational. The decentralized style of living, working and playing in this country is the major reason for the historic 4 percent annual growth rate of energy use in this area.

A time restriction in the saturation concept is evident in this area. The present use of the automobile (approximately one hour per day per capita) is evidence that some future limit must exist, since it is not possible to drive more than an average of several hours a day and still perform all the other functions necessary to life. On the other hand, since the automobile and truck have become such an integrated unit of our transportation and life style system, it is unlikely that radical shifts from this pattern will occur in the near future. Projection of a limit to the per capita energy used in transportation allows the saturation curve of Figure 6 to be made.

NASA-S-73-2495

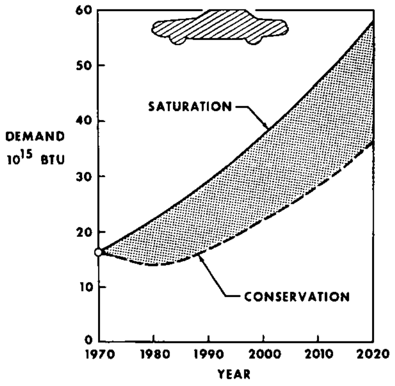


Figure 6. Transportation Demand, 1970-2020

Conservation in this area is not only necessary, but the results are quite favorable. The use of car pools and mass transit facilities are worth considering. A projected change in transportation habits such that 20 percent of the travel would be by single occupancy autos, 40 percent by multiple occupancy and 40 percent by some mass transit form, would result in an 11 percent fuel savings by 1990. The use of more economically sized autos will allow a 33 percent savings in auto fuel use. Additional savings are possible with reasonable shifts in non-employment travel, which presently represents two-thirds of all automobile mileage. The commercial freight traffic, presently 27 percent of the transportation energy market, may be expected to conserve energy by shifting to more efficient modes, thus reducing its energy use by 50 percent. The popular and, thus far, economically favorable strategy of multiple shipment of goods during the manufacturing processes can be expected to disappear as the cost of fuel increases. The rather substantial energy savings made possible by these realistic conservation moves are reflected in the conservation curve of Figure 6.

Electric Power Generation

Since the electric output of the electric generation industry has already been accounted for within the other user areas, the electric power generation area herein will be defined as the remaining 69 percent of the input energy, or that energy which shows up as rejected heat. The relationship between total electric energy, electric power generation and the user areas is portrayed in Figure 7. A total of 83 percent of the energy utilized to produce electricity is derived from fossil fuel sources. The demand for this electrical energy in the user area has grown rapidly in the past (7 percent per year), due to its convenience and active promotion. Because the consumer determines the needs in the area of electric power generation, the user areas define the future needs for generation. Presently 16 percent of residential energy needs are supplied by electricity. This is expected to grow to 30 percent by 1985 and 36 percent by 2020. The commercial and industrial-fuel uses of electricity are projected at the anticipated annual growth rates of 3.5 percent and 3

NASA-S-73-2827

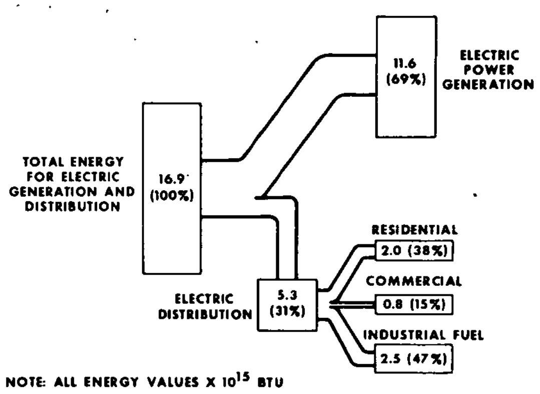


Figure 7. Electric Demand Pattern, 1970

percent respectively. Summation of the demands for these use areas results in the saturation projection of Figure 8.

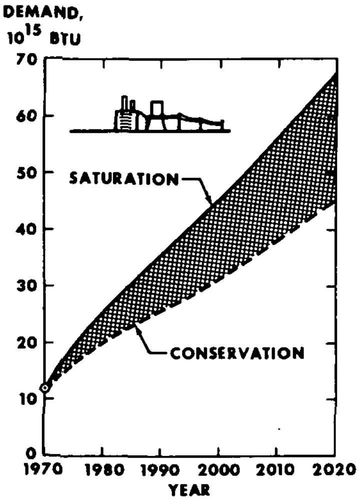


Figure 8.
Electric Power Generation Demand, 1970-2020

The carry-over effect of conservation in the electric use areas is to be quite effective in the conservation of energy for electric power generation. The conservation curve of Figure 8 accounts for 50 percent of the savings due to residential and commercial use and 10 percent savings is possible. Another potential area of conservation, not reflected here, is the use of heat rejected from the generation process, that is, an increased use of the electric power generation energy, after it is used for generation.

Industrial - Chemical

The industrial-chemical area, not a true demand for energy in the usual concept, is the use of fossil type materials as raw materials in the production of goods. Some of the more common products are ammonia, road tars, plastics and resin materials. The rapid growth of 6 percent per year in the recent past has resulted from the many new products from these fossil materials.

Saturation considerations in this area anticipate that this growth rate will decrease to 3 percent annually by 1985. Since these uses are so important to the country, conservation measures will reduce this growth to 2.5 percent by 1985. Saturation and conservation projections are presented in Figure 9.

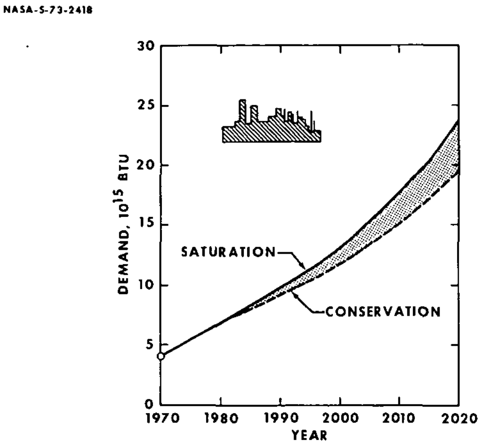


Figure 9. Industrial - Chemical Demand, 1970-2020

It is now possible to observe the total future demand picture for the five user areas. Total saturation demand is presented in Figure 10, while the more realistic conservation curve is in Figure 11. Com-

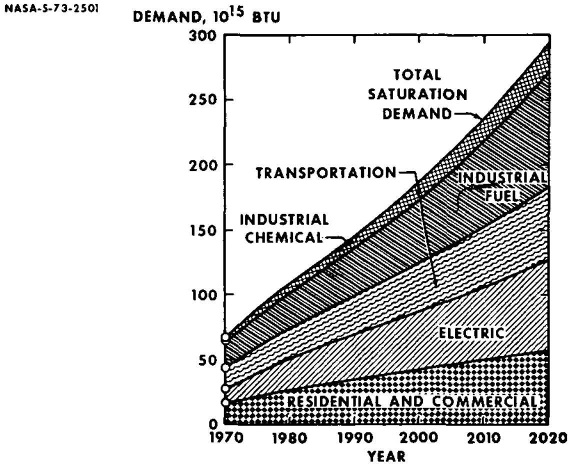


Figure 10. Total Saturation Demand, 1970-2020

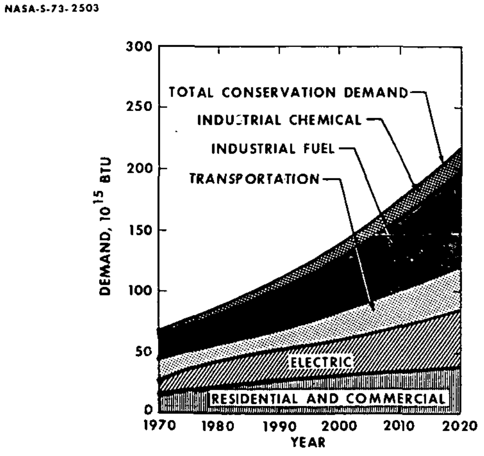


Figure 11. Total Conservation Demand, 1970-2020

parison of these indicates that, in contrast to the exponential projections which forecast that in the year 2000 the energy demand will be 3.2 times the 1970 demand, the saturation concept forecasts that the demand in 2000 will be only 2.8 times the 1970 demand. Conservation measures can reduce this need to 2.0 times the 1970 figure. This is still a sizable increase in energy needs in the next 30 years; however, the 26 percent savings in 2000 may well be one of the factors that allows us to meet our future energy demands—to meet them and still live comfortably.

Why Hydrogen?

Hydrogen fuel may be able to play an important part in the transition period from a fossil to a predominantly nuclear energy economy. Based on present and projected technology, nuclear energy will be restricted largely to the generation of electricity and very large-scale heat energy. There is little anticipated use for nuclear energy for transportation, residential and commercial uses, other than in the form of electricity. Abundant supplies of hydrogen produced from fossil fuels, nuclear energy or ultimately from solar energy can provide the much needed flexibility and environmental acceptability needed in our economy.

As a result of its importance as an industrial gas, much work has been done during the past fifty years on methods for producing and handling hydrogen. The early use of hydrogen to make ammonia for fertilizers and munitions firmly established hydrogen as an important industrial gas for chemical and metallurgical uses. More recently, we have used large quantities of hydrogen as a high energy fuel for space travel. In these cases hydrogen has been produced primarily from fossil fuels because these were the lowest cost methods. With future limitations in the supply of fossil fuels becoming apparent and with the virtual certainty that the fossil fuels will cost more, other methods for making hydrogen are being investigated. An additional incentive to produce hydrogen in large quantities is the need for a clean burning fuel burning to help protect our environment.

How We Will Use Hydrogen

Putting hydrogen's energy to use appears to be a relatively easy task. Industry now uses hydrogen in numerous chemical and manufacturing processes; enlargement of this market poses no insurmountable technical problem. This does not mean, however, that significant problems do not exist, or that careful planning and extensive research will not be needed.

Hydrogen functions in two modes, as a chemical and as a fuel. Chemically it serves as an input to processes for making ammonia, methonol, plastics, synthetic rubber, lubricating oils, and several other products. Present hydrogen input to these processes primarily comes from a synthesis gas plant that consumes natural gas or naptha. A pipeline hydrogen from other sources into these chemical processes will allow normal operation while reducing our petroleum and natural gas requirements by about three percent.

Present fuel uses for hydrogen are rather limited; however, they include welding or cutting of metals, iron ore reduction, and space vehicle propulsion. This does not mean that hydrogen is a poor fuel, only that it is not available at competitive prices compared to other fuel forms.

Hydrogen is an excellent fuel for most applications. It has extremely wide flammability limits and a very high energy density when viewed on a mass basis. The wide flammability limits allow hydrogen air combustion over large ranges of fuel-air ratio, leading to stable flame conditions, flexibility in design of the usage device, and avoidance of nitric oxide emission.

The high energy density facilitates construction of high power low weight devices such as rockets and aircraft. These devices, however, will inherently be large in order to carry the required fuel volume for reasonable duration of operation.

The favorable combustion characteristics allow not only conversion of present furnaces, heaters, and appliances, but also provide flexibility for novel new designs. With proper precautions, all existent devices that burn fossil fuel can be converted to burn hydrogen without loss of effectiveness or efficiency.

New flame-type furnaces can be designed ventless, thereby eliminating all stack heat losses, which can be as high as 40 percent of the fuel energy. Since the exhaust from such a device will contain only water, excess air and traces of oxides of nitrogen (NO_x), the combustor can be vented directly into space to be heated. Condensation and collection of excess water in the liquid form can provide automatic humidity control, while lean fuel-air ratio combustion can provide control of NO_x to acceptable levels.

A second new heating device that shows promise is the catalytic converter or burner. Hydrogen is passed over a catalyst in the presence of air, resulting in flameless low temperature combustion.

Since the combustion temperature is less than 1750K, NO_x is not formed in measurable quantities, eliminating the last harmful chemical product in the exhaust. Prototype catalytic ranges and space heaters have been built; such devices, however, are still considered to be in the research state. Cost and availability of catalytic material may delay the introduction of practical devices on the market.

The water modified hydrogen-oxygen (aphodid) burner (see Figure 12) may provide a way to increase basic steam power plant efficiency from about 40 percent to as high as 60 percent. These high efficiencies may be possible since hydrogen-oxygen combustion temperatures can peak at 3080°K. A turbine incorporating cooled blading may be able to utilize this higher temperature or selected lower temperatures as modified by water injection into the burner. The device does, however, require a supply of oxygen which will, in turn, require site location near an oxygen supply point.

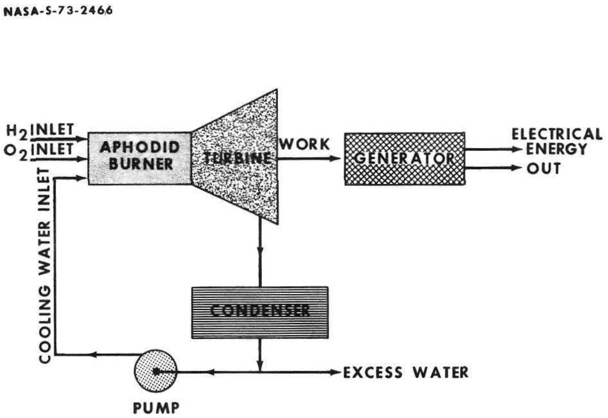


Figure 12.
Water Modified Hydrogen - Oxygen (Aphodid) Burner

In recent years the operation of nearly every type of internal combustion engine using hydrogen has been successfully undertaken; rocket engines as in Figure 13, jet engines as in Figures 14 & 15, reciprocating engines as in Figure 16. Wankel and other engines have utilized hydrogen as a fuel. None of these devices have operated for the extended periods needed to prove reliability, however feasibility has been established. Not only do these engines have favorable performance characteristics but also they are virtually emission free. Only NO_x is present and it appears that even this contaminant can be controlled to acceptable limits by mixture control.

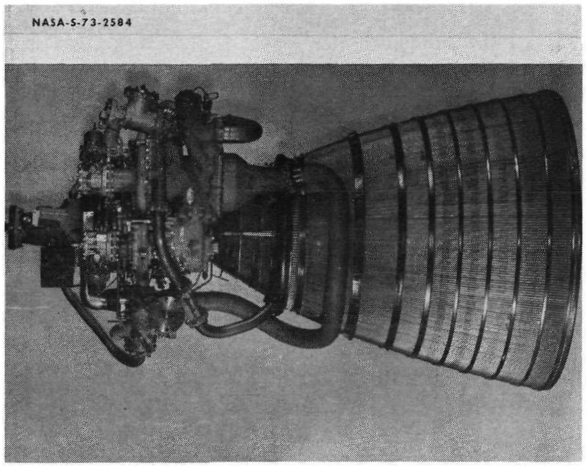


Figure 13. Pratt & Whitney RL10 Engine

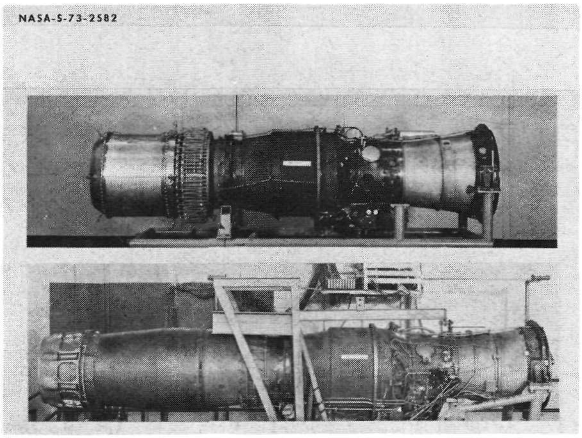


Figure 14. Pratt & Whitney J-57 Engine

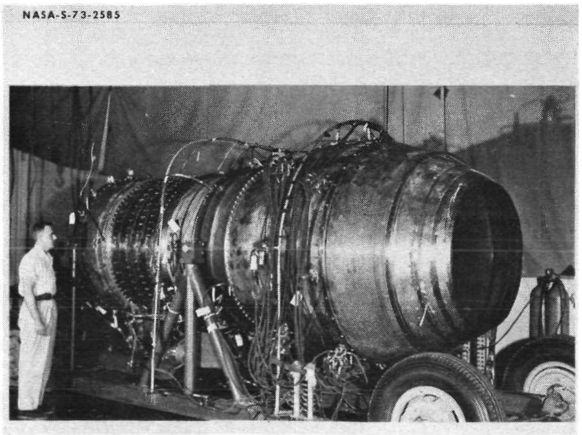


Figure 15. Pratt & Whitney 304 Engine

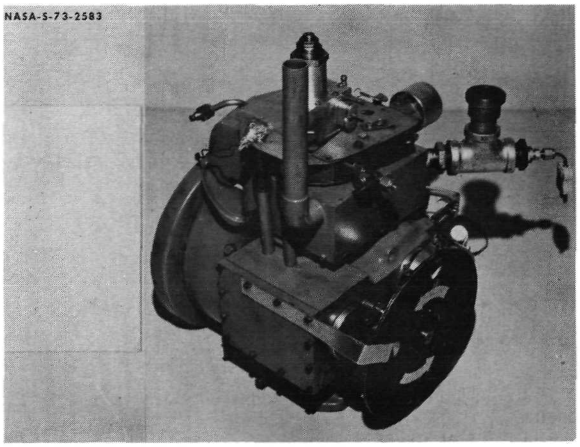


Figure 16.
Oklahoma State University Hydrogen Fueled Engine

Fuel cells (See Figure 17) and magnetohydrodynamic generators appear to remain in the research and development stage for the foreseeable future. Should breakthroughs occur such that these devices become reliable and economic, they can be easily integrated into a hydrogen fuel system.

From a fuel usage standpoint, industry appears to be totally convertible to hydrogen. Furnaces, steam generators, process heaters and stationary internal-combustion engines now in use can be progressively coverted to hydrogen or replaced by new hydrogen fueled equipment. As hydrogen becomes available as a fuel, this area of usage would appear to be the first to adapt.

The safety and economics considerations of changeover from fossil to hydrogen fuel are probably best understood and manageable in the industrial sector. Flexibility and adaptability are vital in an industrial environment. These factors, which have allowed industry to survive in a highly competitive market place, will also allow an open minded evaluation of a promising new source of energy in a society that is vulnerable to energy shortages. Since industry traditionally is the first sector required to shut down in an energy deficient region, one that has a multi-fuel (hydrogen-natural gas, hydrogen-oil) capability retains a decided competitive advantage.

In highly industrialized urban areas, conversion from a fossil based fuel to hydrogen may be more economical than installing and operating the alternative air pollution control equipment. The cleanliness of

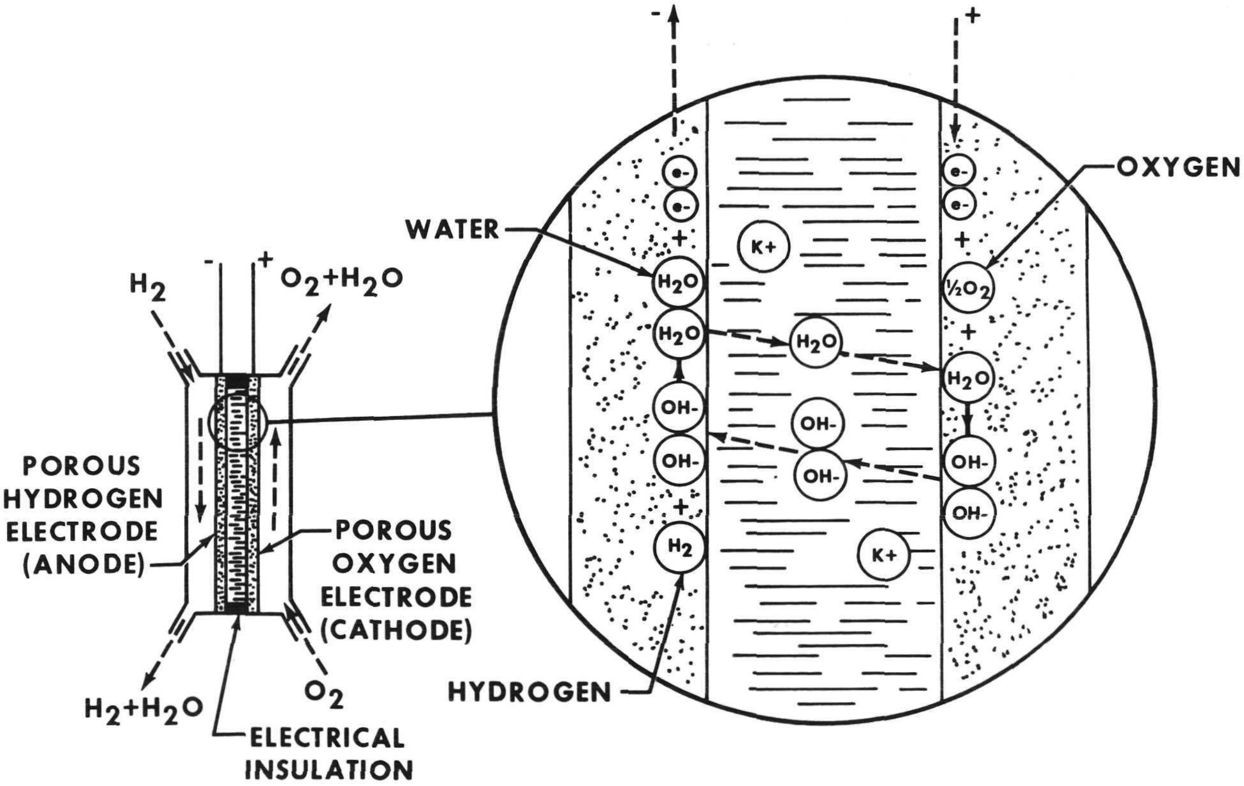


Figure 17. Hydrogen - Oxygen Fuel Cell

hydrogen may allow reclamation and growth in industrial areas now facing restrictions in operation by the Environmental Protection Agency.

The most severe difficulties of implementation of the fuel hydrogen appear to lie in the transportation sector. On-board storage of sufficient hydrogen energy to provide adequate range appears impractical in most mobile applications in spite of the fact that hydrogen has a very favorable energy density on a weight basis. (See Figure 18). Cryogenic liquid, high pressure gas, and metallic hydrides all have undesirable size and weight configurations for reasonable operational range of surface vehicles. All of the above pose unrealistic economic problems to the private transportation sector. The hydrogen fueled automobile or truck appears therefore, to be unrealistic within the near future.

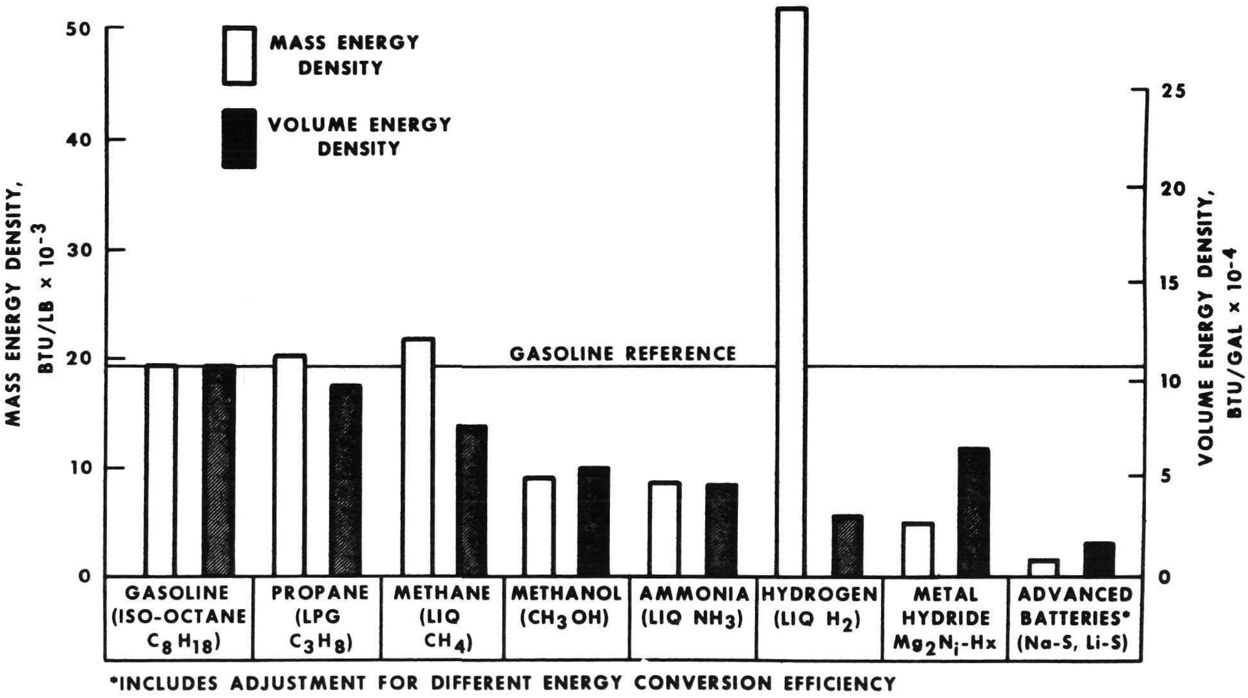


Figure 18. Energy Density Characteristics of Various Transportation Fuels

The liquid hydrogen fueled commercial airplane, on the other hand, may present a more optimistic picture. Because aircraft are weight rather than volume sensitive, a slightly larger, but lighter, aircraft may be able to carry a larger payload with less gross weight at takeoff than its fossil fueled counterpart of the same range. This is possible due to the very high energy to weight ratio of hydrogen. Preliminary studies indicate that liquid hydrogen fueled transport aircraft may be economically and technically feasible.

Future fuels for surface transportation probably will continue to be fossil fuels. It is unlikely that the present gasoline-like motor fuel will be replaced by any synthetic fuel, including hydrogen, for at least the next two decades. When fossil sources are no longer available, other synthetic fuels such as methanol, or ammonia (derived from hydrogen) may prove desirable alternatives to hydrogen.

The cost and complexity probably will preclude any significant change-over of the existing residential and commercial sector to hydrogen. Even though furnaces and appliances can be converted readily from natural gas to hydrogen, the combined cost of the conversion of all appliances, as well as the fuel supply system (meters, pipes, etc.), will prevent large scale conversion of existing systems. In contrast, however, newly constructed developments located near a source of hydrogen can easily use this new fuel. Here the cost of implementation should not exceed that for a comparable natural gas system in an energy scarce area. In this case, local air quality would be protected.

The second most optimistic sector for introduction of hydrogen into our economy is the electric power generation field. Where fossil resources are used in close proximity to a degrading urban atmosphere, hydrogen could be employed with a less harmful impact. Not only can present steam power plants be converted to hydrogen, but future plants can be designed specifically for hydrogen at an increase in efficiency. Assuming an available supply of oxygen from the hydrogen generation facility, the previously described aphodid burner could be employed. Conversion (thermal) efficiencies up to 60 percent appear feasible for this system. No significant handling or safety problems are foreseen, since the electric power generation sector has used hydrogen for years as a coolant in its large turbo-generators.

Society's ability to utilize hydrogen as it becomes increasingly available appears certain. This analysis indicates that the order of priority for conversion should proceed as follows:

industrial-chemical,
industrial-fuel,
electric power generation, and
residential and commercial.

Such a plan should maximize the use of hydrogen and minimize the use of fossil sources whenever a choice of fuels must be made. This would result in a maximum availability of fossil sources to those areas, such as surface transportation, that cannot effectively use hydrogen.

THE PRODUCTION OF HYDROGEN

The production of hydrogen from fossil fuel supplies and water has been examined in detail. Hydrogen can be produced from either of these sources. However, in the production of hydrogen from water, a primary source of energy, such as nuclear, solar, wind, fossil or other energy form, is required.

Hydrogen is used today as a chemical intermediate in the chemical industry in the amount of 3 trillion standard cubic feet per year (3×10^{12} scf/yr). Most of this hydrogen is made from natural gas or naphtha. In the hydrogen fuel concept, where much larger amounts of hydrogen would be required, water, considered inexhaustible, would be the primary raw material source for hydrogen. Hydrogen is currently being made from water by electrolysis in Canada, Norway, India and Egypt. This method of making hydrogen is used either because of the availability of cheap hydroelectric power or a lack of natural gas.

Keeping in mind at all times that hydrogen is not a primary energy source, we investigate the promising primary energy sources for the production of hydrogen. Figure 19 indicates the two main process routes for making hydrogen; first, thermal energy is converted to electricity via a vapor cycle and then to hydrogen by electrolysis, and second, thermal energy is converted directly to hydrogen by a closed-cycle thermal decomposition process. Systems shown by the paths in the figure are evaluated to obtain costs of hydrogen using certain of these alternatives. In addition, environmental factors are taken into account, even though it is difficult to assign dollar values for these factors.

The results we obtained from the analysis are summarized briefly: Hydrogen will be produced by coal gasification in the near term to 1985 and probably to 2000. Concurrently and beyond, hydrogen could be made using nuclear power-electrolysis with presently available technology, but it is felt that the costs incurred using this method would not be competitive with costs using other methods. Beyond the intermediate term, we envision that hydrogen will be produced from nuclear heat and closed-cycle thermal water decomposition. Solar power will replace nuclear heat if the costs of obtaining solar heat are sufficiently reduced by emergent technology. The above remarks also apply to schemes such as wind power combined with electrolysis.

Hydrogen From Coal

In Figure 20, the identifiable and recoverable coal reserves are much greater than either petroleum or natural gas reserves. In recognizing that coal is the largest domestic reserve, President Nixon, in his April, 1973 energy message to the nation, advocated greater amounts of money for coal research. Both coal and oil shale, the reserves of which are also large, have the associated environmental problems of mining, mine safety and waste disposal. Present consumption of fossil fuels is also shown in Figure 20. We presently supply 18 percent of our energy needs with coal—primarily for electric generation. This percentage is estimated to increase to 70

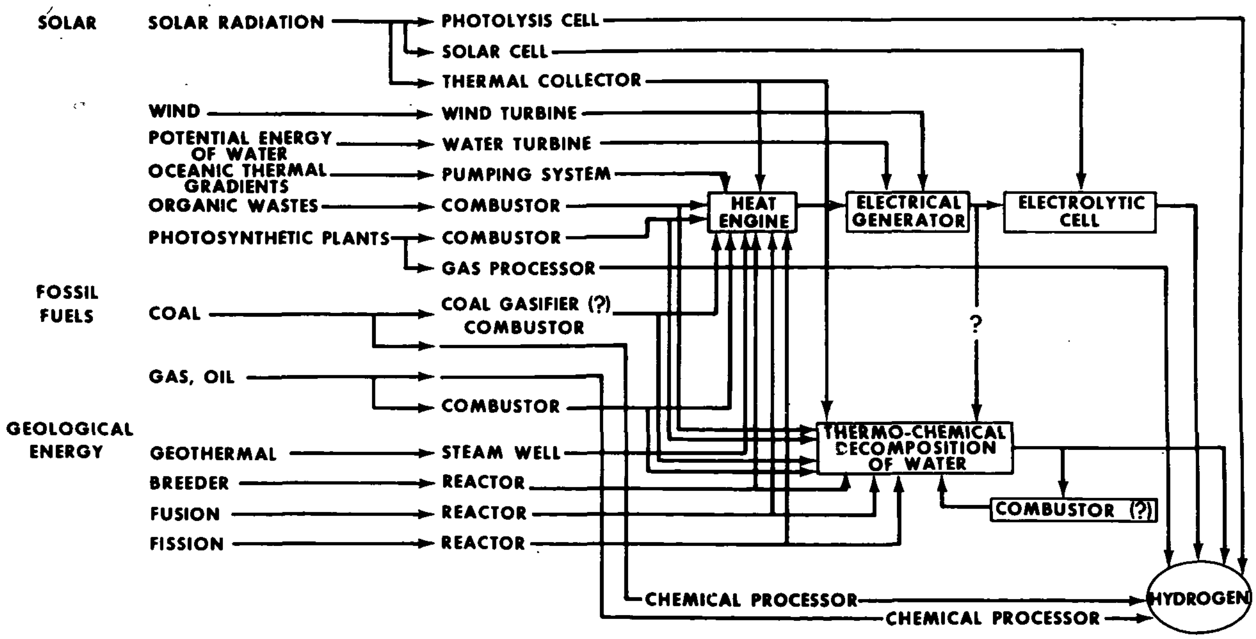


Figure 19. Hydrogen Production Systems

percent by 1985, as detailed in a recent publication (1973) of the Council on Environmental Quality.

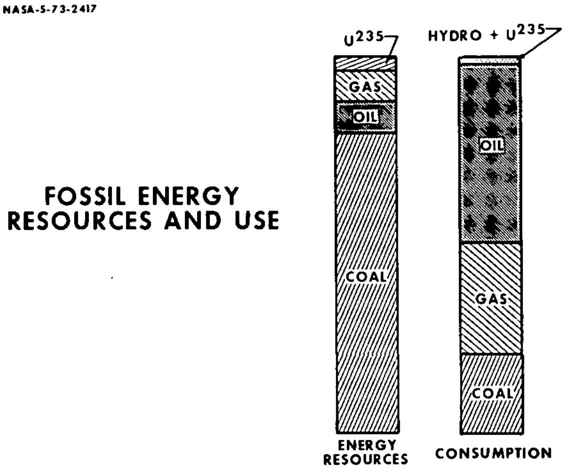


Figure 20. Fossil Energy Resources and Use

From coal, we could synthesize gaseous or liquid hydrocarbons, if a source of hydrogen is available. Steam and heat (possibly from combustion of part of the coal) could be used to make hydrogen as shown in Figure 21. This process is less efficient than making methane from coal, as all the carbon in coal is rejected to the atmosphere as carbon dioxide. In addition, manufacture of hydrogen from coal has not been demonstrated fully on a commercial scale. However, the technology is similar to that of producing methane from coal and the feasibility of the process seems to be assured. In order to lessen the environmental impact of large scale strip-mining of coal, in situ gasification of coal may be used to produce hydrogen from a mixture of oxygen and steam or water pumped into a previously ignited coal seam as seen schematically in Figure 22.

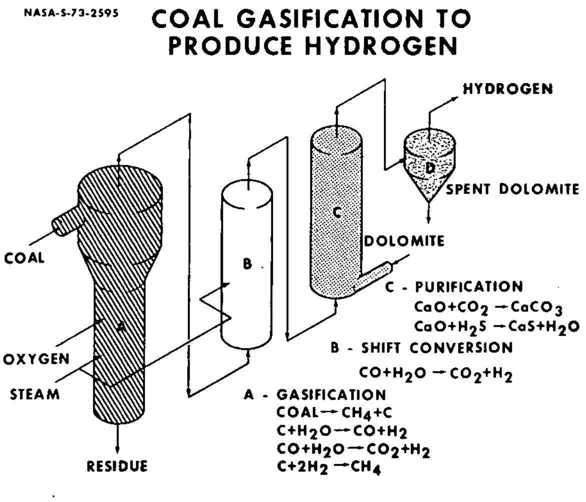


Figure 21. Coal Gasification to Produce Hydrogen

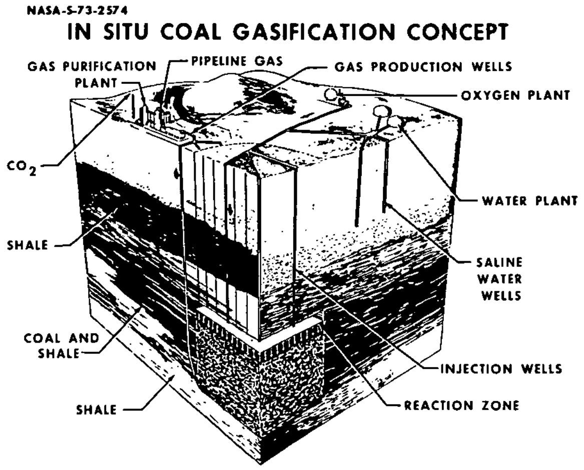


Figure 22. In Situ Coal Gasification Concept

Hydrogen From Nuclear Energy

The next alternative employs nuclear energy by one of the two processes mentioned earlier to produce hydrogen. A schematic of the path, nuclear power-electrolysis is shown in Figure 23. Treated water is electrolyzed by using low voltage direct current power to obtain hydrogen. This process has been evaluated recently by the Synthetic Fuel Panel at Oak Ridge National Laboratory and by the Institute of Gas Technology. Basically, the cost of electrolytic hydrogen depends on the cost of electricity. Proponents of this system derive a low cost for hydrogen by the use of "off-peak" power from base load plants because intermediate and peaking plants supply the highs in electric power demand. In a large hydrogen economy, supplying 20 to 50 percent of the nation's energy requirements, it is difficult to foresee much "off-peak" power being available for electrolytic hydrogen.

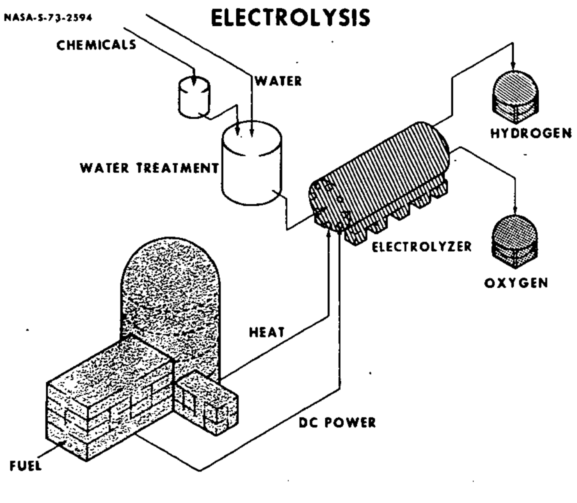


Figure 23. Nuclear Power - Electrolysis Schematic

Conventional electrolysers having conversion efficiencies of 60 to 70 percent are available today. Efficiency is the ratio of electric energy input to the heating value of the hydrogen output. This type of electrolyser suffers from high capital costs due to low current densities, typically 100 to 200 amps per square foot. Advanced concept electrolysers have been proposed and built by various companies (GE, Teledyne, etc.) based on NASA derived fuel cell technology. Electrolysers of this type are capable of operation at higher efficiencies and current densities. Despite these improvements, the price of electricity is still the dominant factor in electrolytic hydrogen costs.

In a second type of process, water can be split by application of thermal energy or heat. One step and multi-step processes for closed-cycle thermal decomposition of water have been proposed and tested. In the one step mode, the hydrogen produced from steam may be separated by means of a palladium membrane. Under equilibrium conditions, temperatures in excess of 2000°K are required for reasonable conversion of water to hydrogen. At Johnson Space Center, NASA is presently researching this process under non-equilibrium conditions at lower temperatures.

Multi-Step Thermochemical Processes

More importantly, a number of multi-step processes have been proposed to split water. The only products of a series of these reactions are hydrogen and oxygen. A plot of enthalpy versus temperature (Figure 24) shows the advantages of a multi-step process.

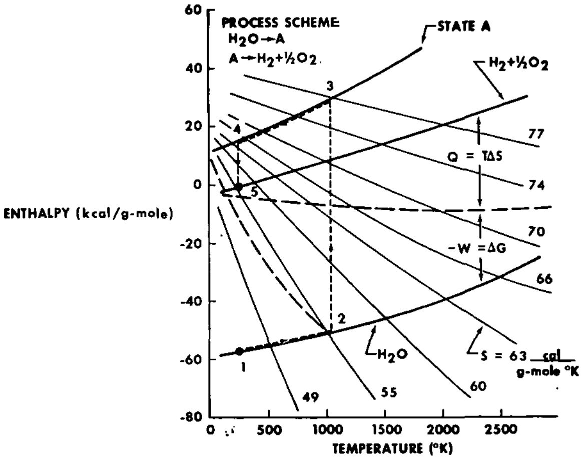


Figure 24.
Enthalpy - Temperature Diagram for Water Decomposition

The path (vertical line) from 1 to 5 represents water electrolysis with a large work (free energy) requirement and a small heat requirement. (This is shown by the length of the path in the W portion as compared to the Q portion.) In contrast, a multi-step thermochemical route is denoted by steps 1 through 5 without any work other than that used to separate the reaction products. This work can be minimized by using easy phase separations (gas-solid). The multi-step process is seen to operate at a much lower temperature, typically 1000°K, as compared to the one-step process at 2000°K. A typical set of processes is seen in Table 1.

TABLE 1. HALIDE PROCESSES

- CALCIUM BROMIDE PROCESS
  De Beni, Euratom, 1970

$CaBr_2 + 2\,H_2O \rightarrow Ca(OH)_2 + 2\,HBr$	730°C
$Hg + 2\,HBr \rightarrow HgBr_2 + H_2$	250
$HgBr_2 + Ca(OH)_2 \rightarrow CaBr_2 + HgO + H_2O$	200
$HgO \rightarrow Hg + \frac{1}{2}\,O_2$	600

- STRONTIUM BROMIDE PROCESS
  De Beni, Euratom, 1970

$SrBr_2 + H_2O \rightarrow SrO + 2\,HBr$	800°C
$2\,HBr + Hg \rightarrow HgBr_2 + H_2$	200
$SrO + HgBr_2 \rightarrow SrBr_2 + Hg + \frac{1}{2}\,O_2$	500

The first process, labeled "Calcium Bromide", is the Mark 1 process invented by Marchetti of Euratom in Italy. Note that the maximum temperature of this process is 730°C or approximately 1000°K. Another process investigated by this European group is shown as the strontium bromide process. At present, Marchetti and his co-workers are investigating a Mark 9 process based on iron oxide and hydrogen chloride reactions. A combination of thermal decomposition and electrolytic processes may be used to advantage in lowering the work (free energy) requirements. It takes less electrical energy or work to decompose hydrogen chloride than water. Examples of these processes are seen in Table 2.

TABLE 2. CHEMICAL-ELECTROLYTIC PROCESSES

- HYDROGEN CHLORIDE ELECTROLYTIC PROCESS
  Hallett, Air Products, 1965

$H_2O + Cl_2 \rightarrow 2\,HCl + \frac{1}{2}\,O_2$		700°C
$2\,HCl \rightarrow H_2 + Cl_2$	(Electrolysis)	300

- MERCURY CHLORIDE ELECTROLYTIC PROCESS

$H_2O + Cl_2 \rightarrow 2\,HCl + \frac{1}{2}\,O_2$		700°C
$2\,Hg + 2\,HCl \rightarrow 2\,HgCl + H_2$		300
$2\,HgCl \rightarrow 2\,Hg + Cl_2$	(Electrolysis)	500

In comparing these processes, we note, in addition to the efficiency (defined as the ratio of the heating value of the hydrogen output to the thermal energy input), the following properties: the maximum temperature of the process heat requirement which governs the type of primary energy input, and the percentage of the heat required at that particular temperature. The latter factor is very important if solar energy is used, because the cost of solar heat increases with the collection temperature. Sixty thermochemical processes were investigated and the number grows as new investigators enter the field.

Solar energy may well be the ultimate solution to the energy problem. Two difficulties exist with solar energy as a primary source of energy; it has a low density and is intermittent (Figure 25). At noon in the Arizona desert, the solar flux amounts to approximately 1 kilowatt per square meter. It has been estimated that this country's energy requirements could be met by a 75 mile by 75 mile area in Arizona covered by solar collectors. The energy supply is apparently free, but the cost of collection is high. Three schemes were evaluated for obtaining hydrogen from solar energy. The first method, using silicon solar cells at $7000 per square meter, was much too expensive. The second method used a parabolic trough collector to produce steam which could be converted to electricity by a vapor cycle, followed by electrolysis of water to produce hydrogen. This method also was considered too expensive. The third method used solar energy in conjunction with the water thermal decomposition step discussed in the previous paragraph. The capital cost for this method was estimated at $500 to $600 per kilowatt of installed capacity, which is comparable to present day nuclear plants. The primary output of solar energy conversion is electricity and the problem of energy storage for night and cloudy hours of the day would have to be solved to effectively use solar energy. The relative ease of storage of hydrogen would add much greater flexibility to a solar system, if hydrogen can be produced efficiently and economically from this primary source of energy.

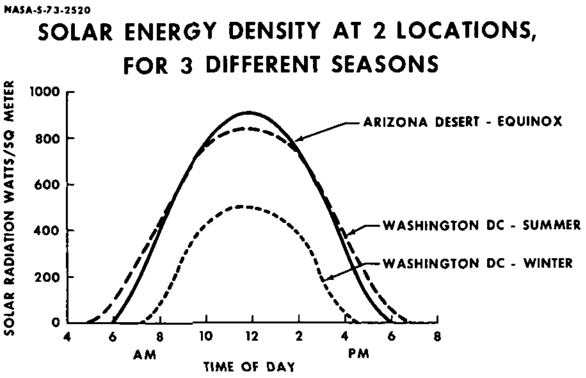


Figure 25. Solar Energy Density at Two Locations for Three Different Seasons

Other process paths that are not presently feasible, but remain as candidates for further study, include solar-photolysis, hydrogen production from wastes via bioconversion methods, and from oceanic thermal gradients.

COST OF PRODUCING HYDROGEN

Cost projections form part of a systems analysis. The five most promising system alternatives for evaluation are listed below: (Not in order of importance or preference):

nuclear power - electrolysis
coal gasification
nuclear heat - thermal decomposition
solar heat - thermal decomposition
wind - electrolysis

Figure 26 summarizes the alternatives considered in the study. An optimistic and a pessimistic projection for each process has been given for the present, or for when the future technology is projected to be developed.

NASA-S-73-2618

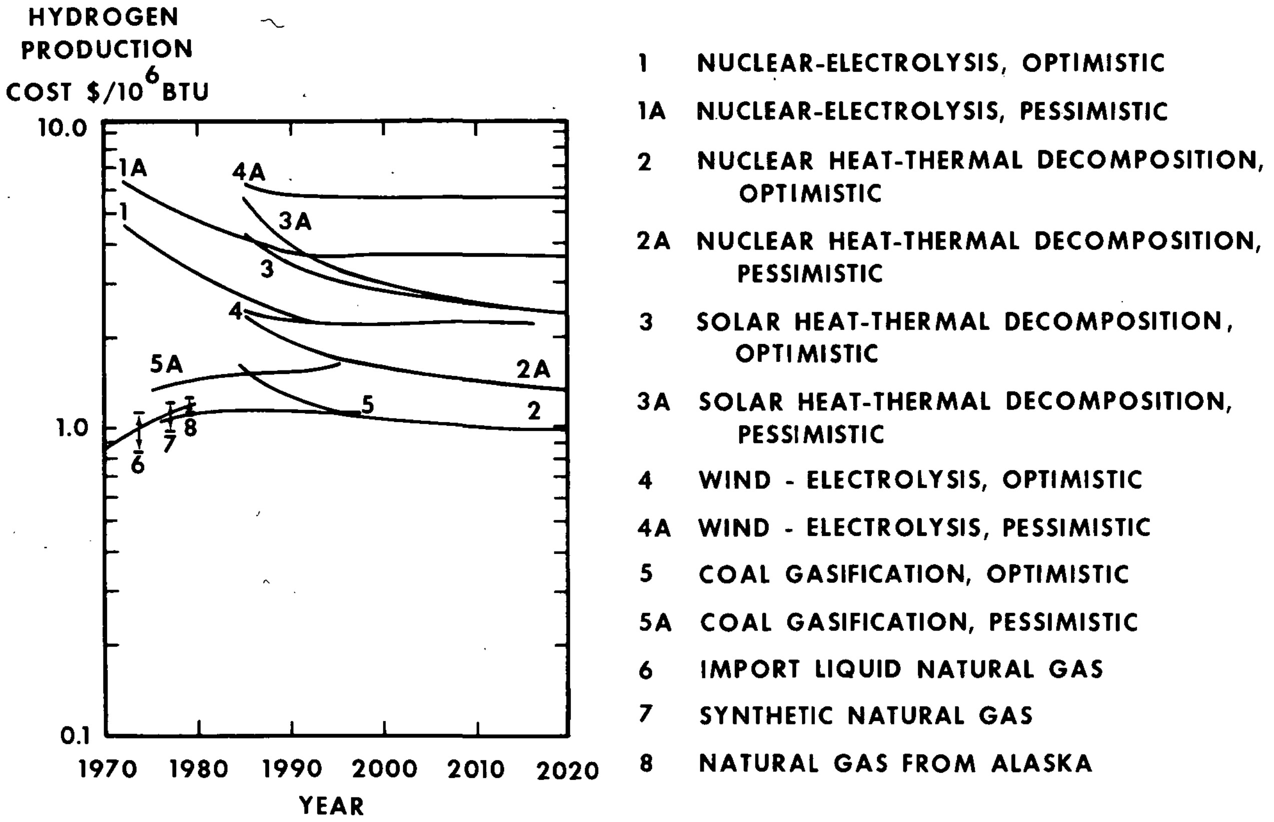


Figure 26. Hydrogen Production Cost for Various Alternatives

Nuclear Power - Electrolysis

The cost of hydrogen via this route depends on the cost of electricity. Off-peak forecasts of 2.5 mills per kilowatt-hour (kwh) would yield a cost of hydrogen in the range $1.00 to $1.50 per million Btu. Presently there is little off-peak power in this cost range and none envisioned for supplying hydrogen economy. The cost of electric power is more likely to be from 7 to 12 mills per kwh. With costs in this range, hydrogen by electrolysis would be in the $3.00 to $5.00 per million Btu range. Lines 1 and 1A of Figure 26 indicate these trends. We have not included credit for by-product oxygen from the electrolysis step. Sale of this oxygen could possibly lower costs by 30 percent. This option is uncertain because markets for the oxygen must be found.

Coal Gasification

The lowest costs are in the range of $1.00 to $1.50 per million Btu for hydrogen produced by the coal gasification process. See lines 5 and 5A of Figure 26. This process would compete with those for making methane from coal since costs are in the same range. Moreover, the use of methane produced from coal would not require a change in burners, pipeline systems and conventional practice. Because of these factors, the production of methane from coal will probably precede hydrogen from coal.

Nuclear Heat - Thermal Decomposition

If the technology should be developed by the year 1985 and efficiencies in the 50 percent range realized for this process, estimates of costs are \$1.00 to \$1.50 per million Btu for hydrogen (lines 2 and 2A) produced from nuclear heat, followed by thermal decomposition. This alternative, besides competing favorably with coal gasification processes, would have less environmental impact. This process shows great promise because of the predicted efficiencies and the lower cost for hydrogen compared to that obtained from the nuclear power - electrolysis processes. It is this fact that lends impetus to the growing amount of research being carried out in this area today, both in the United States and abroad, primarily in Italy and Germany, where a high temperature pebble-bed nuclear reactor operates routinely at 1100°K in this service.

Solar Heat - Thermal Decomposition and Wind - Electrolysis

Both of these options are considered in the intermediate and long term period. Due to the diffuse intermittent nature of the sources of energy and the large capital costs of collection, a cost of \$2.00 to \$3.00 per million Btu for the production of hydrogen is estimated. This range is similar to that for the alternative nuclear power - electrolysis in the intermediate time period. If hydrogen should be needed before this, and could not be obtained from coal, nuclear power - electrolysis could satisfy that demand, as the technology is currently available. One would, of course, have to pay a high cost differential.

From an environmental point of view, coal is probably the worst offender in terms of "social costs." This is due to strip mining, mine safety, and sulphur and ash disposal problems. Nuclear plants are probably the next worse offender. Questions have been raised concerning siting, safety, and waste disposal of the spent fuel. The ultimate form of energy may be derived from solar sources, including wind power.

In summary, it is feasible to produce hydrogen by several schemes. Some of these schemes can be implemented immediately; nuclear power - electrolysis at costs in the \$3.00 to \$4.00 per million Btu range, and coal gasification at approximately \$1.50 per million Btu. This cost could be maintained in the immediate term to 2000 and in the long term to 2020 by using a primary heat source coupled with a water thermal decomposition process, if the latter process can be developed commercially. Solar energy may prove competitive at that time. We see no one process as completely dominating the total market as a source of energy for hydrogen production systems. The choice will depend on economic, environmental and other factors.

TRANSMISSION AND STORAGE OF GASEOUS HYDROGEN

All economical methods will produce hydrogen in a gaseous form. The use of hydrogen, gas or liquid, as a fuel will necessitate the development of large-scale transmission and storage systems. In order to move this energy carrier from producer to user it will be necessary to utilize transmission and storage methods that have been found to be economical and practical by producing industries in the United States. A hydrogen gas pipeline system similar to the existing natural gas pipeline system appears to be the most practical solution. The pipeline system must be capable of delivering hydrogen gas directly from the generating plant to the user. It will be necessary to provide some storage capacity to meet daily and seasonal peak shaving requirements. Daily needs may be economically satisfied by line pack storage. Seasonal peak shaving requirements may be satisfied most economically by large scale underground storage in depleted natural gas fields, aquifers, or other suitable natural formations. More costly peak shaving storage may also be accomplished by high pressure tanks, liquid hydrogen, and gas storage in mined caverns.

One important question arises from all studies concerned with the transmission of hydrogen. Can the present natural gas transmission system be used? The answer is uncertain because the transmission of hydrogen at high pressure may cause embrittlement of pipe material. It will be necessary to examine the feasibility of converting portions of the existing natural gas pipeline to hydrogen transport. Some research will be needed to establish specific design criteria for various portions of this system. It appears that conversion of present pipelines can be accomplished with a moderate amount of problems, but there is a possibility that an entirely new transmission and storage network may be necessary. A new hydrogen pipeline system can be implemented using present day technology. Existing natural gas transmission lines could be used to transmit an equal amount of energy in the form of hydrogen gas, but such a system would require approximately four times the present compressor capacity and over five times the compressor horsepower. The projected cost of hydrogen gas transmission is, therefore, higher than natural gas transmission, but will be significantly less than overhead electrical transmission (Figure 21). It will be economical to transmit large quantities of energy through a hydrogen gas pipeline system. The cost of hydrogen generation will affect the overall economy of a hydrogen energy system much more than the cost of transmission and storage of hydrogen gas.

Potential Hydrogen Embrittlement

The metallurgical problem that is of most concern if we are to use existing pipelines for hydrogen is known as hydrogen environment embrittlement, which was first recognized in the mid-1960's. When a metal susceptible to hydrogen environment embrittlement is plastically deformed in the presence of hydrogen gas, cracking can occur at the surface. The problem is generally observed in relatively pure hydrogen at high pressures and moderate temperatures. Actual deformation of the metal is required in the presence of hydrogen for embrittlement to occur. Combinations of residual stress and stress concentrations that occur from fabrication of the pipeline or external stresses such as caused by pipeline movement can add to the working stress value and actually cause yielding at localized points. In the presence of natural gas this localized yielding has not been serious, but in the presence of hydrogen the localized yielding may result in cracking. As far as could be determined, no research on pipeline steels with regard to hydrogen environment embrittlement has been reported. It has been determined that certain impurities can inhibit or eliminate the susceptibility of a metal to hydrogen environment embrittlement. Most of the proposed chemical and thermochemical processes will not yield gaseous hydrogen of ultra high purity.

It appears that most operating conditions in a hydrogen system would favor the use of existing pipelines. However, until safety is assured, as a result of research in pipeline materials under actual operating conditions, any conversion project must be approached with caution.

Liquid Hydrogen

Liquid hydrogen may also be considered as an energy carrier. Transmission and storage characteristics of liquid hydrogen are unique and specially trained personnel are needed to handle hydrogen in this form. The liquefication of hydrogen is costly, although the required technology has been developed for some time. The expense arises from two facts: First, the process requires a great deal of energy, and second, the process involves very complicated, and hence expensive, equipment. In addition, if storage of the liquid hydrogen is required, the storage tank cost must be added to the cost of liquefaction.

As a result of these costs it is apparent that hydrogen will be transported and stored as a liquid only if there is no alternative. One such area of use may be the storage of energy for peak-shaving in a large power system where suitable gas storage facilities are not available. If the hydrogen must be liquefied for some purpose, such as peak-shaving, then the cryogenic properties of the liquid may be useful for other purposes. One potential use is the cooling of underground electrical cables to minimize the resistive power losses. Such cables could not compete with present overhead cables, but they may have sufficient environmental and aesthetic advantages to be justified in the future.

Metal Hydrides

Hydrides have some useful and advantageous properties when compared with gaseous and liquid hydrogen, particularly volume energy density. Even though the gas is stored at densities greater than liquid hydrogen, in hydride usage there are no associated liquefaction and cryogenic storage problems. However, even with the advantage of processing economics and handling safety over liquid hydrogen storage, it appears that hydrides as fuel storers will be limited to small scale specific uses rather than to large scale general uses. The reasons for this are the very poor mass energy densities and the probable high costs of metals. In addition, large-scale storage would involve excessive amounts of the world production of many of the metals used to make hydrides. The economics of hydride systems are uncertain and must be analyzed carefully to get a fair comparison with gaseous and liquid hydrogen storage systems. Typical metal hydrides are listed in Table 3.

TABLE 3. TYPICAL METAL HYDRIDES

Material	Weight Percent Hydrogen
$LiAlH_4$	10.5
$BaBH_4$	10.6
$LaNi_5H_6$	1.4
B_2H_6	21.0
MgH_2	7.6
$LiBH_4$	18.3

NONTECHNICAL ASPECTS OF A HYDROGEN ECONOMY

We include in our study of the hydrogen fuel system some preliminary estimates of how that system would impact upon, and be impacted by, society. There are many ways in which society will change during the next decades; and there are many ways in which hydrogen may, or may not, be incorporated into our energy system.

It is a hallmark of the technological society that we define problems and then set about solving them, rather than asking if the condition is really a problem or only defined as such, and whether we might be better off living with it. To a technological society, the fact that we seem to have developed more energy demand than we can supply is a problem, and the obvious solution is to build more power plants. Further, due to social and intellectual inertia, the type of plant we decide to build is probably the type to which we are already accustomed, rather than something new and unusual. We may be forced to do just that.

Americans believe in progress; that progress means growth; and that growth is keyed to energy use. The American energy system feeds a need for abundant, ever-increasing quantities of low-cost energy. It was based on assumptions that domestic sources were virtually limitless. But the present energy shortage upsets beliefs and belies assumptions. The fundamental question now is, can we continue our present exponential rate of energy consumption? Clearly, the answer is no. In a finite world there are limits to growth. This does not imply that, as natural energy resources dwindle, we shall all freeze to death in the dark; but, it does mean that Americans must make two new assumptions:

> New energy sources must be found,
> Energy prices will be higher.

We believe that hydrogen can play a significant role in the future American energy system.

The current energy shortage is not simply a technological problem subject to technological solutions. It is also a safety, legal, economic, environmental, political and social problem. We have sought to analyze a potential switch to hydrogen fuel in those terms. Our major conclusions are:

> Environmentally, hydrogen is a desirable energy carrier. It is clean burning, transmissible and storable underground. It is ecologically compatible because of its relatively short recycling time. Some present and proposed methods of production, however, may be environmentally objectionable.
>
> Hydrogen fuel would be readily acceptable in the American energy system. A changeover would have minimal impact on social, legal, political and economic institutions.
>
> Hydrogen fuel's only potential drawback may be public fears that it is more dangerous than today's fuel (The Hindenburg Syndrome/-Hydrogen Bomb). Public education and safety programs can change the image and gain acceptance for a marginally increased, acceptable risk.

Is Hydrogen Safe?

In the area of safety, the states have had the major responsibility. Within the last few years, however, a very definite trend has developed; its major points are:

> Increased federal responsibility in both safety codes and workmen's compensation,
>
> Increased federal regulation of safety with the preemption of state authority to set higher or different standards.

Should hydrogen enter the energy system, we can expect comprehensive federal regulation of hydrogen and a comprehensive safety code. Also, should a conflict result between federal and state authority over safety and health conditions connected with the use of hydrogen, we can expect that the courts, even in the absence of legislative expression, will find that Congress has preempted state authority.

Given the general concensus that petroleum fuels are being rapidly depleted, that their prices will rise, and given the powerful and still growing concern for environmental protection, American society may be faced with a trade-off in which a risk of some increased danger will be exchanged for having energy in the quantities desired. This is not to say that hydrogen should not and cannot be developed until the environmental risk is low. It is, however, to argue that we cannot dismiss hydrogen simply because it is marginally less safe now than are the other fuels to which we have become accustomed.

The largest single obstacle to a hydrogen economy is probably public fears about safety. It is widely believed that hydrogen is a dangerous substance. This belief is correct. But all forms of energy are dangerous, if improperly used. There are few Americans indeed who have not experienced energy hazards and accidents. It is even possible that initial public concern may lead to development of a hydrogen energy system hedged with safeguards which render it safer than is our present system. Hydrogen is dangerous in different ways than is gasoline, natural gas or electricity, but is not necessarily an absolute danger. We believe that society can learn to protect itself from most errors and live with the remaining risk, as we already do with existing energy systems.

Much of the fear of hydrogen is based on unfamiliarity coupled with the image of a famous disaster. Given timely enactment of the necessary safety codes and the application of what is largely state-of-the-art technology to safety devices, the remaining requirement will be public education. There is a conventional public education and public relations method which should be able to counter unfounded public fears about hydrogen. It is the truth. The H-Bomb image is so wildly at variance with fact that it can and should be easily corrected for all but the very few. The Hindenburg Syndrome is rather more difficult. The dangers exemplified by that incident are real and must be dealt with. It will be necessary to show that hydrogen dangers can be met and that safety standards can obtain acceptable risk levels.

Legal Aspects Of A Hydrogen Economy

The American energy system is heavily regulated by the federal government. But, Congress has relied upon the states in many instances to supplement the federal government's regulatory power. Even when federal authority has been exercised, the usual pattern is a dual system of federal and state authority. State authority is perhaps most pervasive in the coal mining industry, where comprehensive safety codes, siting requirements and pollution standards abound. State residual authority in the petroleum industry is likewise quite comprehensive. A well known illustration is the powerful Texas Railroad Commission. Some generalizations and forecasts can be made about governmental regulations in the near future from a comparison of two recent Supreme Court cases.

In *Otter Tail Power Company* v. *United States*, the Supreme Court was presented with the question of a power company's refusal to deal with certain city corporations wanting to provide their own service to residents by purchasing, at wholesale prices, electrical energy produced by the company. Although the case concerned the anti-competitive effect of the power company's refusal to deal, the Court noted that the Federal Power Act, though comprehensive, still allowed dual governance of economic decisions between the public sector (federal government) and the private sector (private owners). Thus, as private ownership is maintained, commercial relationships are governed, in the first instance, by the private business judgment of the company. This results despite the fact that the company is a highly regulated natural monopoly. In other words, there is still a zone of freedom allowed by a regulatory act where private decision making is generally unregulated.

Similarly, there are many cases where federal regulation is not exclusive, but rather shared with the states. Such an issue was recently involved in *FPC* v. *Louisiana Power & Light Company.* That case presented the fundamental question of whether or not the FPC was empowered by the Federal Power Act to take certain regulatory action over the Company. The Company argued that the FPC had no jurisdiction. The Supreme Court, construing the Natural Gas Act of 1938, noted that the FPC had been granted broad powers "to protect consumers against exploitation at the hands of natural gas monopolies." To that end Congress "meant to create a comprehensive and effective regulatory scheme" of dual state and federal authority. The Court also noted that although federal jurisdiction was not to be exclusive, FPC regulation was to be broadly complementary to that reserved to the states, so that there would be no "gaps" for private interests to subvert the public welfare. Thus the question became: Which jurisdiction should fill the gap? To this question the Court answered that

> When a dispute arises over whether a given transaction is within the scope of Federal or State regulatory authority, we are not inclined to approach the problem negatively, thus raising the possibility that a no-man's land will be created. That is to say in a borderline case where Congressional authority is not explicit, we must ask whether State authority can practically regulate the given area and if we find it cannot, then we are impelled to decide that Federal authority governs.

Noting that there is inevitably a conflict between producing states and consuming states (which could create contradictory actions, regulations, and rules that could not possibly be equitably resolved by the courts), the Court felt that a uniform federal regulation was desirable. The Court, therefore, concluded that the matter in question was indeed within the jurisdiction of the FPC. The important fact from the case is that competition for energy among the states gives rise to a diversity of state resolutions, thus impelling the Court to find that the area is federally regulated. This insures regulation in the national interest, but diminishes the regulatory power of the states.

For a number of years, spokesmen for the energy industry have noted the need for a national energy policy and coordination among the various federal and state regulatory agencies. Prompt action seems certain. As recently as April, 1973, President Nixon proposed the establishment of a cabinet-level agency entitled the Department of Energy and Natural Resources, which would be responsible for the balanced utilization and conservation of our nation's energy and natural resources. The proposed Department would consolidate many of the regulatory functions scattered throughout the federal structure.

Thus, it may be that the federal and state regulatory structures will be consolidated into a single federal cabinet-level department. Surely, as the demand for energy increases and the supplies decrease, this agency will be given more and more functions of research, development, funding and regulation of the entire energy picture. It may also be forecast that as the problems of energy use and supply become more critical, more and more functions will be taken away from the states by the federal government. This is indicated by the Supreme Court's decision in ***FPC* v. *Louisiana Power & Light Company*** where we found the U. S. Supreme Court saying that a federal regulatory agency, in effect, abhors an energy system vacuum.

Since several of the suggested methods for the production of hydrogen would use large quantities of water and produce substantial quantities of reject heat, it has been suggested that the plants be located offshore. Proposed offshore locations run all the way from the shoreline, to the territorial sea, to the contiguous zone, to the continental shelf sea area, to the high seas. Each one of these siting locations itself, along with the production process by-products (primarily salts and reject heat), and the use of large quantities of water, all raise serious international law questions.

The threshold question is, who owns the seas? The traditional answer to this question has been, no one. Under the basic principle of the freedom of the seas, the water itself, the marine life, and the minerals (in and under) belong to no one; or, in other words, they were treated as *res nullius*. Since the seas and its resources belong to no one, it follows that anyone could use them in any manner for any purpose. There are, however, growing signs of an inclination to treat the oceans and its resources as being shared. This change indicates that the seas are limited to reasonable uses. Overboard reject heat and production by-products may constitute an unreasonable use.

There are still many open questions in international law and there are many developing ideas. The ultimate shape of international law must await the results of the 1974 world conference on the Law of the Seas, but one final note must be made. That conference may write into the new law of the seas a wholly new concept. That emerging concept may be labeled Shared Development. Significantly, the conference was called to write a treaty for the development and sharing of the ocean's resources. Similarily, the basic premise of the report to the United Nation's 1972 Conference on the Human Environment was that a certain level of development not yet reached in the developing countries is a prerequisite for a decent environment and all nations must help the have-nots. Thus, if a hydrogen production facility were to be sited on the high seas, it may well run into severe objection on environmental grounds, and/or strong demands from the developing countries of the world for a share of the fuel produced.

Environmental, Economical and Social Factors of a Hydrogen Economy

Hydrogen is environmentally an almost ideal fuel. It is significantly cleaner than hydrocarbon fuels, and its only combustion by-products should be easily controlled. Hydrogen transmission by underground pipeline offers aesthetic advantages over conventional electrical transmission. Hydrogen's environmental impact is likely to be highly positive, allowing cleaner cities and factories. The adverse impact, if any, will be connected chiefly with the method by which hydrogen is originally produced.

United States material wealth and national power have rested upon a relative abundance of natural resources, an industrious and capable population, an abundance of energy and an occasional bit of luck. Data indicate a close relationship between high energy consumption rates and high Gross National Product per capita for a large sample of nations. American society is an affluent (even effluent) society in which the availability of massive quantities of energy at low prices has been a major supporting element. In the current energy shortage we face important questions: Can enough energy at low enough prices be assured that we can maintain our way of life indefinitely into the future? Failing that, can other ways of life be found which are less energy-intensive, but still satisfying? Can other factors substitute for high-level energy consumption (better information, different social values emphasizing areas of low energy use, etc.)? Do we have the intellectual tools to really understand and analyze such questions?

We know little about the role of energy as a social force, but we do know that the role is important. It is probably much more important than we bothered to notice during times when energy and reserves were abundant. We know very little about how to calculate social costs.

Industrialized, high-technology society rests upon a base of energy, but each different energy base and each different application method exerts peculiar effects upon the larger social context. A large scale hydrogen economy will require capital investment expenditures beyond the capacity of all but the largest institutions and may result in new patterns of public-private ownership. A switch to a hydrogen energy system will also alter existing economic flows, both domestic and international. Legal provisions, political power and pressures, and environmental constraints must be redesigned and recalculated. But similar changes have been experienced before, as the nation went from wood to coal, from coal to petroleum, and—perhaps more apropos to the hydrogen economy—as natural gas use spread swiftly during the 1950's.

We are now beginning another change in our energy base, but this time there are several questions. It is neither clear what the new energy base will be nor is it clear what medium will be chosen to carry and distribute the energy. We may be moving toward a mixed base power system where nuclear (fission, breeder and even fusion) will coexist with solar, geothermal, ocean temperature gradients, and perhaps others even more exotic. We may use electricity to distribute the base power, or we may use hydrogen, or both.

There are other complications to this energy change. For the first time, environmental preservation has become a general force in society with legal, political and economic muscle unknown in prior energy/society relationships. We are even beginning to face the certainty that infinite growth in all things is not a real possibility, which leads inexorably to a previously unthinkable question: If we must "stop" growth, when and on what terms shall we stop?

We can state that, to the degree that a new fuel is compatible with present uses of the old fuel, and to the degree that replacement can be carried out at low cost in dollar terms and life style changes, it will be quite socially desirable. Hydrogen offers potential improvements in the environment, and protection against external influence. It is now time to develop careful studies which can clarify and perhaps even answer some of the questions raised in this report.

Political Aspects Of A Hydrogen Economy

American use of energy has meshed with several strong values in the American social, political, and economic system to produce a peculiar set of inputs and outputs. The society has made several demands related to energy provision and utilization:

> that progress must exist in an observable fashion, generally in the form of an ever-rising standard of living measured chiefly in material goods, that the premise of a consumer-controlled, market economy based upon a system of private property and private competitive enterprise must be maintained as a value and as a symbol that the public image of the United States as a great nation be preserved. All of these requirements produce an implicit energy policy,
>
> the supply of energy must be adequate at all times, which means that it must constantly grow larger,
>
> the price of energy must be kept at a level which does not impede its use to support progress,
>
> energy production should be carried out primarily by private enterprise, although government regulation is allowed as a (regrettable) necessity due to the interstate character of energy supply, natural monopolies, and other factors.

There is a very serious, potentially revolutionary political content in the energy shortage. The entire American economy, many social values and major political patterns depend upon massive and growing quantities of (relatively) cheap energy. Suggestions that we may be forced to reduce our energy consumption are usually considered crackpot solutions. Despite pleas to conserve energy by driving more slowly, change the thermostat setting or make some other saving in energy consumption, the emphasis is nearly always on ways in which supplies can be increased to meet the demand. The present shortage is viewed as real, but temporary. Suggestions for real and permanent reductions in energy consumption are greeted with warnings of stagnation, unemployment, reduced living standards and a loss of international status.

The United States now depends very heavily upon petroleum energy. Since we are no longer self-sufficient in petroleum energy, and since we already use far more than a proportional share of the world's scarce hydrocarbon resources, we must move away from that potentially precarious base as rapidly as possible. It would indeed be sobering to find ourselves faced with a choice of sudden and drastic curtailment in energy consumption and consequent economic dislocation, or the possibility that a growing petroleum shortage may lead to American and

European military seizure of Middle Eastern oil fields. Clearly, there is potentially enormous political conflict involved in energy matters, and of a different type than the fairly well understood and endemic conflict between public and private power or the perennial maneuvering over the oil depletion allowance. Those have been marginal frictions over how and on what terms energy would be provided, compared to the now wide question of whether energy can be or should be provided.

Hydrogen is no solution to the energy shortage despite the occasional hyperbole. As this report makes clear, hydrogen is not a source of power but a means by which energy may be transported and stored. If the primary power problem can be solved, hydrogen does offer several advantages over our current extreme dependence upon hydrocarbon fuels. In this sense it can contribute to an easing of the shortage and become a part of our normal energy system.

IMPLEMENTATION OF A HYDROGEN ECONOMY

Hydrogen is currently used in many industrial chemical processes, and we believe that hydrogen can be introduced into industrial process heat use as soon as it can be made available on a competitive cost basis. Electric power generation, using hydrogen as a peak-shaving fuel and as an energy storage system, is now in the development stage and shows considerable promise. Because of the very large volume of hydrogen required and the problems of conversion of existing gas line systems and gas equipment to burn hydrogen, the residential and commercial use of hydrogen will occur later. Except for the possibility of use in airplanes, the use of hydrogen as a fuel for transportation probably will occur last.

From these observations we have concluded that any shift to a hydrogen economy must be a sequential one. Although the chemical industry uses large tonnages of hydrogen, there is no established market for hydrogen as a fuel, except in the space program. We believe that direct experience in producing, pipeline transporting and using hydrogen as an energy carrier is needed to demonstrate its feasibility for use in the nation's energy system.

Maximum participation by industry is desired to achieve the transition. In order to encourage participation, we propose that a guaranteed market be established for a number of years by a demonstration project. One possibility would be to select a power plant which would be willing to shift to hydrogen, because of its location in an area with serious pollution problems. The supply of hydrogen fuel would be solicited by bids from industry at a premium price for a specified number of years. The bidders would be required to supply the hydrogen from a fuel conserving process and to transport it by pipeline for some specified minimum distance. The bidder would be permitted to recover his development and design costs, capital costs and operating costs, spread over the life of the contract. A government subsidy or private foundation grant would be needed to pay the difference between the cost of hydrogen and the cost of conventional fuel. The bidder would be encouraged to develop other markets which also could be supplied by the hydrogen plant or an expansion of it.

Potential locations for a demonstration plant (a Hyplex) would depend on the type of process to be used. If hydrogen is to be produced from coal, the project could be sited in the general areas of Joliet, Illinois; Pittsburgh, Pennsylvania; St. Louis, Missouri, or any of several other locations. In each case the location is within pipeline distance of coal fields in which a gasification plant could be built. Suitable underground formations are available for large volume storage and several power plants which could convert to hydrogen are operating in these areas. A potential hydrogen burning peak load unit is now being tested by Rocketdyne and Commonwealth Edison at Joliet. Steel mills, chemical plants and other industrial fuel users are within pipeline distance in each area.

If nuclear energy is to be used to generate the hydrogen, similar combinations of power plants and industries can be identified, where the nuclear plant could be located offshore or in the desert and the hydrogen pipelined to the point of use. An example would be Los Angeles.

Concurrent with or subsequent to the Hyplex demonstration project, a larger demonstration project will be needed as part of the sequential development of a hydrogen economy. In order to include the residential and commercial markets, an entire city (Hycity) would need to be operated on hydrogen fuel. An interesting possibility would be to design the area for the next nuclear fuel processing plant on the basis of hydrogen fuel. This facility will be needed by 1985 and will require a 2000 megawatt nuclear power plant to operate the processing plant. In addition, a 1000 megawatt plant will be required as a stand-by plant to prevent the possibility of a catastrophic power failure to the processing plant. With proper storage facilities, the standby power plant could be used to produce hydrogen for the city of 10,000 which would be associated with the plant.

As a final step, before full introduction of hydrogen fuel into the economy, an island might be converted to the use of hydrogen fuel. In this case, the transportation area could be added to the previously established markets. On an island such as Hawaii, all of the energy must be imported, thus any cost differential would not be as great as for areas where cheaper fuel is available. Final integration of hydrogen into the energy system of the United States would be the result of economic and environmental advantages of hydrogen as an energy carrier.