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HYDROGEN TOMORROW

DEMANDS & TECHNOLOGY REQUIREMENTS

REPORT OF THE NASA HYDROGEN ENERGY SYSTEMS TECHNOLOGY STUDY

JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY

PREFACE

For many years NASA and the Jet Propulsion Laboratory have recognized the need to apply available expertise to the solution of problems of national interest outside the fields of aeronautics and space. We have shared a keen interest and enthusiasm for contributing to the energy field, including Hydrogen Energy Systems.

The Hydrogen Energy Systems Technology Study reported in this document was undertaken in the interest of augmenting our understanding of the hydrogen energy field and assuring that all potentially fruitful opportunities for energy systems via hydrogen technology are examined. Considerable scattered work in hydrogen technology and hydrogen systems had previously been undertaken by various institutions, and some consideration has been given to hydrogen in other broad studies. This study is specifically an effort to determine national needs for research and technology in hydrogen production, handling, and use, and to recommend ways to meet such needs. It covered the broadest spectrum possible within the available resources, but is not all inclusive and should not be considered the last word on the subject.

The study was initiated and funded by the NASA Office of Energy Programs. The Caltech Jet Propulsion Laboratory conducted and managed the study under its prime contract to NASA, supported by several NASA centers through a Working Panel. In addition, representatives of other Government agencies interested in hydrogen, industry-supported research institutions and experts from universities participated in a Review Group at my invitation. I would like to take this opportunity to thank the reviewers for their participation and their contribution to the broad perspective of this effort.

W. H. Pickering
Director
Jet Propulsion Laboratory

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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DEMANDS & TECHNOLOGY REQUIREMENTS

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CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
DECEMBER 1975

ABSTRACT

Results of the NASA 1975 Hydrogen Energy Systems Technology (HEST) Study are reported. The Study projected national needs for hydrogen, evaluated technologies of production, handling, and utilization, and determined the critical research and technology activities required to meet the needs. It adopted an approach of seeking the broadest available spectrum of information and insights from NASA and other government agencies, from universities and from industry, and of assessing, validating, and integrating the results of other hydrogen-related studies in order to form specific conclusions.

The HEST Study found current U.S. hydrogen utilization to be dominated by chemical-industry and petroleum-processing applications, and to represent 3% of total energy consumption. The Study's projections of hydrogen use show growth in the remainder of this century by at least a factor of five, and perhaps a factor of twenty. New applications in the manufacture of synthetic fuels from coal and directly as an energy storage medium and fuel are expected to emerge later this century. Of these new uses, electric utility energy storage for peak-shaving, supplements to the natural gas supply, and special purpose transportation fuel such as aircraft, show promise.

The Study concludes that the development and implementation of new means of supplying hydrogen, replacing the use of natural gas and petroleum feedstocks, are imperative. New production technology is essential to support even the lowest growth estimate. Methods based on alternative fossil feedstocks, such as coal and heavy oils, which are less expensive and nearer to technical maturity than non-fossil production systems, should be made operational while these feedstocks are abundant. Concurrently, the long-term tasks of advancing electrolysis technology, researching other water-splitting techniques, and integrating these with developing nuclear and emerging solar primary-energy systems, must be carried on, together with work on hydrogen combustion systems and research in materials and safety engineering. Systems studies and assessments of the economic, social, and environmental impacts of hydrogen technology are also called for.

ACKNOWLEDGMENTS

The HEST Study was initiated and carried out under the direction of the NASA Office of Energy Programs. Supportive efforts were provided by the NASA Johnson Space Center, Kennedy Space Center, Langley Research Center, Lewis Research Center, and Marshall Space Flight Center, with participation by Ames Research Center.

We wish to express our gratitude generally for the important, valued, and dedicated contributions to the HEST Study effort and to this report by many individuals and organizations, which are listed as fully as we know how in Appendix A to the Report. Certain people have played key roles in the progress and success of the HEST effort, and we gratefully and specifically acknowledge their help here:

Mr. David R. Stone, Program Manager in NASA's Office of Energy Programs, has given energetic help and guidance which have greatly benefited the direction and pace of the effort.

Dr. Ramachandra Manvi has guided the effort at all levels from the beginning as well as being an important and indefatigable participant, leading two tasks and authoring many portions of this report.

Mr. William Escher, consultant, has provided very valuable general guidance to the Study as well as energetic participation in the organization and creation of specific elements.

Mr. James H. Wilson, documentation representative, has participated from the beginning in reporting our meetings and activities and in writing, editing, and producing our documents, including this Report.

The JPL HEST Team, the NASA Working Panel, and the Review Group have given advice, constructive criticism, encouragement, and a variety of help well beyond the bounds of their formal organizational roles. Some specific Review Group Comments regarding the report are given in Appendix K.

JPL Management from the Director and Deputy Director to the responsible supervisors, including the Civil Systems Program Office and especially Dr. M.E. Alper, Manager of Energy and Environmental Systems, have been helpful, supportive, and encouraging.

The HEST Study represents not the last word but a step toward taking the measure of our needs, present and future, for hydrogen and for advances in hydrogen technology. We have endeavored to draw together the best information and ideas as of 1975.

James H. Kelley, Manager
Eugene A. Laumann, Deputy Manager

Hydrogen Energy Systems Technology Study
Jet Propulsion Laboratory

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

Hydrogen, the most abundant element in the universe, has been known to man for about two centuries. It was initially used as a buoyant gas, then as a synthetic-fuel constituent. At present, hydrogen is used almost entirely as a unique industrial chemical in petroleum processing and in the synthesis of ammonia and methanol. New uses are expected to appear, such as in the gasification and liquefaction of coal and as a direct special-purpose fuel.

Hydrogen is not, however, a primary energy source – it must be manufactured. Practically all the hydrogen now produced in this country is manufactured from natural gas and light oils. With the availability of these resources seriously declining, it will be essential that hydrogen be produced from other energy sources if the projected demands are to be met.

The National Aeronautics and Space Administration (NASA) is the major U.S. user of pure hydrogen as fuel. NASA has conducted extensive research into the use of hydrogen for space and aeronautical applications. This work and other related research has established NASA as a major source of experience in hydrogen combustion, handling, storage, materials compatibility, and in thermochemistry and electrochemistry which could be of considerable value in the development of hydrogen applications and advanced production techniques. As part of a continuing effort to assure that the significant Federal investment in NASA's aeronautics and space technologies is effectively and efficiently applied to energy-related problems, a Hydrogen Energy Systems Technology (HEST) study was initiated.

The purpose of this study is to appraise the research and technology needs for hydrogen production and use, and to identify and properly relate NASA experience to meeting these needs. Preliminary plans which define and evaluate approaches to meeting these technology needs will be formulated while assessing the applicability of NASA technology. This effort could serve as a basis of NASA support in the establishment of detailed technology plans to facilitate an economical supply of hydrogen to meet future national demands.

A. Objectives and Approach

The specific objectives of the first phase of the study were:

1. To determine the future demand for hydrogen based on current trends and anticipated new uses.

2. To identify the critical research and technology advancements required to meet this need considering, to the extent possible, raw material limitations, economics, and environmental effects.

The purpose of this report is to document the results of Phase I. In Phase II, preliminary program plans will be formulated from which an assessment of the applicability of NASA experience and technology will be made.

The study was conducted by a team at the Jet Propulsion Laboratory, supported through a Working Panel by personnel from six NASA Centers. A Review Group, composed of representatives from federal agencies, universities and industry-supported institutions, was formed to review and critique the study. A position of inquiry rather than advocacy was maintained by the team throughout the study. To avoid duplication of effort, existing information and expertise were utilized as available. In addition to reviews of literature and the conduct of analyses, extensive contacts were made with industry and with university and government researches to obtain up-to-date data and relevant information on hydrogen requirements and current programs.

B. Present Hydrogen Uses

The worldwide production and use of hydrogen has increased by more than three orders of magnitude in the last four decades. In 1938 approximately 70 million cubic meters (2.5 billion standard cubic feet) of hydrogen were produced world-wide. By 1973 the world total was estimated at over 250 billion cubic meters (9000 billion standard cubic feet). About a third of it was produced and used in the United States, requiring 3% of the U.S. energy consumption for hydrogen production. Production in this country has grown by a factor of more than 40 since 1945, and tripled in the past decade. The distribution of hydrogen among the major consumers in the United States in 1973 is shown in Figure 1. Here the estimates of hydrogen quantities include hydrogen produced and used within a chemical plant (captive hydrogen) as well as hydrogen delivered to users (merchant hydrogen).

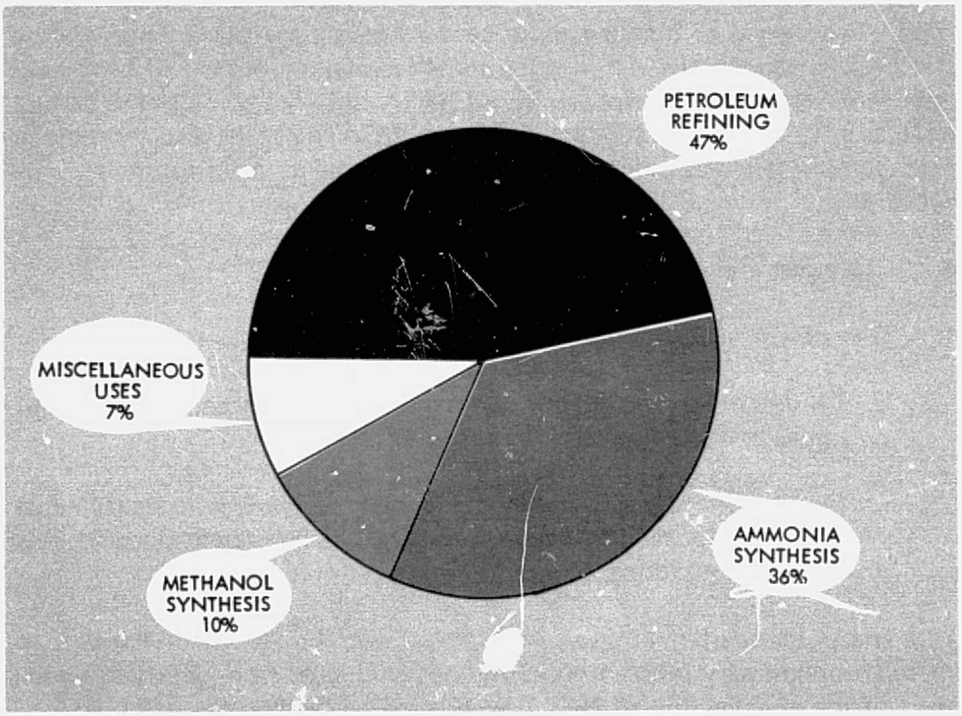

Fig. 1. Distribution of the 8×10^{10} cubic meters (3000 billion cubic feet) of hydrogen consumed in the U.S. in 1973

In addition to the dominating applications in petroleum refining, ammonia synthesis for fertilizer production, and methanol manufacturing, hydrogen has a broad spectrum of miscellaneous and special uses. Hydrogen is used in the production of foodstuffs, including margarines and cooking fats, and in the manufacture of soap. It serves in the refining of certain metals, in semiconductor manufacture, and for the annealing of metals. It is employed in uranium extraction and processing, and for corrosion control in nuclear reactors. Hydrogen cools electrical generators in utility power stations. It is a feedstock in organic chemical synthesis leading to production of nylon and polyurethane. It is used in the manufacture of float glass. It is a high-energy rocket fuel, and an experimental aviation and automotive fuel.

Hydrogen was a major constituent of the illuminating coal gas and the industrial producer gas of the nineteenth and early twentieth centuries. In those forms hydrogen was successfully transported by pipeline and stored. In modern times when pure hydrogen has been handled at relatively high pressure and in the cryogenic liquid state, embrittlement and other problems in materials have sometimes resulted but have been overcome with applied research and technology. Safety was once considered a serious problem for hydrogen utilization because of its high flammability, but in modern applications the hydrogen safety record has been excellent.

Most of the hydrogen currently produced in the United States is obtained by the reaction of natural gas or light oils with steam at high temperature. The petroleum-refining industry, which accounts for about 47% of the hydrogen demand, uses both oil and natural gas as feedstocks for its hydrogen. Almost all others obtain their hydrogen by natural-gas reforming. Very small quantities of high-purity hydrogen are also derived from the electrolysis of water. Current distribution of energy resources for hydrogen in the U.S. are shown in Figure 2.

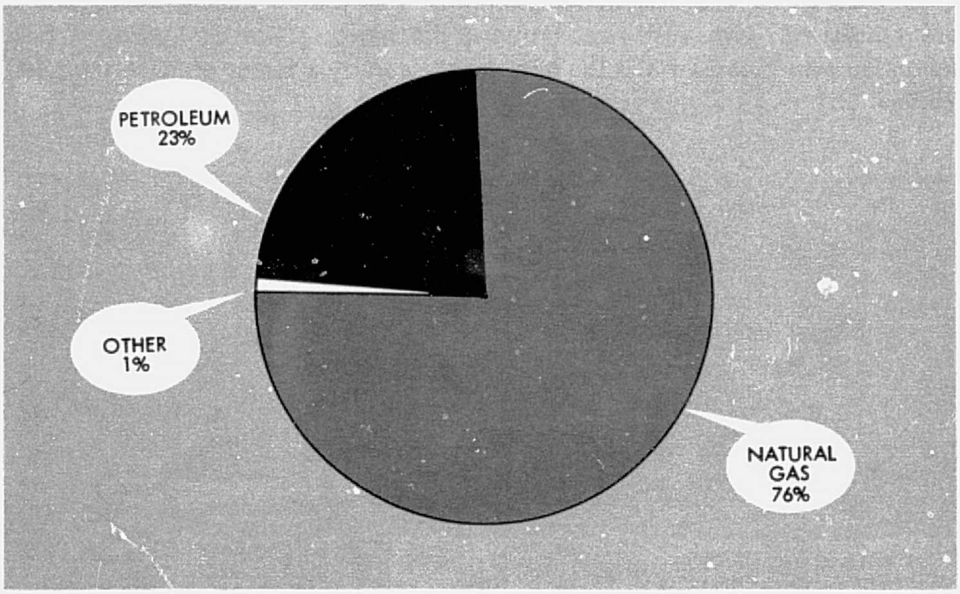

Fig. 2. Distribution of energy/feedstock resources for the hydrogen produced in the U.S. in 1973

C. Hydrogen Use Projections

Hydrogen use projections were developed, based upon historical relationships between hydrogen and energy use and upon documented projections of energy use. Two recent projections of national energy use were selected as a basis for estimates of future hydrogen needs. The two projections were selected because of their depth of technical documentation and because they represent diverse views of future national energy requirements. The first projection is based upon one of the scenarios developed by the Ford Foundation Energy Policy Project. Referred to as the Ford Technical Fix Baseline (FTFB) projection, it projects relatively conservative energy demands on natural gas, oil and coal to the year 2000, with a continued supply of natural gas and oil through this time period. In contrast, the Nuclear Electric Economy (NEE), as proposed by the Westinghouse Electric Corporation, makes higher energy use projections to the year 2000 based on electricity derived from nuclear and coal energy sources.

Two concepts of hydrogen use, called the Reference and Expanded Hydrogen Use Scenarios, were developed to bracket the range of probable hydrogen futures. The Reference Hydrogen Use Scenario assumes continued historic uses of hydrogen with the addition of some new uses in coal gasification and liquefaction consistent with the FTFB energy projection. The Expanded Scenario used the NEE energy projection to establish an Expanded Use Projection. The Expanded Scenario adds limited new uses such as experimental hydrogen-fueled aircraft, some mixing with natural gas, and energy storage by utilities, and assumes higher growth rates of traditional uses than does the Reference Scenario. The Reference and Expanded projections are charted by use category in Figure 3 for the years 1985 and 2000. Figure 4 shows the hydrogen growth history and the projections plotted from 1950 to 2000 on a logarithmic scale. The Reference projection shows an increase by 1985 to 1.7 times current usage; by the year 2000 to 5.5 times. Growth factors for the expanded projection are 3.4 by 1985 and more than 20 by the year 2000. This illustrates that projected growth rates are consistent with historical growth; the nation's use of hydrogen has increased by a factor of 3 in the past decade and by a factor of 20 in the past 25 years.

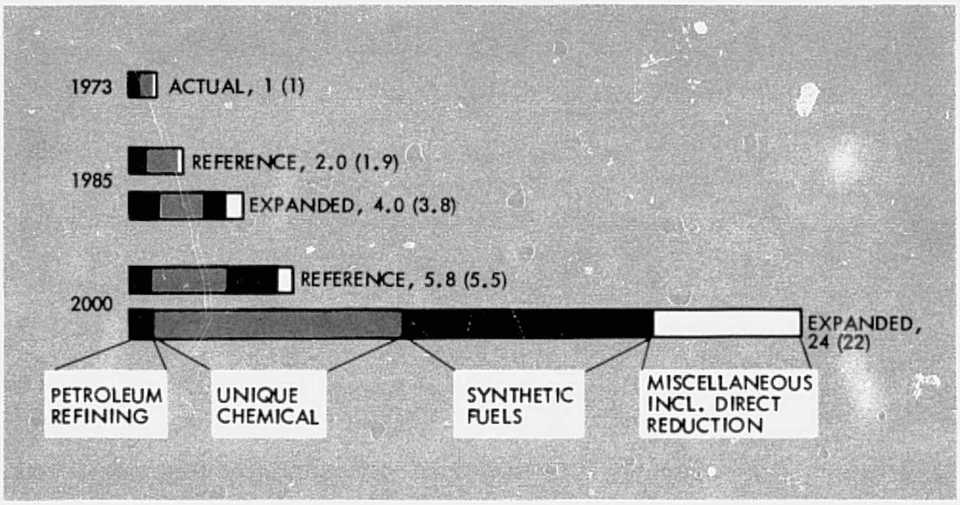

Fig. 3. Hydrogen projections by use sector, 10^{18} J (10^{15} Btu)

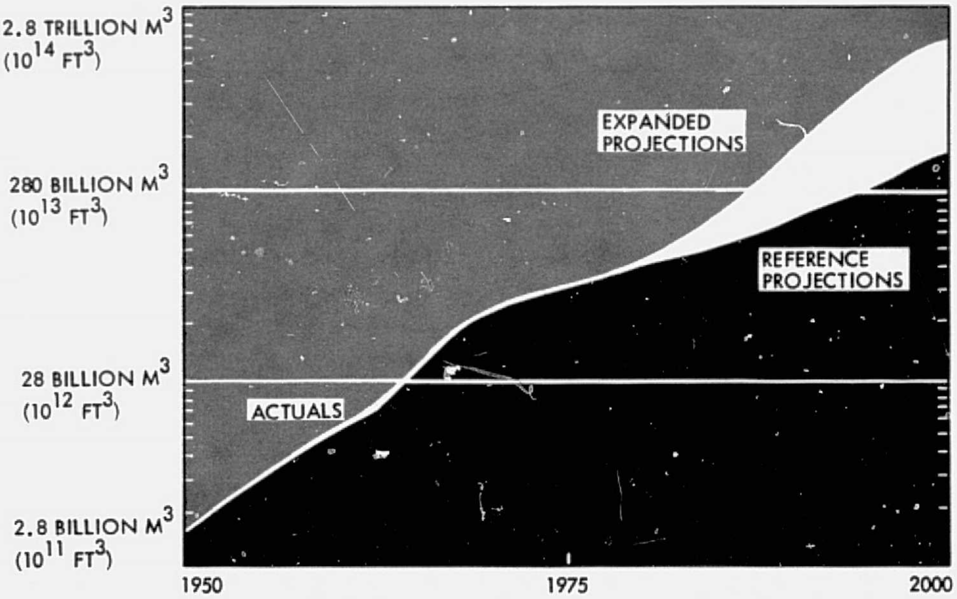

Fig. 4. Growth in hydrogen demand in the U.S.,1950 - 2000 (logarithmic plot)

D. Resource Implications

The Ford Technical Fix Baseline (FTFB) energy projection suggests that the continued primary dependence on natural gas and oil permits a viable economic climate through the year 2000. Many other recent energy projections indicate that at least by the year 2000 these resources will be significantly depleted. If hydrogen use in the future falls between the lowest and the highest projections which have been given, there will be a continuously increasing demand for the depleting fossil feedstocks, natural gas and oil. This widening gap between domestic supply and demand will continue to increase the demand for expensive import oil and liquefied natural gas. This demand pressure will lead to shortages and increased costs and, ultimately, to the piecemeal search for alternative resources and supply modes.

Alternate resources are available for making hydrogen, but they are not now as economic or as energy-efficient as natural gas. Before natural gas was widely available, hydrogen was made from coal. Low natural-gas prices caused coal to be displaced, but coal could again be used to produce hydrogen. In each fossil-fuel-based hydrogen production process, water provides a significant portion of the hydrogen produced. The natural gas, oil and coal provide some of the hydrogen and in addition provide the energy to drive the reactions. Other energy sources, such as nuclear and solar, can also be combined with water to produce hydrogen through water-splitting reactions. The relative energy requirements and costs for producing hydrogen from alternative energy sources are compared to those for hydrogen production from natural gas in Table 1. Minimum and maximum process efficiencies and feedstock costs are used to provide the values given.

Table 1. Relative efficiency and cost of hydrogen production methods

Primary Resource	Cost Range $/GJ	Relative Cost	Relative Energy Requirements
Natural Gas (baseline)	0.82 - 6.59	1.0	1.0
Oil (partial oxidation)	1.55 - 7.76	1.1 - 1.9	1.1 - 1.2
Coal (gasification)	1.26 - 4.90	0.8 - 1.5	1.1 - 1.2
Nuclear (electrolysis)	2.69 - 32.13	3.3 - 4.9	2.3 - 4.8
Solar (20% collection efficiency)	4.76 - 209	5.8 - 32	4 - 6

The availabilities of these alternative energy resources vary. The United States has abundant quantities of coal. This fact, taken with the more favorable relative energy requirement and relative cost shown in the table, favors coal as the first alternative to natural gas and oil as the source for future hydrogen production.

Hydrogen produced from nuclear and solar energy sources is not expected to be competitive until after the turn of the century. Nuclear energy has been confronted by difficulties for years and cannot keep up with its demand for electrical power. Until these difficulties are overcome, producing hydrogen in a dedicated nuclear plant which could be producing prime-rate electricity may not be practicable. Solar energy, though abundant, is geographically diffuse, intermittently available, and relatively expensive to collect. These factors tend to place it at a distinct capital-cost disadvantage with respect to the other alternatives.

E. Production and Distribution Implications

At present, less than 7% of the hydrogen produced is delivered to users as "merchant" hydrogen. The balance is produced and used within a process system as "captive" hydrogen. Several of the newer hydrogen production methods using coal feedstocks require large facilities to achieve economies of scale. The facilities will necessarily produce large quantities of hydrogen, not all of which would be consumed by a single process. In fact, the more efficient processes could produce mixed products such as methane, hydrogen, liquid fuels, and chemicals. For these facilities to be effective, multiple customers for their output will be necessary and some of those customers will be industries which now use only captive hydrogen. Thus, a shift in the ratio of captive to merchant hydrogen users can be expected to take place. Based on our analyses, by the year 2000 merchant hydrogen could supply as much as 75% of the total hydrogen demand.

F. Technology Requirements

1. Increased efficiency for production from coal. Production of hydrogen is required to support the manufacture of synthetic fuels from coal. Present commercial methods suitable to hydrogen production operate at low pressures and are relatively inefficient. To increase efficiency, processes utilizing high pressures need to be developed and demonstrated. There is a great deal of experimentation going on within the Government and industry on high-pressure gasification of coal to produce both low-Btu and high-Btu fuel gases. Development of processes which make pure hydrogen from coal can take advantage of this related R&D work. Development of gasifiers specifically tailored to hydrogen production, new processes in air separation for oxygen production, and high-temperature desulfurization processes could add significantly to the efficiency of hydrogen production.

2. Energy storage and production from non-fossil energy sources. Electrolysis is the leading process for early production of hydrogen from nuclear, solar, geothermal, or wind energy sources, and could provide hydrogen either for direct sale or as an electric-utility storage medium. Current electrolysis techniques operate at low pressures and are relatively low in efficiency. Operation at high pressure, increasing electrolysis efficiency, and other means which reduce total capital costs, need to be developed. The electrolyzer industry is not currently supporting research programs large enough to bring about significant improvements. Basic research in electrochemical and fluid fundamentals, especially electrode kinetics and gas evolution, should be expanded. Applied research and development should be conducted on catalysts, electrode materials, new separators and electrolytes. Reasonable research objectives and system-design parameters should be established early to provide a firmer basis for program decisions and guidance for future research. To support the hydrogen energy-storage application, technological advancements are also needed in fuel cells, high-temperature turbines, and hydrogen storage systems.

Water splitting based on thermochemical or combined thermochemical/electrochemical processes show promise where a high temperature heat source is utilized. Certain fundamental data in the area of chemical, thermodynamic, transport properties, and materials compatibility need to be generated and made available. Additional efforts should be directed toward finding more efficient cycles that operate with relatively non-corrosive reactants. Standardized procedures to evaluate thermochemical process efficiencies and system design criteria need to be established. More in-depth efforts are required to better evaluate technical risks and to better assess potential costs. In addition to the thermochemical cycles, the development of high-temperature heat sources from nuclear or solar energy and the advancement of high-temperature heat-exchanger technology are needed to enhance the competitive position of these cycles with respect to water electrolysis.

Other techniques of water-splitting, such as photochemical or biological processes, are essentially infant technologies but show promise for the long term. The appropriate research strategy would be one of long-range basic research. This research would also add to the current knowledge of photosynthesis and biological processes involved in the production of food.

3. **Improved energy utilization.** Long-term phased research directed toward the application of hydrogen as a portable fuel for transportation is needed. Based on the results of existing studies, early work would stress aviation applications including handling, storage, and distribution as well as aircraft use. Hydrogen fuel utilization in other sectors of transportation, except for special applications with unique advantages, could be given less emphasis. Hydrogen for ground transportation systems will not be competitive with coal-derived liquid fuels, which will be more easily stored in the vehicles and adaptable to existing supply systems. Research into several other areas of hydrogen applications is considered less important at this time than the above areas. Hydrogen for industrial process heat and pure hydrogen for residential and commercial use will not be cost competitive for a number of years. Development of these applications should be relatively uncomplicated whenever hydrogen becomes cost competitive.

4. **Systems studies and assessments.** Systems studies should be carried out to evaluate the potential technical difficulties in substituting new merchant sources of hydrogen for traditional captive hydrogen supplies. Questions related to compatibility, byproducts production and energy demands, should be investigated.

A series of technology assessments should be executed to evaluate the impact of hydrogen source and supply changes on the environmental, social and economics spheres of our society. Then, if detrimental effects are encountered, appropriate corrective actions can be taken.

G. Hydrogen Technology Benefits and Program Planning

Serious disruptions in the fertilizer and fossil fuel industries, manufacturing, and commerce, will occur unless strong priorities are given to these uses of natural gas and oil or unless new technologies are developed so that transitions away from these feedstocks can be made. Cost-comparison analyses performed for this study, based on the projected demands, indicate that the development of improved hydrogen production processes, using alternate energy sources, can result in accumulated savings of as much as forty billion dollars by the year 2000 for the reference projection and substantially more for the expanded projection. Even for the lower quantities in the reference projection, research leading to hydrogen production from advanced coal technology could result in savings of 5 to 10 billion dollars, as well as conserving substantial quantities of coal, gas and oil. The magnitude of savings will be a function of the actual energy requirements and energy costs through the year 2000, but the technology advancements are required for any of these options. The development of the alternative production methods and use technologies will require concentrated research and technology development at a higher level of cost and risk than individual corporations could assume. The benefits to the nation from developing these alternatives would be substantial, however, in conserved energy resources, in cost savings, and in an assured supply of hydrogen independent of natural gas and petroleum.

Therefore, in order to provide the needed stimulus in new hydrogen production and use technologies, the federal government should plan and institute a program of research and development to generate and disseminate data required to evaluate alternative processes and design options. Further benefits would accrue through a coordinated national research and technology program involving both government and the affected industries cooperatively striving toward recognized goals through complementary and non-duplicative activities. Short-term goals of the program should emphasize production of hydrogen from the most abundant fossil fuels. Long-term goals should emphasize new energy-efficient uses of hydrogen and non-fossil water-splitting production methods.

The federal government should take the lead in formulating a plan for coordinating these activities as well as for its own hydrogen technology R&D program. Factors which should be considered in the plan development include:

- Determination of cost- and risk-reduction benefits to the nation to be derived from Federal government support of specific items of hydrogen technology.
- Evaluation of alternative program options to arrive at the most cost-effective approach.
- Determination of the degree of Federal government and industry participation required.
- Interaction with related Federal programs in energy storage, transportation, and synthetic fuel development from fossil fuels.

PART ONE
ANALYSIS AND CONCLUSIONS

Chapter I

INTRODUCTION

A. BACKGROUND

At present hydrogen is used almost entirely as a unique industrial chemical in petroleum processing and the synthesis of ammonia and methanol. Hydrogen has no substitute in these applications. New uses are expected to appear, such as in the gasification and liquefaction of coal and as a direct special-purpose fuel. The magnitude of these applications will depend on what the country's energy future is.

Hydrogen is not, however, a primary energy source – it must be manufactured. Practically all the hydrogen now produced in this country is manufactured from natural gas and naphtha. With the availability of these resources seriously declining, it will be essential that hydrogen be produced from other energy sources if the projected demands are to be met.

Stimulated by long range national energy concerns, and in direct response to the international petroleum crisis of 1973, a number of government and private agencies have studied current and future national energy demands. Virtually every study has concluded that changes must occur in the national energy supply and demand structure, but none has addressed the use of hydrogen as a distinct factor. However, a number of hydrogen-focused studies, which included analyses of elements of the greater energy problem, have identified the need to expand hydrogen applications and production as a means of accommodating the growing feedstock shortages. Some of the studies have advocated the adoption of hydrogen as a future universal energy carrier, eventually replacing natural gas, liquid fuels, and at least part of the energy role of electricity. Each of these studies (listed in Appendix B) has contributed to an understanding of the energy problems and the advancement of the body of knowledge regarding hydrogen technology applications and potentials.

Early in 1974, a review by NASA of its contributions to the President's Five-Year Energy R & D Program and the Project Independence Study suggested that further evaluation of hydrogen needs and technology was required. NASA's future hydrogen needs for space vehicle fuel, though not large on the national scale, are significant. In planning for the future supply of hydrogen for NASA use, it was found that the liquid-hydrogen industrial capability built to supply Apollo Project needs in the 1960's has either been curtailed or found other markets in industry, and, as a result, the future needs of the Space Shuttle may not be met by the existing industrial capability. The foreseeable decline in natural gas supply and its probable increase in cost indicated the desirability of developing alternative hydrogen-supply options.

As part of a continuing effort to assure that the significant Federal investment in NASA's aeronautics and space technologies is effectively and efficiently applied to energy-related problems, a Hydrogen Energy Systems Technology (HEST) Study was initiated to consider the total national needs for hydrogen technology. NASA's prior and present work in the use of hydrogen for space and aeronautical applications, its experience in hydrogen combustion, safe handling and storage of cryogenic hydrogen, its research in materials compatibility and chemistry, and assessments of hydrogen applications offered a basis for performing and responding to such a study. Accordingly, the NASA Office of Energy Programs solicited the interest and support of the NASA centers. The Jet Propulsion Laboratory (JPL) was requested to organize a team to conduct the study. To support and advise the study team, a NASA working panel was convened, bringing together the broad hydrogen experience within the agency. A review group, composed of representatives from several federal agencies, energy-industry supported institutions and universities, was formed to review and critique the study results, assuring that they were complete and carried adequate national perspective. The participants are named in Appendix A. The Hydrogen Energy Systems Technology Study conducted its initial working panel meeting in September 1974.

B. OBJECTIVES

The purpose of this study is to appraise the research and technology needs for hydrogen production and use and to identify and properly relate NASA experience to meeting these needs. Preliminary plans which define and evaluate approaches to meeting these technology needs will be formulated while assessing the applicability of NASA technology. The specific objectives of the first phase of this study were:

1. To determine the future demand for hydrogen based on current trends and anticipated new uses.
2. To identify the critical research and technology advancements required to meet this need considering, to the extent possible, raw material limitations, economics and environmental effects.

This report contains the results of the first phase: how much hydrogen is and will be used, and for what purposes; how it is and will be produced and handled, and what energy resources are required; and what generally needs to be done in research, technology advancement, and planning, to assure a reasonably orderly realization of hydrogen's future. In Phase II, preliminary program plans will be formulated from which an assessment of the applicability of NASA experience and technology will be made.

C. APPROACH

The approach taken to reach the objectives of this study was to carry out an inquiry into rather than an advocacy of hydrogen energy systems and applications, and to build upon rather than duplicate prior and concurrent work. Maximum use was made of existing knowledge and skills, beginning with those found in NASA. The study's findings are its own, responding to its given objectives.

The study was initiated with an extensive literature search and data gathering effort. Concurrent research and planning were identified through discussions and personal contacts with many workers active in the field. The reports and results of recent hydrogen studies were analyzed and their findings and conclusions were evaluated.

Historic and current uses of hydrogen were reviewed. The types of products for which hydrogen is used and the quantities used per unit of product were established. Energy scenarios, and the economic growth rates assumed for each, were used to project the growth of each type of product. The advent of new hydrogen uses was predicted together with anticipated growth rates by assessing viability of current practices, comparing the advantages of the available alternatives and estimating the attractiveness of the hydrogen application.

Extensive contacts with the industries manufacturing and using these products were made to obtain information and validate data. Based on these data, calculations of the requirements for hydrogen by each product industry were made as functions of time. The sums of these requirements formed the hydrogen use projections.

Current, emerging, and proposed production methods for hydrogen were investigated. These investigations included surveys of the literature and discussions with hydrogen manufacturers, researchers, and other experts in the field. Analyses of the accumulated data were performed. The state of technology development for each method was investigated, and comparisons were made of relative costs and energy requirements for the production methods. Investigations of the technology status of hydrogen storage, transportation/transmission, distribution, and use systems were included to provide a basis for assessments of the total system, from production to end use. Hydrogen supply options were projected from these assessments.

By comparing the hydrogen demand and supply projections with the state of technology, the research and technology deficiencies were identified. Time frames when new research and technology are required were developed. Conclusions regarding energy and feedstock related research and technology constitute a rational basis upon which specific detailed program plans can be constructed.

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Chapter II

FUTURE HYDROGEN USE

The use of hydrogen has historically been related to energy consumption because hydrogen is primarily used as a feedstock in petroleum processing and in the manufacture of ammonia, methanol, and other chemicals. These products are, in turn, intimately associated with energy usage. This trend in hydrogen use is expected to continue. Thus, national energy scenarios have been selected as a basis for projecting how much hydrogen will be required for established uses and how these quantities might be affected by new energy system uses for hydrogen.

A. ENERGY SCENARIOS/PROJECTION BASE

Numerous energy scenarios have recently been developed. Within each scenario, there are many alternatives and trade-offs to be considered. The selection of energy scenarios for this study was based on the following considerations:

Timeliness; e.g., formulation of the scenario after the oil embargo.

Availability of detailed information about the scenarios.

Attainment of wide circulation, visibility, and critique.

Scenarios already well analyzed by their authors for different purposes.

Addressing and recommending changes to national energy policy.

Energy demand predicted at the year 2000.

Documented primary energy sources and their mix to meet total energy needs.

A suggested implementation plan that includes utilization of improved technology (for conservation and higher efficiency).

Present economic growth maintained.

Needed industrial skills available.

Scope limited to U.S.

The two different energy scenarios that were selected are well known, recent, represent opposing views of the future and are reasonably well documented:

Ford Technical Fix Baseline (FTFB).

Nuclear Electric Economy (NEE).

Each of these scenarios contain implicit assumptions which are subject to debate. Both the FTFB and the NEE scenarios assume historical growth in energy demand, with extrapolation of the recent semi-wartime economy into peacetime. Historical growth in energy demand is mainly a consequence of inexpensive energy. The degree to which escalating fuel prices will reduce demand is unknown. The development of a complex dynamic energy demand and supply model was not undertaken during the HEST study. We have judged that the FTFB and NEE scenarios allow the projection of hydrogen use for differing energy futures, providing bounds on the projections while showing sensitivity to the energy future.

In addition, the Federal Energy Administration (FEA) energy scenario, developed as part of the Project Independence study [Federal Energy Administration, 1974]* was utilized during the study. The FEA scenario ends in 1985, but it was considered primarily because of its use for national policy decision making. It is not further discussed here because it did not alter the hydrogen projection bounds.

1. Ford Technical Fix Baseline

The FTFB scenario was developed as one of several scenarios by the Ford Energy Policy Project [Energy Policy Project, 1974]. It assumes end use of energy corresponding to historical growth of energy and is the average of two other Ford projections: Self Sufficiency and Environmental Protection. It relies heavily on oil and gas as primary energy sources and shows slow use of coal until after 1985 and, in general, limited use of nuclear energy.

FTFB projects lower future growth than historical growth in consumption of energy resources because of technological and social changes which improve the efficiency of end use. These advances include:

Improvements in construction and space conditioning systems for buildings.

Use of solar energy for buildings.

Use of industrial process heat to generate electricity on site and use of waste heat.

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*All references in this Report are noted in brackets [ ] with the full citation given in the Bibliography.

Recycling of materials.

Lowering of automobile weight and improvement of gasoline mileage.

Use of more diesel and electric propulsion.

Support for urban mass transit.

2. Nuclear Electric Economy

The NEE scenario also incorporates energy end use corresponding to historical growth, with heavy reliance on nuclear and coal as primary energy sources [Ross, 1973]. NEE is proposed by a major manufacturer of nuclear reactors which is also an established supplier of the electric utility industry (Westinghouse Electric Corporation).

NEE includes energy saving via more efficient end-use devices but is close to extrapolated historical growth. It also assumes major transformation to:

(1) Electric cars, rail and some trucks.

(2) Heat pumps for residential and commercial space conditioning.

(3) Waste heat to generate electricity.

(4) Other electrification.

3. Comparison of Projections

The total projections based on these scenarios are shown in Fig. II-1, and Table II-1 shows the magnitude and percentage of energy sources for 1973, 1985, and 2000 for the two selected energy projections.

The NEE scenario increases the use of coal significantly by 1985: 36×10^{18} J (34×10^{15} Btu) compared to 14.0×10^{18} J (13×10^{15} Btu) in 1973; and then shows both strong coal and nuclear use in the year 2000. Both oil and gas are considered to be maintained at current levels of use up to 1985, followed by a drop below current production levels by the year 2000.

The FTFB scenario essentially reverses this emphasis. Oil and gas production are considered to increase through 1985 and even to the year 2000. Coal use grows more slowly to 1985 than in the NEE projection, and is assumed to be double today's use by the year 2000. The FTFB projection assumes nuclear power to be only 7.4×10^{18} J (7×10^{15} Btu) by the year 2000. This is just a fraction of 99×10^{18} J (94×10^{15} Btu) predicted by the NEE projection. In fact, the FTFB does not consider the breeder reactor to be used by the year 2000.

B. HYDROGEN USE PROJECTIONS

A process similar to the development of the energy projections as described above has been employed in the derivation of hydrogen projections. First, two hydrogen scenarios were developed based on energy-use features defined by the FTFB and NEE energy scenarios and their quantitative projections. These are called the Reference and Expanded use scenarios for hydrogen. They are considered to define the range of reasonably probable hydrogen futures. Using the assumptions embodied in these scenarios together with appropriate quantities from current hydrogen usage and from the two energy projections (Table II-1), derived quantitative hydrogen use projections at the two levels (Reference and Expanded) were calculated. The premises and rationale for the scenarios, and their various features and implications, are discussed in Chapter VI.

1. Reference Use Scenario and Projection

The Reference Hydrogen Use scenario is associated with the FTFB energy future. The assumptions for the Reference scenario follow:

Lower unit consumption rates for product quantities implied in FTFB.

Continuation of established uses at unaccelerated historical growth rates.

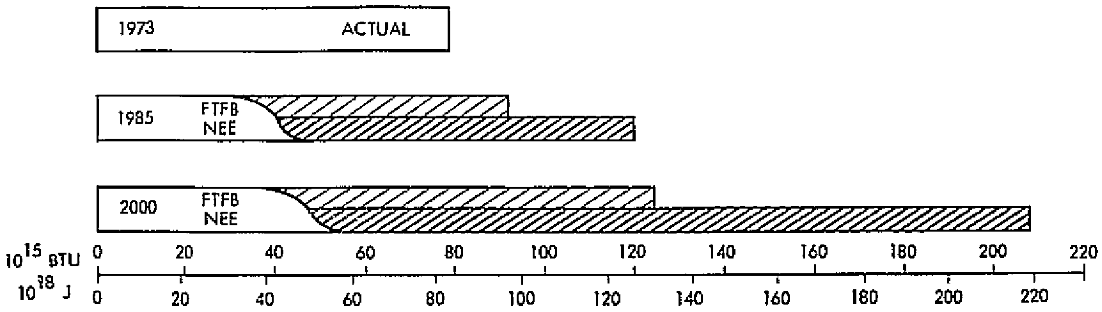

Fig. II-1. Projections of total U.S. energy use

Table II-1. Energy projections, 10^{18} J (10^{15} Btu)

Energy Sources and Uses	1973[a]	FTFB[b] 1985	FTFB[b] 2000	NEE[c] 1985	NEE[c] 2000
Coal	14.0 (13.3)	16 (15)	29.0 (28.5)	37 (35)	70 (66)
Direct	14.0 (13.3)	16 (15)	23 (22)	35 (33)	41 (39)
Syn. Liq. Fuel	–	0 (0)	3 (3)	0 (0)	14 (13)
SNG	–	0 (0)	1 (1)	2 (2)	15 (14)
Conversion losses from coal to synthetics			1.6 (1.5)		
Oil	36.7 (34.8)	41 (39)	49 (46)	31 (29)	23 (22)
Domestic	23.3 (22.1)	31.1 (29.5)	37.5 (35.5)	24 (23)	21 (20)
Imported	13.4 (12.7)	10 (9)	9 (9)	6 (6)	2 (2)
Oil Shale and Tar Sands	–	0.5 (0.5)	2 (2)	–	–
Gas	23.9 (22.7)	30 (28)	36 (34)	27 (26)	10 (9)
Domestic	22.9 (21.7)	28 (26.5)	34 (32)	24 (23)	10 (9)
Imported	1 (1)	1.6 (1.5)	2 (2)	3 (3)	0 (0)
Nuclear and Other	4.1 (3.9)	11.1 (10.5)	17 (16)	32 (30)	116 (110)
Nuclear	0.9 (0.9)	6.8 (6.5)	7 (7)	26 (25)	99 (94)
Hydro	3.2 (3.0)	3 (3)	4 (4)	5 (5)	6 (6)
Solar, wind, etc.	–	1 (1)	5 (5)	–	11 (10)
Total Sources	79 (75)	97 (92)	131 (124)	127 (120)	219 (207)
Coal	18%	16%	22%	29%	32%
Gas + Oil	77%	73%	65%	46%	15%
Nuclear	1%	7%	6%	21%	45%
Hydro + Other	4%	4%	7%	4%	8%
Electricity[d]	26%	26%	25%	50%	73%
Transportation	20 (19)	20.7 (19.6)	26 (25)	29 (27)	25 (24)
Commercial and Residential	19 (18)	24 (23)	26 (25)	22 (21)	31 (29)
Industrial	25 (24)	36 (34)	58 (55)	31 (29)	44 (42)
Energy Processing[e]	15 (14)	16 (15)	20 (19)	45 (43)	118 (112)

[a] Actual data from U.S. Department of the Interior, 1975.

[b] Basis for projecting lower-bound reference hydrogen use projection.

[c] Basis for projecting upper-bound expanded hydrogen use projection.

[d] Percent of total energy required for electric power generation.

[e] Primarily made up of waste heat in electricity generation.

Limited usage of hydrogen in direct reduction of iron ores (e.g., H-iron).

Hydrogen requirements for synthetic fuel production levels as specified in FTFB.

New hydrogen energy applications deferred until after the year 2000 because:

The FTFB projection assumes use of conventional fossil fuels and nuclear energy up to the year 2000.

Implementation barriers and economics favor direct substitution of fuels such as Substitute Natural Gas and Syncrude rather than the introduction of hydrogen.

The resulting quantitative projections based on the Reference Hydrogen Use Scenario assumptions are displayed in Table II-2, referenced to 1973 data and extending to the year 2000. This projection is considered to represent a lower bound for hydrogen demand through the remainder of this century.

2. Expanded Hydrogen Use Scenario and Projection

The Expanded Hydrogen Use Scenario is based on the NEE energy scenario plus certain assumptions regarding new hydrogen energy applications. The Expanded Hydrogen Use Scenario is intended to represent a reasonable maximum case of hydrogen usage. Its basis is:

Expanded traditional usage levels based on:

The higher unit consumption rates for product quantities implied in NEE.

Continuation of established uses at recent historical growth rates.

Maximum estimated possible usage in direct reduction of iron ores.

Table II-2. "Reference" Hydrogen Projection by end uses

End Use, 10^{18}J (10^{15} Btu)	1973		1985		2000		Comments*
Unique Chemicals							
Ammonia	0.379	(0.359)	0.767	(0.726)	1.828	(1.731)	6% growth
Petroleum Refining	0.492	(0.466)	0.697	(0.660)	0.825	(0.781)	FTFB projections
Methanol and Others	0.103	(0.098)	0.232	(0.220)	0.642	(0.608)	7% growth
Hydrogenation of Oils, etc.	0.005	(0.005)	0.012	(0.011)	0.033	(0.031)	7% growth
Subtotal	0.98	(0.93)	1.71	(1.62)	3.33	(3.15)	
Synthetic Fuels							
Tar Sands			NIL		NIL		
Oil Shale			0.026	(0.025)	0.106	(0.100)	FTFB projections
Coal Gasification			NIL		0.535	(0.507)	FTFB projections
Coal Liquefaction			NIL		1.160	(1.100)	FTFB projections
Subtotal	NIL		0.026	(0.025)	1.81	(1.71)	
Direct Reduction	NIL		0.457	(0.061)	0.23	(0.22)	HEST estimates
Miscellaneous, including welding, cooling, process heat, and others	0.069	(0.065)	0.16	(0.15)	0.40	(0.40)	7% growth
Space Shuttle	NIL		0.0014	(0.0013)	0.0014	(0.0013)	NASA projections
TOTAL	1.0	(1.0)	2.0	(1.9)	5.8	(5.5)	Average growth rate 6-8%

*See Table VI-16 for detailed source data

Hydrogen requirements for synthetic fuel production levels specified in NEE.

Limited hydrogen energy applications by the year 2000 for:

- Electric Utility energy storage for peak shaving.
- Transportation vehicles, based on such factors as performance advantages for aircraft, air-pollution reduction, and military logistical fuel-supply considerations.
- Blending of hydrogen with natural gas to meet natural gas shortfalls.

The Expanded hydrogen use projection is considered to represent an upper bound for hydrogen demand during the remainder of this century. It extends recent historical growth rates for each application into the future. This is in contrast to the Reference scenario and projection which was based on the assumption that the unique chemical uses of hydrogen were representative elements of the entire chemical industry and growth rates were derived for these uses from the chemical industry growth rate.

Table II-3 presents the calculated values of the Expanded Use projection in the same format as Table II-2 does for the Reference projection. Certain new use categories are shown in Table II-3, for which there are no corresponding entries in the previous table.

3. Comparison of Projections

The Reference hydrogen use projection yields an annual usage total of 5.8 X 10^{18} J (5.5 X 10^{15} Btu) for the year 2000; the Expanded hydrogen projection develops a corresponding total of 24 X 10^{18} J (22 X 10^{15} Btu). These figures, broken down by use sectors (petroleum refining, unique chemical, synthetic fuel, and direct reduction combined with miscellaneous uses) are shown in Fig. II-2. The twofold difference between the 1985 totals is mainly due to an increased synthetic fuel production assumed for the Expanded Hydrogen Use scenario, with contributions from petroleum-refining and the chemical industry, which are assumed to have higher demand than assumed for the Reference projection.

There is a fourfold difference in the totals from the two projections by the year 2000. In Fig. II-2, the petroleum-refining use sector shows little difference in the two projections by the year 2000, but the new transportation and utility applications have increased the "miscellaneous" category dramatically in the Expanded projection. Also, the use of hydrogen in synfuels and by the chemical industry, partly in new end applications, is assumed to grow more rapidly in the Expanded projection than in the Reference projection.

These projections are used as a basis for determining hydrogen supply options and technology requirements as described in the next two chapters.

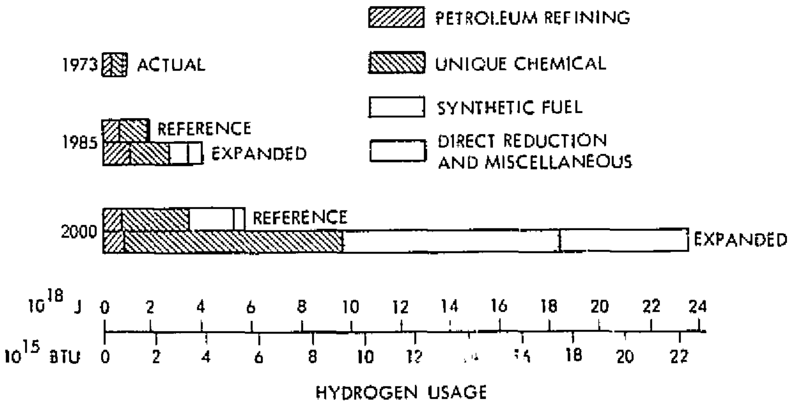

Fig. II-2. Reference and Expanded hydrogen use projections

Table II-3. Expanded hydrogen projection by end uses

End Use, 10^{18}J (10^{15} Btu)	1973	1985	2000	Comments*
Unique Chemicals				
Ammonia	0.379 (0.359)	1.102 (1.044)	4.181 (3.960)	9.3% growth
Petroleum Refining	0.492 (0.466)	1.116 (1.057)	0.815 (0.772)	NEE Model Projections
Methanol and Others	0.103 (0.098)	0.608 (0.576)	5.559 (5.265)	15.9% growth
Hydrogenation of Oils, etc.	0.005 (0.005)	0.011 (0.010)	0.029 (0.027)	6.4% growth
Subtotal	0.98 (0.93)	3.0 (2.8)	10.6 (10.0)	
Synthetic Fuels				
Tar Sands		NIL	NIL	
Oil Shale		NIL	NIL	
Coal Gasification		0.511 (0.484)	3.577 (3.388)	NEE Model Projections
Coal Liquefaction		0.117 (0.016)	4.296 (4.069)	NEE Model Projections
Subtotal	NIL	0.53 (0.50)	7.9 (7.6)	
Direct Reduction	NIL	0.22 (0.21)	0.69 (0.65)	Futures Group Projections
Transportation				
Space Shuttle		0.0014 (0.0013)	0.0014 (0.0013)	NASA Projections
Air			0.993 (0.940)	HEST Estimates
Ground			1.016 (0.962)	
Water			0.634 (0.600)	
Subtotal	NIL	0.0014 (0.0013)	2.6 (2.5)	
Utilities				
Electric		0.1 (0.1)	0.897 (0.850)	Captive Use in Peaking Blending Up to 8% by Volume
Gas		NIL	0.248 (0.235)	
Subtotal	NIL	0.1 (0.1)	1.1 (1.0)	
Miscellaneous, including welding, cooling, process heat, and others	0.069 (0.065)	0.19 (0.18)	0.655 (0.620)	8.7% growth
Subtotal	0.069 (0.065)	0.19 (0.18)	0.66 (0.62)	
TOTAL	1.0 (1.0)	4.0 (3.8)	24 (22)	

*See Table VI-17 for detailed source data.

Chapter III

N76-18656

SUPPLY OPTIONS

At the present time, most of the hydrogen manufactured is produced and consumed on site and is called captive hydrogen. Feedstock prices establish the hydrogen costs and it is unlikely that industries which rely on their own assured supply of hydrogen will switch to externally supplied merchant hydrogen in the near term. On the other hand, with time, the prices of traditional captive-hydrogen feedstocks will rise, hence creating a market for merchant hydrogen produced from feedstocks and techniques less affected by rising costs. In an integrated hydrogen-energy system, it is envisaged that hydrogen would be produced, transmitted and distributed in a manner similar to present-day utility operations. For such systems, merchant-hydrogen quantities may be bounded by two quantity extremes, namely, a low merchant-to-captive ratio and a high merchant-to-captive ratio.

Basically, the low-merchant case constitutes a continuation of present practices where the bulk of hydrogen is produced at industrial sites as a captive in the process system. The low-merchant case is amenable to either the Reference or the Expanded Hydrogen Use projections through the year 1985. After the year 2000, the Reference projection can still be accommodated by the low-merchant case. The NEE energy projection, with its prime dependence on coal and nuclear energy sources and the large quantities of hydrogen required in the Expanded Hydrogen Use projection, presents major difficulties in continuing present practices.

The high-merchant case departs significantly from present hydrogen supply practices. It is compatible with both the Reference and the Expanded projections during all of the time periods under consideration. The high-merchant case suggests that for the purposes of benefitting from the economies-of-scale, very large quantities of hydrogen would be produced at centralized locations and delivered to hydrogen consumers and processors. To accomplish this, bulk-storage systems and distribution systems from the large coal-based hydrogen facility to dispersed hydrogen-using plants or hydrogen-related industrial clusters will be required. If a large growth in nuclear power usage occurs (per the NEE projection), electrolytic merchant hydrogen generated by nuclear power stations during off-peak periods is a possibility, particularly in regions located far from coal-rich areas.

As coal, the most abundant fossil fuel, becomes depleted, a shift toward non-fossil energies such as nuclear, solar, winds, tides, and geothermal energy, is inevitable. Since fossil sources will be unavailable or too costly, techniques such as electrolysis and advanced methods such as thermochemical, photolytic, and thermal splitting of water must be implemented. Nuclear sources coupled with electrolysis or advanced thermochemical cycles appear to be more practical to implement as large dedicated hydrogen-producing facilities than relatively small dispersed nuclear powered facilities at a multiplicity of industrial sites. Consideration of public acceptance and safety would also tend to favor a lesser number of large dedicated nuclear-powered facilities. Many advanced energy sources including winds, tides, and geothermal are all site-specific. Thus, when such sources are used for hydrogen production, it is likely that hydrogen will be produced at the site of the energy source, thus minimizing electrical transmission losses.

These considerations strongly indicate that, in the far-term, the post-fossil fuel era, a shift to merchant hydrogen will occur. In this context, it is likely that a gradual shift will occur from the low-merchant to the high-merchant case. This shifting is contingent upon the availability or development of necessary technology and suggests timeframes in which the technology would be needed.

The general trends summarized above are quantified in Chapter VII by developing supply options matched to the use projections developed in the previous Chapter. The supply options will be examined here in terms of end-use categories to provide insight into use/supply interrelationships.

Table III-1 shows the estimated maximum merchant-hydrogen fraction for several processes. The maximum merchant-hydrogen fraction is defined as the maximum externally supplied hydrogen which could be used for the particular application divided by the total hydrogen demand for that application. Using these fractions and quantities estimated in Chapter II, the expected merchant hydrogen quantities are tabulated in Table III-2 for the Reference and Expanded Use Projections.

As indicated by the high-merchant case, shown in Fig. III-1, there is potentially a very large merchant-hydrogen market and major shifts in this direction could occur, especially when fluid fossil sources are severely depleted (by the year 2000 according to most energy projections). The quantities of hydrogen projected are indicative of a multi-billion dollar industry which can potentially impact nearly all sectors of society.

A. SUPPLYING THE LOW-MERCHANT CASE

In the low-merchant supply projection, most of the hydrogen is produced and consumed on site, primarily for chemical applications. At the present time, hydrogen uses are supplied mainly by steam reforming of natural gas. This source of hydrogen will continue to play a major role in the near future. As natural gas becomes less available, additional substitution of naphtha and heavy oils will take place. As these fuels become costly and less available, the producers of hydrogen

Table III-1. Maximum potential merchant hydrogen fractions

Application[a]	Maximum Merchant Hydrogen Fraction
Ammonia	1.0
Methanol	0.61
Refinery Operations	0.73[b]
Fats and Oils	1.0
Coal – SNG	0.64
Coal – SNC	0.77
Shale – Oil	1.0[c]
Electric Utilities	0.0
Gas Utilities	1.0
Direct Reduction	1.0
Miscellaneous	1.0
Transportation	1.0

[a] These processes are discussed in Table VII-4 and its footnotes.

[b] For plants with extensive hydrocracking

[c] Significant fuel gas production possible

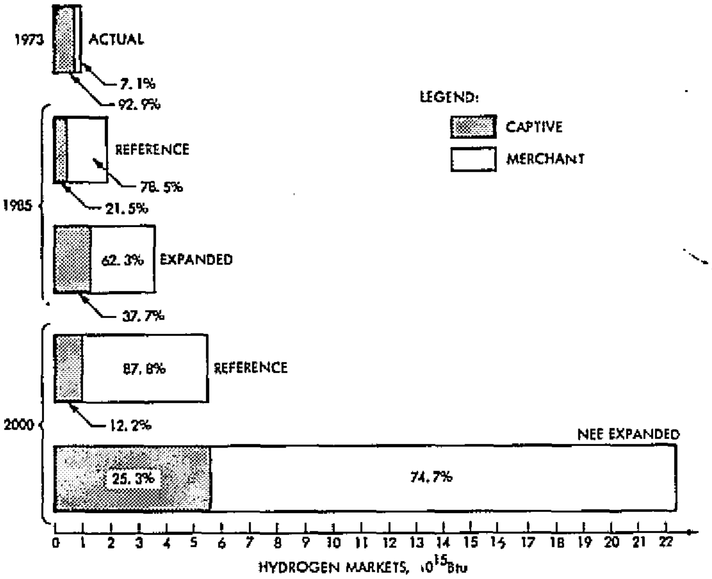

Fig. III-1. Potential high-merchant hydrogen markets

for unique chemical uses will be forced to switch gradually to other sources. Table III-3 lists the significant hydrogen production techniques. The first five are currently used and are considered to be major approaches for supplying the low merchant option. All five will play minor roles after the year 2000 as gas and oil resources are depleted. The switch to coal will start before 1985 and become a major source of hydrogen after 1985.

Estimates of the primary energy sources required for a low-merchant supply are made in Chapter VII and are listed in Table VII-6. The Reference Projection requires 4.4% of the

Table III-2. Merchant hydrogen projections,* 10^{18} J (10^{15} Btu) of hydrogen

Use Category	Year 1985				Year 2000			
	Reference		Expanded		Reference		Expanded	
	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
Total Merchant	0.09 (0.09)	1.5 (1.4)	0.13 (0.12)	2.5 (2.4)	0.39 (0.37)	5.1 (4.8)	3.5 (3.3)	18 (17)
Total Demand	2 (1.9)	2 (1.9)	4 (3.8)	4 (3.8)	5.8 (5.5)	5.8 (5.5)	24 (22)	24 (22)
Percentage of Total	5	79	3	63	7	88	15	75

*Sources and calculations are detailed in Chapter VII.

Table III-3. Projected hydrogen supply technology sequence

Process	Contribution in This Time Frame		
	1975 - 1985	1985 - 2000	Later
1. Steam Water Gas from Coal/Coke	Large	Large	Small
2. Steam Reforming of Methane	Large	Large	Small
3. Steam Reforming of Naphtha	Large	Large	Small
4. Partial Oxidation of Heavy Oils	Large	Large	Small
5. Refinery Catalytic Reforming of Naphtha	Large	Large	Small
6. Coal Gasification	Small	Large	Large
7. Electrolysis of Water	Negligible	Small	Large
8. Thermochemical and Other Suggested New Water Splitting Processes	None	None	Large

total energy consumed in 1985 and 9.8% in the year 2000, whereas the Expanded Projection requires 7.7% of the total in 1985 and 33.9% in the year 2000. In order to meet the Expanded Projections, large fractions of the primary energy resources (33% of the coal and 35% of the nuclear energy) are required to be earmarked solely for hydrogen production in the year 2000. It is considered unlikely that this would happen. The Expanded Use scenario, which in fact is a partial Hydrogen Economy, would be extremely difficult to implement because of its heavy demands on primary energy resources. Unless NEE primary-energy-resource estimates are revised upward, it will not be possible to provide the energy sources required to meet the Expanded Use Projection. Therefore, the low-merchant case is discussed in terms of the Reference Projection only.

Estimates of the hydrogen quantities that will be produced by the available feedstocks is shown in Fig. III-2. Approximate overall hydrogen production efficiencies from fossil-fuel sources are shown in Fig. III-3. These are used, together with the data of Fig. III-2, to estimate the primary energy requirements, shown in Table III-4, to produce the hydrogen. The overall efficiencies that should be used depend upon the technology available in a particular time frame. For example, natural gas is presently converted to hydrogen at efficiencies of about 60%, but 80% is possible with advanced processes. If natural gas pipeline losses are considered, the overall efficiency of producing hydrogen from gas is in the range of 54-75%. Before 1985, average overall efficiency values, and, after 1985, higher values, were used in the estimates.

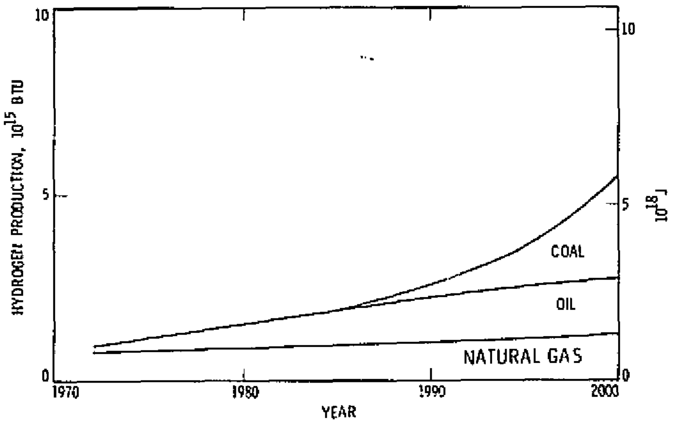

Fig. III-2. Hydrogen production by sources for low-merchant option (Reference projection)

The percentage of the nation's primary energy used to produce hydrogen for chemical feedstock is projected to increase from nearly 3% in 1972 to about 4.5% in 1985, and to about 10% in the year 2000. Because of the shift to coal and oil as raw materials, the overall hydrogen-production efficiency is seen to decline (see Fig. III-3) and consequently the efficiency-related costs go up.

An important feedstock used in all methods of hydrogen production is water. The amount of water consumed in chemical reactions to produce hydrogen from fossil-fuel resources is shown in Fig. III-4. It is to be noted that this study requirement does not include water for cooling and

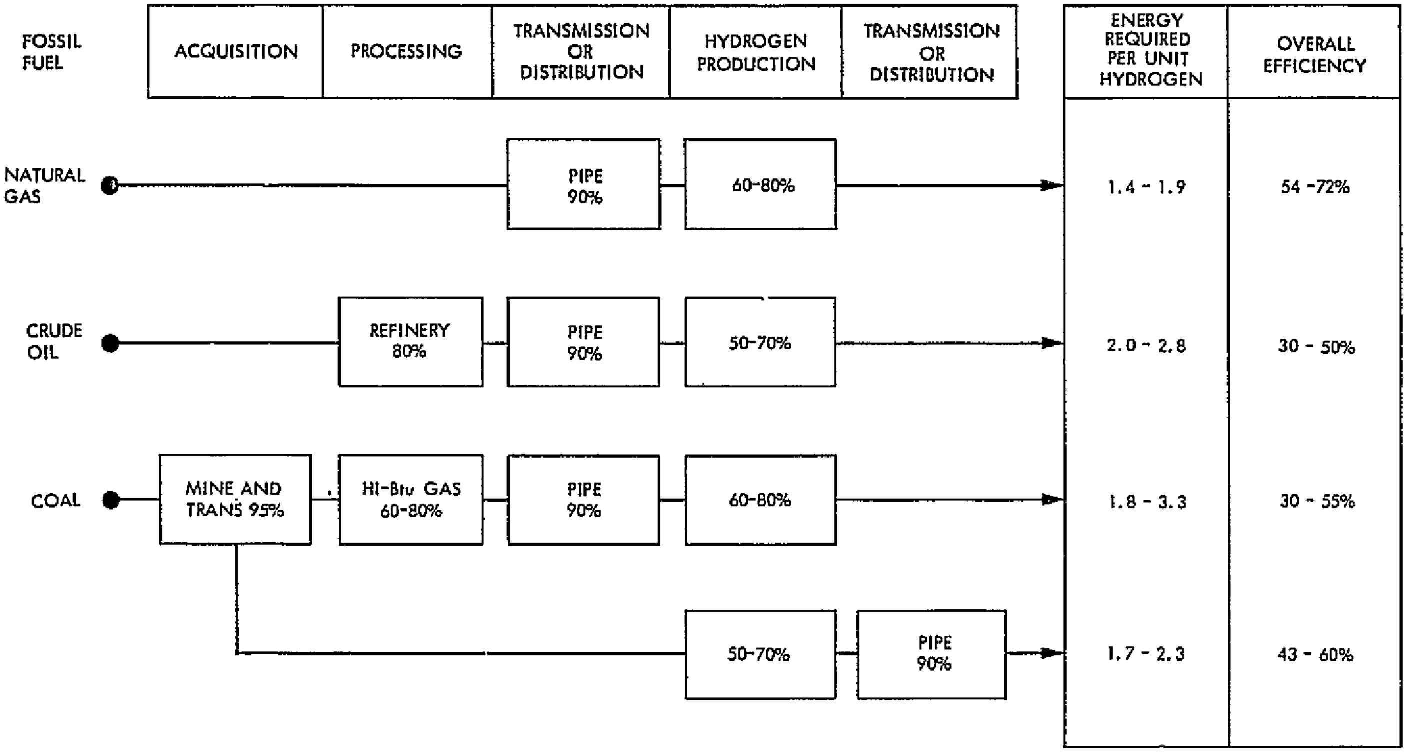

Fig. III-3. Hydrogen production efficiencies from fossil fuels

Table III-4. Primary energies for hydrogen supply — reference projection, low-merchant option 10^{18} J (10^{15} Btu)

Primary Energy Source	1985			2000		
	Resource Needed For Hydrogen Supply	Total Available	%	Resource Needed For Hydrogen Supply	Total Available	%
Natural Gas	1.9 (1.8)	29 (28)	6.4	2.5 (2.4)	36 (34)	6.9
Oil	2.3 (2.2)	41 (39)	5.6	3.8 (3.6)	49 (47)	7.8
Coal	0.04 (0.04)	16 (15)	0.3	6.5 (6.2)	29 (28)	22.0
Nuclear and Others	0.05 (0.05)	18 (17)	0.3	0.26 (0.25)	32 (30)	0.8

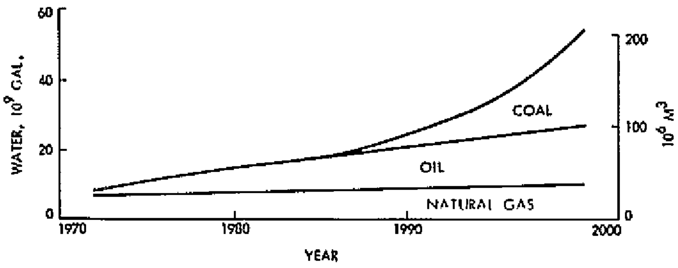

Fig. III-4. Water consumption, low-merchant option (Reference projection)

other needs. At least one study [Davis, 1975] indicates that these quantities of water are available.

B. SUPPLYING THE HIGH-MERCHANT CASE

The high-merchant option is based on development of a utility-type hydrogen production and distribution system. Any such system is required to bridge the fossil-fuel and post-fossil eras. The hydrogen production and supply should be smoothly shifted from gas- and oil-based to coal, and eventually to nuclear, solar, and other non-fossil-energy-based systems. For hydrogen users to accept externally-supplied hydrogen, a well-planned distribution system, and a guaranteed, stable hydrogen supply at established prices are essential.

Estimates of the primary energy sources required for a high-merchant supply are made in Chapter VII and listed in Table VII-8. Through the year 1985, the same primary energy resources are required as the low-merchant case, but by the year 2000, both the Reference and the Expanded Projections require increases in primary energy to support the high-merchant case; 12.2% for the Reference Projection and 37.2% for the Expanded Projection. The reason for this greater proportional requirement for primary energy is that the high-merchant case is more highly dependent on coal and nuclear energy which have lower energy conversion efficiencies. The total primary energy requirements of the Expanded Projection are made more severe by the high-merchant case and consequently it is less probable that the Expanded Projection will occur.

Plants supplying hydrogen from coal are expected to be particularly compatible with the high-merchant case. Very large centralized coal plants supplying a number of customers show potential benefits in economy-of-scale, lower cost product distribution, better controlled feedstock and water supply and centralized environmental control. Large multimodular plants can more easily guarantee continuous delivery, minimizing maintenance delays and unplanned shutdowns.

Both Expanded and Reference Projections use significant amounts of non-fossil (hydro, solar, wind, etc.) energy supplies. In the high-merchant supply option, these sources can be made available for hydrogen production. Figure III-5 shows the primary energy sources for the high-merchant hydrogen production option with the Reference Projection. Consistent with the energy scenario from which the Reference Projection was derived, the non-fossil sources replace portions of the oil and coal.

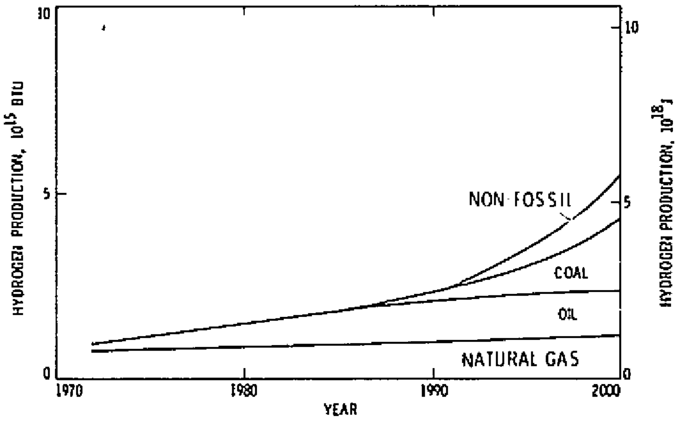

Fig. III-5. Hydrogen production by sources for high-merchant option (Reference projection)

Figure III-6 presents hydrogen production efficiency estimates for nuclear systems and Fig. III-7 presents estimates for other non-fossil energy systems. Using more advanced electrolysis plants (90% efficiency), nuclear production has overall efficiencies between 23% and 29%. Plants based on renewable energy sources vary widely in overall efficiencies, and the meaning of efficiency is different when applied to renewable energy sources. The average value of 22% overall efficiency is used to represent a mix of solar thermal, wind, and geothermal.

Energy requirements for the high-merchant hydrogen production option, based on the Reference use projection, were determined from the production data of Fig. III-5 and the efficiencies of Figs. III-6 and III-7. These energy requirements are shown in Table III-5.

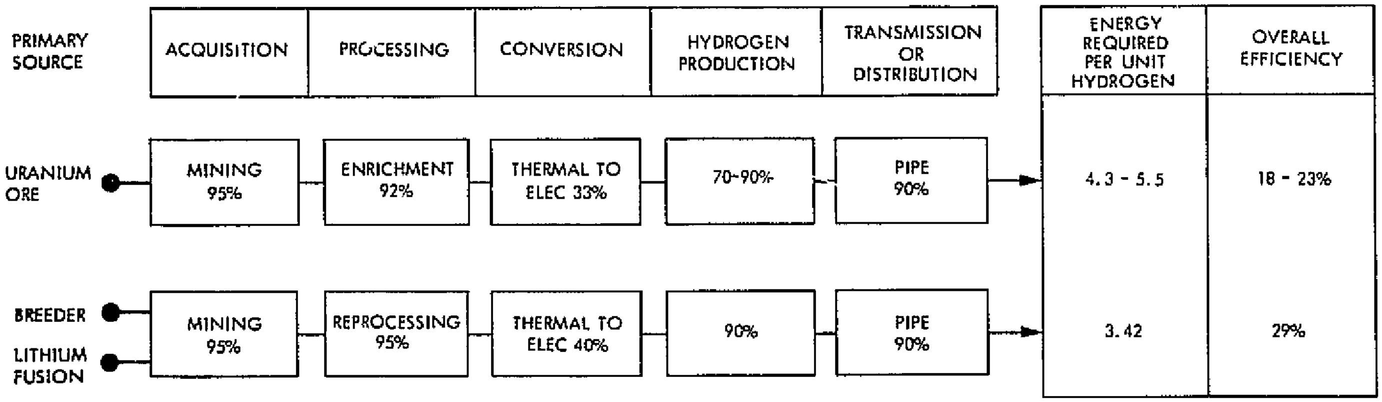

Fig. III-6. Hydrogen production efficiencies from nuclear energy

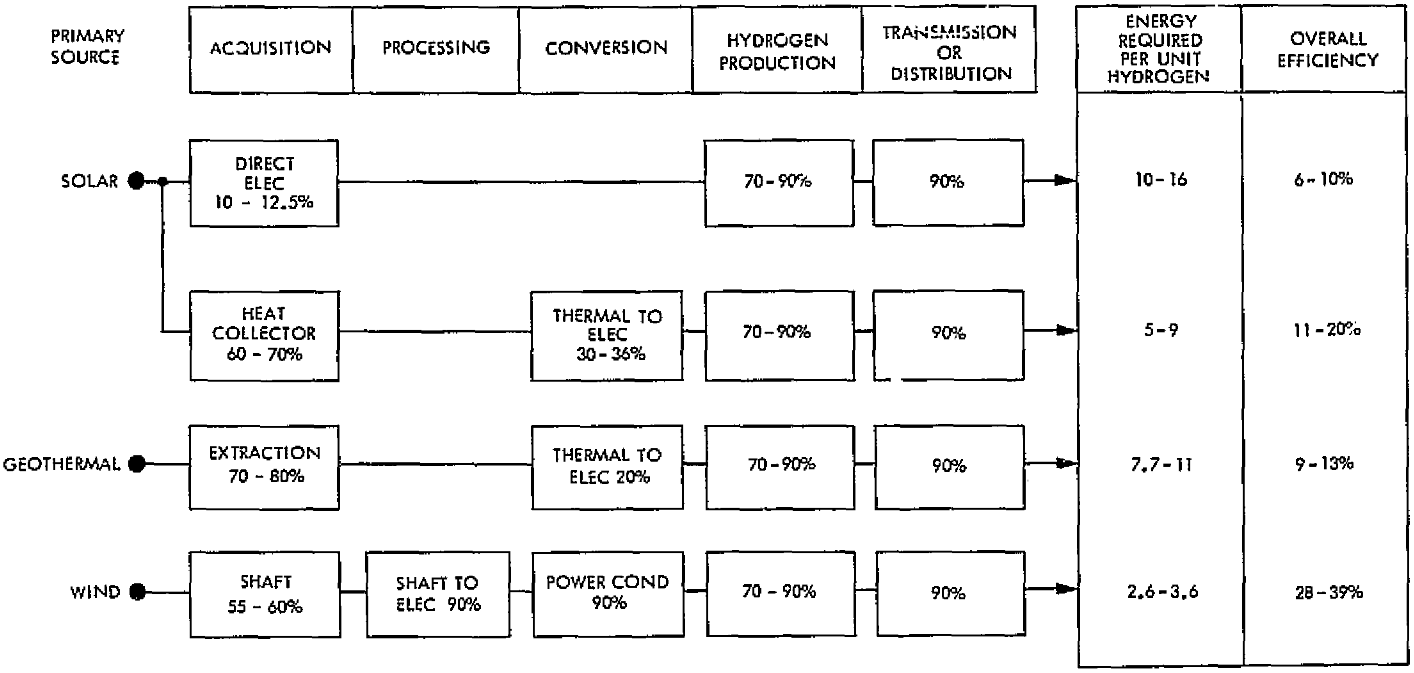

Fig. III-7. Hydrogen production efficiencies from advanced renewable energy

Table III-5. Primary energies for hydrogen supply — reference projection, high-merchant option 10^{18} J (10^{15} Btu)

Primary Energy Source	1985			2000		
	Resource Needed For Hydrogen Supply	Total Available	%	Resource Needed For Hydrogen Supply	Total Available	%
Natural Gas	1.9 (1.8)	29 (28)	6.4	2.5 (2.4)	36 (34)	6.9
Oil	2.3 (2.2)	41 (39)	5.6	3.1 (3.0)	49 (47)	6.3
Coal	0.04 (0.04)	16 (15)	0.3	4.5 (4.2)	29 (28)	15.0
Nuclear and Others	0.05 (0.05)	18 (17)	0.3	5.8 (5.5)	32 (30)	18.3

The amount of water consumed theoretically in this supply option is shown in Fig. III-8, assuming that solar plants produce electrolytic hydrogen. For the Expanded Projection, four to five times these quantities of water would be required, by the year 2000. Supplying this large amount of water could be a major problem.

C. SUPPLY TRANSITION

To provide the amounts of hydrogen calculated in the Use Projections, construction of new production facilities will

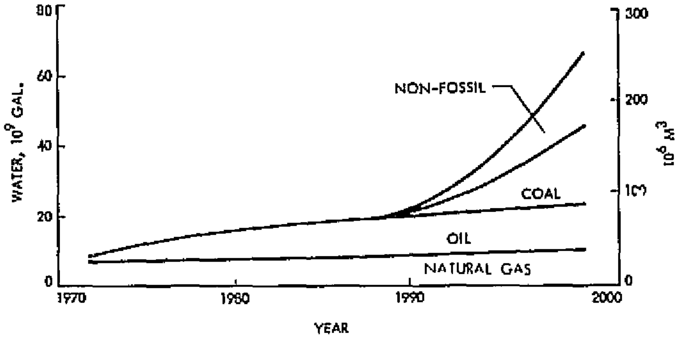

Fig. III-8. Water consumption, high-merchant option (Reference projection) be required. Table III-6, summarizes the approximate number of new plants of 7.1 X $10^6 m^3$/day (250 X 10^6 scf/day) equivalent size each required to meet increasing demands and the cost to build them. The high merchant supply option is predicated on shifts to merchant supply modes and processes. In terms of the time required to implement new processes, there will be essentially no major change evident by 1985. In our estimations, we have assumed that being large, the high-merchant fossil-based plants have higher overall efficiencies, higher load factors, and reflect economies of scale. Nevertheless, the total number of new plants required for the high-merchant supply option is higher because electrolytic plants based on solar, wind, and nuclear have low load factors.

Hydrogen production from partial oxidation processes, coal gasification, and electrolysis are substantially more capital intensive than steam reforming of natural gas. The capital requirements for hydrogen production facilities by the year 2000 are in excess of 18 billion dollars for the low merchant option, and almost 74 billion dollars for the high merchant option. Thus, based on current understandings of the economics of hydrogen production, the cost of the high merchant supply option is generally higher than the low merchant supply option.

In view of the significantly higher capital cost of the high merchant supply, why should we be interested in this option? The primary reason is that gas and oil feedstocks should be conserved so that their use can be extended for the longest practicable time for non-energy uses. For the year 2000, 13.45 X 10^{18} J (12.81 X 10^{15} Btu) of fossil fuel is required to supply the low merchant option, and 10.58 X 10^{18} J (10.08 X 10^{15} Btu) of fossil fuel is required to supply the high merchant supply option for the reference use projections. By implementing the high merchant supply option, it is possible to save 2.87 X 10^{18} J (2.73 X 10^{15} Btu) of hydrocarbons. To accomplish the saving, an increase in investment costs of nearly 56 billion dollars over the low merchant supply option are required. Assuming a 20-year life, overnight construction and a 9% interest rate, the capital recovery is 6.16 billion dollars per year. Dividing the annual cost by the annual energy saved provides a value of \$2.14 per 10^9 J (\$2.25/10^6 Btu) for the energy saved. It is most likely that fossil fuels

Table III-6. New plant requirements for hydrogen supply options

Energy Source/ Process	Year 1985		Year 2000			
	Low Merchant and High Merchant		Low Merchant		High Merchant	
	New Plants[a]	Total Cost[b] \$X 10^6	New Plants[a]	Total Cost[b] \$X 10^6	New Plants[a]	Total Cost[b] \$X 10^6
Natural Gas/Steam Reforming	5	125	10	250	8	190
Residual Oil/Partial Oxidation	25	1,875	25	1,875	11	660
Coal/Gasification	1	135	148	13,020	82	5,210
Solar, Wind, Nuclear, Hydro/Electrolysis	-	-	-	-	108[c]	66,000
Total	31	2,135	183	15,145	209	72,060

[a] Number of new plants of 7.1 X 10^6 m^3/day (250 X 10^6 scf/day) equivalent capacity.

[b] All costs in constant 1975 dollars and are based on the analysis of Chapter VII. Plant size refers to hydrogen output.

[c] Assumes low-cost advanced-technology systems.

are going to be much more costly than \$2.14/10^9 J (\$2.25/10^6 Btu) before the year 2000.

The secondary reason for switching to high merchant supply option is that a shift must eventually be made to a more desirable supply position than the present one in which the end users are faced with raw material shortages and are consequently converting to whatever fossil fuel is available on an emergency basis. The high merchant supply option, if planned and implemented, provides such an opportunity. This means relying on coal initially, and gradually shifting to nuclear and renewable solar energy sources for permanent, long lasting solutions to the hydrogen supply program.

Figure III-9 shows the conditions surrounding a possible transition phase from the present and near-term low-merchant situation, to the far-term high-merchant case. The lower line is the path we are now on, and its projection is the low-merchant limit. A transition, planned or unplanned, to or near the high-merchant limit can be expected to occur. It is considered highly desirable to have the technology needed for the high-merchant option available and in operation during the intermediate term. The capability limits of present technology preclude the start of such a transition in the near term. An abrupt transition is both physically impossible and economically undesirable. This transition is dependent upon the timely availability of appropriate and mature technologies.

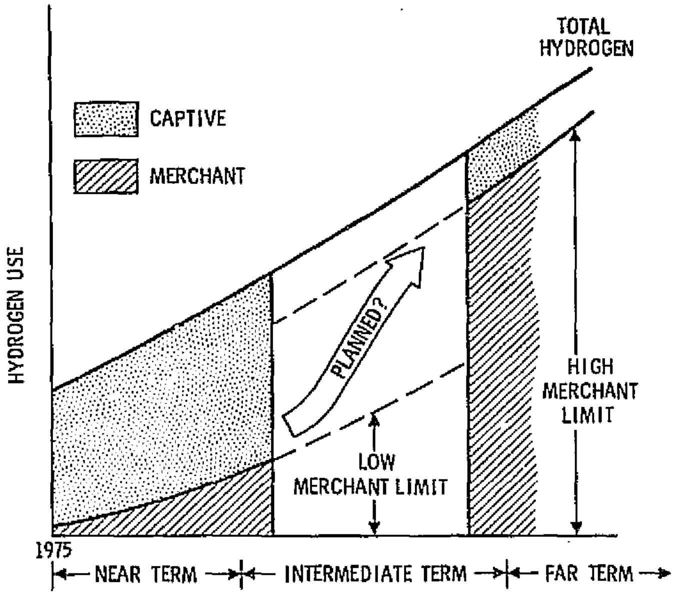

Fig. III-9. Transition to the high-merchant supply option

Chapter IV

TECHNOLOGY ISSUES

Future demands for hydrogen are expected to fall between the Reference and Expanded hydrogen use projections derived in Chapter II. The actual hydrogen use will be influenced by a great many factors, including public policy, industrial choices, and technical and resource changes. However, it is unlikely that hydrogen usage will depart significantly from the projected range. One of the principal factors influencing future hydrogen use and future supply options will be the state of development of the technologies of hydrogen production, handling, and use. The directions of future changes in hydrogen production and use depend on early perception of needs and deficiencies in the present technologies and on the ability to meet these needs effectively. This chapter identifies these areas and discusses the technical issues raised.

A. TECHNOLOGY SELECTION

Supplying the hydrogen to meet future demands, by different methods, will mean choosing from among technological alternatives. Some of these technologies are now in operation; some are developed and would merely need to be implemented; others will develop without special efforts. There remain many areas which require special emphasis and support.

The implementation of new hydrogen technologies will be strongly influenced by the ability to develop favorable characteristics in the technical areas of efficiency, economics, and environmental effects. These characteristics apply to the definition of required technology in the crucial area of resources for hydrogen production, as well as to the use and handling technologies and downstream aspects of production.

1. Efficiency

The primary energy resources required to supply the hydrogen demand established in the Reference Projection are summarized in Table III-4. This Table shows that significant fractions of the available fossil energy sources are needed to meet the hydrogen demands of this projection. It is not clear whether these quantities of natural gas, oil and coal will be available for hydrogen production in the year 2000. Efficient feedstock utilization in hydrogen production and conservation and efficient use of the hydrogen are clearly called for. Since large quantities of fossil sources will be required, a considerable amount of research and development work is warranted, particularly in the following areas.

Fossil Fuel Availability – Improve total production and overall productivity and efficiency of extraction processes; provide manpower training, and implement policies or business strategies to enhance investment opportunities and thereby attract necessary capital for extraction.

The issue of increasing fossil fuel supply is not unique to hydrogen production. It is a major concern of the federal energy policy makers, and covers a wide spectrum in which hydrogen is one important component.

Efficient Hydrogen Production – Increase the fundamental understanding and advance the technology of hydrogen production processes to provide the building blocks for new and improved processes.

The possibility of more efficient utilization of natural gas and oil for hydrogen production has already attracted the attention of present large users (oil refineries and methanol and ammonia producers). Efficient hydrogen production from coal via technologically advanced systems is still in its infancy, with many ideas only at the concept stage or at the bench-test level.

For liquid hydrogen applications, the liquefaction process is a significant energy consumer. Thus, if liquid hydrogen becomes a widely used fuel, it will become increasingly important to improve hydrogen liquefaction efficiency.

Hydrogen Conservation – Improve hydrogen utilization efficiency and reduce hydrogen requirements.

Hydrogen consumption can be somewhat reduced with better chemical conversion yields, such as in ammonia synthesis. Recovery and reuse of hydrogen in chemical plants and refineries may become attractive as energy resources become less readily available. Even though hydrogen conservation techniques are certainly worthwhile, they are not expected to appreciably alter the total hydrogen demand since most hydrogen uses involve processes of relatively high efficiency already.

Hydrogen Distribution Efficiency – Improve the efficiency of high-pressure hydrogen gas distribution systems.

Hydrogen gas has relatively low energy content per unit volume, and to make transmission and handling efficient it must be compressed to high pressures. The work done in compressing the gas can represent a loss in overall process efficiency; increasing compressor efficiency will reduce that work.

2. Economics

Steam reforming of natural gas is the most economical option for producing hydrogen. This is clearly shown by the comparative analysis of production processes in Chapter VII. The drawback is that the continuous use of natural gas offers no lasting solutions; it simply prolongs the dependence on a fossil fuel that is at the heart of the energy crisis. This also is true for steam reforming of naphtha and other volatile hydrocarbon feedstocks.

The partial-oxidation method of hydrogen production leads to an average cost somewhat greater than production by steam reforming, but the difference is not great. The partial oxidation of oil offers no viable long-range benefits because oil is one of the feedstocks in short domestic supply. Coal must be considered the prime feedstock for partial oxidation. Recent data show that the prices of all hydrocarbons are moving upward and a future downturn is highly improbable. We know that the cost of production will increase as the more inaccessible deposits are tapped, or as the countries in possession of these feedstocks believe that it is a matter of justice that they receive higher prices [Avila, 1973]; therefore, it seems improbable that the price of any commodity which uses conventional fossil fuels as the feedstock will ever be cheap again.

Gasification of solid wastes is a recent innovation that is nearing market readiness [Corlett, 1975]. Gasification using air or oxygen results in the formation of synthesis gas. Methanol and ammonia production using this gas looks attractive. It is estimated that 0.19 kg of methanol or 0.22 kg of ammonia may be obtained per kilogram of solid waste. The government (FEA RFP 50172 of Feb. 7, 1975) is exploring policy alternatives to stimulate the recovery of energy from waste. In view of the large amounts of solid organic wastes generated every year (3×10^{12} kg), hydrogen supply for ammonia and methanol production could potentially be obtained from this source. However, municipal agencies collect only a small part of this waste (6 to 7%). Because of dispersed and uncertain solid waste supply, it is difficult to estimate the hydrogen supply potential. A detailed system study on hydrogen production from solid organic wastes is warranted and further research and development work is also required. This supply option looks very promising [Michel, 1973].

Large-scale production of hydrogen by nuclear-powered electrolysis of water is a strong contender for the far term, but offers little promise for the immediate future. The process is still in need of research and development work and is expected to be more costly than fossil-fuel-based processes for a considerable period of time. Because of safety or environmental hazards, long delays have caused nuclear investment to escalate to the range of $500-1000/kW. The cost of fast breeder nuclear power will probably be higher than 15 mils/kWhr compared to current nuclear-electric rates of about 12 mils/kWhr. Due to these costs and the uncertainty of power availability, coal gasification is a more viable choice for hydrogen production than nuclear electrolysis in the near future.

Projected costs and development problems of hydrogen production by thermochemical and other water-splitting methods precludes their early commercial implementation. However, the eventual long-term solution to the fossil-fuel-depletion problem will necessarily require the utilization of these advanced methods.

The concept of a shift toward significant increases in merchant hydrogen production is dependent on the improved economy of scale associated with future advanced hydrogen production processes. In addition to the economics of the production process itself, peripheral economic considerations such as logistics and management also tend to favor large centralized facilities over multiple dispersed facilities. The problem, then, is to bring hydrogen production systems to the point where they provide viable options when the economic climate permits, rather than to force an unreasonable solution before it is economically mandated.

Depending on the specific application, capital and manpower needs of competing hydrogen production and implementation systems could influence the selection of a system. For example, a large assured demand might favor a large coal gasification process whereas small, widely dispersed demands could favor small electrolytic units even though their unit production costs might be higher. Generally, processes with lower capital requirements are easier to implement and this must be weighed against operational efficiency and risks in terms of variations in the market.

The diversity of situations encountered in the industrial complex tend to indicate that a mixture of different hydrogen production methods and associated systems will be implemented. For instance, electrolysis could be used in regions where low-cost hydroelectric power is available, and coal might be used by industries located in coal-rich regions, while naphtha could be used where it is available as a by-product of a petrochemical complex.

Because of the uncertainty of future energy and feedstock costs and availability, all the major options need to be developed so that the selected system can be tailored to the requirements of each circumstance. Since developmental costs are generally small compared to implementation costs, it is likely that development of a spectrum of viable options will be cost-effective.

3. Environment

The production of hydrogen from coal or by thermochemical cycles which may use large quantities of materials can have significant environmental implications. Strip mining vast quantities of minerals will, in particular, present environmental problems. Surface soil reclamation will be necessary, requiring the expenditure of additional energy. The possible proliferation of nuclear energy plants for the purpose of applying that energy to the manufacture of hydrogen will present the potential problem of nuclear accident and contamination identical to that of the nuclear-electric facilities that presently exist.

One environmental aspect of hydrogen production methods which employ fossil feedstocks is the generation of carbon dioxide. All far-term solutions to the energy problem (as well as most other aspects of our society) must evolve toward completely renewable energy systems. Thus, one of the primary appeals of hydrogen energy systems is the observation that hydrogen comes from water and returns to water, and no environmental degradation is possible if the energy source (for example, solar or fusion) and production process are non-polluting. This essential appeal is lost when hydrogen is manufactured from coal involving a unidirectional conversion of solid hydrocarbon to atmospheric carbon dioxide. There has been a significant rise in global atmospheric carbon dioxide over the past few decades and there is genuine concern over global climatic modification which may accompany conversion of a major part of our coal reserves to carbon dioxide [Jones, 1975]. For this reason alone it would be preferable to see early emphasis on production of hydrogen from non-fossil sources rather than coal, despite the economic disadvantage.

The full impact on the environment of pending energy and hydrogen-related decisions is not fully understood. Efforts need to be expended to define the probable impact of the implementation of the hydrogen technologies on the environment. In some cases, however, additional technical data will be required to make reliable environmental impact assessments.

B. IMPLICATIONS OF HYDROGEN USE PROJECTIONS

The anticipated relationship between resources (feedstocks) and use areas as a function of time is indicated in Fig. IV-1. The periods shown are determined by the projected phasing of energy resource availability. The research and technology required to implement this resource-use sequence in the areas of both supply and demand are also indicated. The two major factors which govern this particular sequential ordering are (1) the efficiency, economic, and environmental comparisons and (2) the relative technological readiness of supply and use systems.

The top of Fig. IV-1 shows assessment studies encompassing environmental-social issues as well as techno-economic considerations. These studies will guide the detailed research and technology. Further, this category embraces a spectrum of supportive activities in related research, materials, and safety. The vertical bars indicate the time period in which each technology must be available for successful implementation of the basic resource-use sequence shown. Assessments are mainly needed in the near-term period to develop a solid basis for the overall effort, whereas activities such as "supporting research and materials and safety" should continue during the entire duration of the program.

Technology status and the time to bring technology to the point of utilization determine the time scale reflected in Fig. IV-1. A long time-period (on the order of 10 to 20 years) is characteristically required to carry an energy technology from focussed research to commercial implementation, and still longer is needed to achieve significant market penetration [Mansfield, 1971]. Even after a technology is well understood, up to a decade is required to build a major energy facility and put it into operation.

Three chronological periods are designated in the Figure, the first beginning with the present, the next beginning some time around 1985, and the third beginning shortly after the end of this century. The technology for the near-term period is an extension of the present, with little opportunity for new technology to make itself felt.

In the intermediate period, it will be necessary to turn to other process technology, particularly coal gasification, to maintain production levels of hydrogen, as depicted in Fig. IV-1. Key problem areas in coal-gasification technology include coal handling, high-pressure gasification, and perhaps hydrogen handling. The principal one of these, the development of high-pressure gasifiers, applies also to hydrogen production from heavy oils. Electrolysis of water should emerge on a significant scale as a hydrogen source in this period. Its primary use may be for utility energy storage applications as well as for pure hydrogen production. Achievement of high pressure and higher efficiency operations are primary goals in the development of electrolysis technology. Combustion and fuel-cell technology improvement is also needed in the utility application.

Hydrogen-fuelled aircraft technology will be needed to support experimental aircraft during the intermediate period for commercial implementation early in the far term. Rising liquid fuel costs and decreasing availability coupled with efficiency benefits to be derived from using hydrogen as a fuel will stimulate this shift.

The far term is characterized by the replacement of fossil fuels by nuclear and solar primary energy sources as shown on Fig. IV-1. The far term is an era of advanced technology. Technical problem areas for this phase are twofold: assurance (and acceptable cost) of the primary energy itself, and production of hydrogen by splitting water.

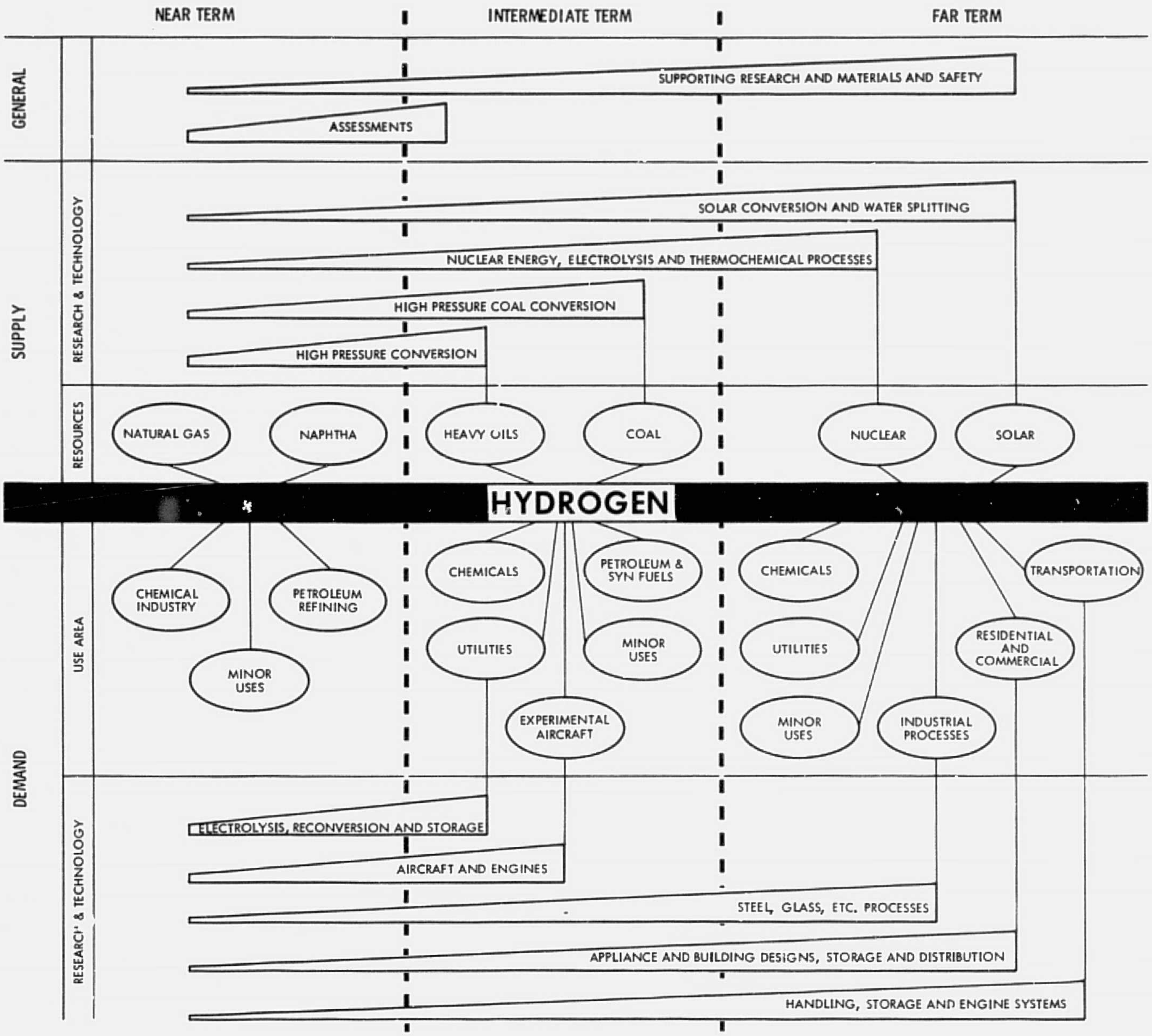

Fig. IV-1. The relationship of hydrogen research to technology requirements

C. TECHNOLOGY NEEDS

Several areas of hydrogen supply and demand were indicated in Fig. IV-1 as requiring research and technology development to satisfy specific technological deficiencies. The technology needs exist primarily in the areas of production and utilization.

1. Production

The technology needs for hydrogen production depend on the demand for hydrogen and on demand for competing uses of energy feedstocks. The development of technology thus depends to some extent on the overall demand for energy and must be related to the energy scenarios presented in Chapter II. Manufacture of hydrogen by feedstocks other than natural gas or oil is characterized by substantially increased energy consumption as indicated in Chapter VII, so that the supply of hydrogen will be increasingly related to the availability of energy.

Future supply and demand for energy (and hydrogen) are uncertain, but the technology for the introduction of new supplies of hydrogen must be developed for any of the projected use rates. Thirty years have been required for nuclear reactors to reach the level of about 8% of the installed electrical power capacity of this country, and this timeframe is typical of the history of the oil and gas industries. As a result, it is necessary to develop the fundamental technology of advanced processes well before they are needed.

The selection of energy feedstocks to produce hydrogen will be tied to their availability, cost, and reliability of supply. Figure IV-1 projects the relationships between the technologies of production and utilization of hydrogen as derived from this study, and forms the framework for delineating specific technology needs. It reflects the lengths of time expected to be required to provide the technologies needed.

Table IV-1. Technology deficiencies for hydrogen production techniques

Partial Oxidation of Heavy Oil

- High-temperature desulfurization (increase in process efficiency)
- Shift-catalyst (improvement to decrease residual CO)
- CO_2 and low-temperature H_2S scrubbing (to decrease power consumption)

Partial Oxidation of Coal

- All of the deficiencies listed for partial oxidation of Heavy Oil above, and
- Pressurized coal-feeding systems (from atmospheric up to 7000 kN/m^2 or 1000 psi)
- Reliable continuous ash removal (from ~ 7000 kN/m^2 or 1000 psia to atmospheric)
- Materials resistant to sulfur and hydrogen (at ~ 7000 kN/m^2 or 1000 psi)
- High efficiency oxygen plants

Electrolysis

- System analysis of nuclear electrolysis, including:
  - Heat exchange process in the reactor
  - Integration of electrical generator/conditioner and electrolyzer
- Low-voltage ($<$ 1.6 volts) electrolysis, requiring either high-temperature ($>373^\circ K$ or $212^\circ F$) alkaline electrolytes, or radically improved oxygen evolution electrodes
- High-pressure (7000 kN/m^2 or 1000-psi) electrolyzers

Thermochemical Production

- Definition of specific technology problems must follow the completion of fundamental work and data acquisition in following categories:
  - High-temperature reactions of inorganic chemicals, especially those which consume H_2O and evolve H_2 and O_2
  - Chemical, thermodynamic, and transport properties, and material compatibility
  - More efficient cycles which operate with relatively noncorrosive reactants
- Standardized procedures to evaluate thermochemical process efficiencies
- System design criteria
- Heat-source technology, including:
  - High-temperature nuclear or solar sources
  - High-temperature heat-exchanger technology

Solar Photolysis

- Definition of specific technology problems must follow the acquisition of fundamental data in many areas, including:
  - Photooxidation and photoreduction in organic solutions
  - Photolysis in dye solutions which absorb photons and transfer energy to water

Direct Thermal Water Splitting

- Definition of specific technology problems must follow the acquisition of fundamental data and development of design concepts in many areas, including:
  - Solar-reflector concentrators to achieve high working temperature
  - Gas-product separation at working temperature

Table IV-1 presents specific advances in oil and coal processing that are needed to optimize hydrogen production technology. Under conservative estimates for hydrogen demand in the year 2000, each 1% increase in process efficiency would reduce the annual coal consumption by about 3 billion kilograms per year. Cost analyses in Chapter VII indicate that for the low-merchant supply option, reference projection, cost savings of $5-10 billion could be accumulated by the year 2000 if coal-processing efficiencies were improved by 10 percentage points. The high-merchant supply option considers hydrogen production by the use of non-fossil energy and water electrolysis. If electrolyzer efficiencies were improved by 18 percentage points (a feasible goal), almost $35 billion in cost savings could be accumulated by the year 2000.

The new energy sources such as nuclear, geothermal, solar, ocean thermal gradients and similar sources must produce hydrogen by decomposing water. They are much more energy-intensive than fossil processes where a portion of the hydrogen can be efficiently obtained by decomposing the source itself. For economical production of hydrogen, electrolyzers are needed that efficiently convert electrical power to hydrogen. Where waste-heat sources are available, methods of producing hydrogen from water and heat efficiently should be developed. Where high-temperature nuclear or solar heat sources are available, thermochemical cycles should be developed if they can be made competitive with electrolysis. Finally, the direct use of solar radiation by photovoltaic or photolytic methods offer the potential of applying high-technology to exploit a renewable energy source.

2. Utilization

Hydrogen must be manufactured from energy feedstocks. It is presently either a valuable chemical or a premium fuel in all of its uses. If hydrogen becomes readily accessible, its use will most likely increase substantially. For example, industrial processes such as paper manufacture that use oxidants may convert from the use of electrically-derived chlorine compounds to peroxide compounds which require hydrogen as a major chemical feedstock. New uses of hydrogen are difficult to predict because, while energy resources are limited to only a few kinds, uses are virtually endless. Present uses, however, are well understood, and projections to the near future show a large and increasing hydrogen usage.

In the far term, as shown in Fig. IV-1, the technologies of hydrogen transportation, storage, and distribution must be ready for implementation when demand develops. Broad new applications and uses of hydrogen, if warranted on the basis of assured supply and economics, will be possible in the areas of residential, commercial and industrial heating, and industrial-process applications. Research in the application areas of transportation, heating and industrial processes should be developed by this period to permit the introduction of these added uses.

In general, hydrogen use technology appears to be in a higher state of development than production technology because only a few major new uses for hydrogen have been identified. The technology deficiencies in those areas are listed in Table IV-2. Detailed amplification of use areas is given in Appendix D.

Table IV-2. Technology deficiencies for hydrogen use

Utilities Applications
    Fuel cells (efficiency, catalysis, endurance, cost)
    Turbines (efficiency, high-temperature)
    Hydrogen storage (cost, endurance)

Air Transportation
    Overall assessment, including logistics
    Cryogenic insulation (cost, endurance)
    Liquefaction (cost, efficiency)
    Ground handling and fueling methods (safety)
    Storage (cost, materials, safety)
    Engines (efficiency, high-temperatures)

Industrial Processes
    Chemicals from merchant hydrogen
    New uses (methods, processes)

Residential and Commercial
    Appliance designs (cost, efficiency, safety)
    Building designs (cost, efficiency)
    Storage and distribution (cost, efficiency, materials)
    Odorants and illuminants

Ground Transportation
    Bulk storage and handling (cost, materials, safety)
    On-board storage (cost, weight, materials, safety)
    Engines (efficiency)

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Chapter V

CONCLUSIONS

Hydrogen has and will continue to have a role in the nation's economy, at present as a chemical feedstock and, additionally in the future as an energy carrier. Continuation of the traditional hydrogen supply methods entails a national reliance for hydrogen on dwindling natural gas reserves. The consequences of this situation would include an unreliable hydrogen supply and unpredictable cost increases. To bring about actions which will avoid or minimize these and associated disruptions in those parts of the economy dependent on hydrogen, further research, technology advancement, and assessments are required.

In this chapter, conclusions are presented according to general areas of technology with some specific examples of research and technology needs identified. These conclusions provide a base for the future development of detailed program plans and identify research needs that are not being given attention or that we feel are not being supported at a sufficient level.

A. HYDROGEN PRODUCTION

Current methods of producing hydrogen from natural gas and light oils, although very efficient, are being confronted by signs of the imminent shortage of feedstocks. For this reason, given the projected demand growth, emphasis must be given to advancing hydrogen production technology based on more readily available feedstocks. Electrolyzers use large amounts of electrical energy, and the electricity required to power them is becoming increasingly more expensive. Commercial methods for producing hydrogen from coal exist. However, they are inefficient and operate at low pressure. Near-term emphasis must be placed on obtaining hydrogen more economically from coal. Also, hydrogen production from renewable energy sources must be pursued. A significantly broadened base of fundamental research is required in order to enhance advanced-process development.

1. Partial Oxidation Processes

Early research efforts should concentrate on the production of hydrogen by partial oxidation from the heavier fossil fuels such as residual oil and coal. Existing coal-gasification technology provides the foundation for future studies of the improved production of hydrogen from coal. High-pressure gasification, efficient desulfurization and gas purification, improved catalysts, the separation of product gases, materials compatibility with hydrogen and improved methods of handling feedstock materials are areas requiring further work. In some energy projections, the need to have a major coal-gasification capability will exist by 1985. This means that immediate emphasis must be given to this area of technology. There is extensive experimentation going on within the Government and industry on high-pressure gasification of coal to produce both low Btu and high Btu fuel gases. Development of processes which make pure hydrogen from coal can take advantage of this related R&D work. Development of gasifiers specifically tailored to hydrogen production, new processes in air separation for oxygen production, and high temperature desulfurization processes would add significantly to the efficiency of hydrogen production.

In view of the availability of large quantities of solid waste, the production of hydrogen by partial oxidation from such material should be pursued. A detailed systems study and further research are warranted.

2. Electrolyzers

It has been projected that the first production of hydrogen from nuclear and solar energy sources will be through the electrolytic energy conversion process. Therefore, when the need emerges to turn to nuclear and solar energy sources, electrolyzer technology must be available at relatively high productivity and low cost. The electrolyzer industry is not currently supporting research programs large enough to bring about significant improvements. Basic research in electrochemical and fluid fundaments, especially electrode kinetics and gas evolution, need to be expanded. Applied research and development needs to be conducted on catalysts, electrode materials, new separators for alkaline cells and solid-polymer electrolytes. Specific research objectives and system design parameters need to be established early to provide a firmer basis for program decisions and guidance for future research. To support the hydrogen energy storage application, technological advancements are also needed in fuel cells, high-temperature turbines, and hydrogen storage systems.

3. Thermochemical Cycles and Direct Water Splitting

A thermochemical cycle consists of a series of chemical reactions which recycle the reactants, and requires three or more chemical stages operating at various temperatures. Considerable research will be required before feasible cycles can be evolved. The potentials for high efficiency and favorable economics for all-thermochemical cycles warrant further evaluation, however. Certain fundamental data in the area of chemical, thermodynamic, transport properties, and materials compatibility need to be generated and made available. Data is needed on the rates of forward and back reactions, methods of reactant and product separation, toxicity and corrosivity. Additional efforts should be directed toward finding more efficient cycles that operate with relatively non-corrosive reactants. Standardized procedures to evaluate thermochemical process efficiencies and system design criteria need to be established. More in-depth efforts are required to better evaluate technical risks and to better assess potential costs.

Hybrid cycles are those in which some reactions proceed by the input of thermal energy and contain at least one reaction that is accomplished by electrical energy input. To be economically competitive, hybrid cycles require significantly lower consumption of electrical energy than simple electrolysis of water. Continued research on a two-stage hybrid cycle based on electrolysis of sulfurous acid to produce hydrogen and thermal decomposition of sulfur dioxide to produce oxygen should be supported as part of the evaluation of thermochemical cycles for hydrogen production.

Thermochemical processes which promise greater overall efficiencies than advanced electrolysis systems will most likely require very high temperature. Therefore a high-temperature nuclear or solar heat source will need to be developed if these cycles are to be exploited.

Direct thermal water splitting theoretically creates the largest demand for energy of all the methods considered for the production of hydrogen. Therefore, the direct thermal splitting of water will probably be the least desirable hydrogen production technique, unless other special conditions exist. The use of solar energy sources or perhaps a photocatalytic process may make direct water splitting a competitive technique. Innovative ideas and creative research proposals in the broad area of water splitting are needed, particularly those which are related to the use of nuclear, solar and geothermal energy sources.

A biological process abundant in nature, utilizing solar energy to produce carbohydrates, is the photosynthesis of green plants, which operates at about 10% efficiency. Proposals have been made to modify this process in such a way that its products are hydrogen and oxygen. Hydrogen could also be produced through manipulation of metabolic or fermentation processes. With research, future scientific progress may allow realization of these goals.

B. HYDROGEN USE

Hydrogen is now being used in many ways. It is both produced and used routinely in the chemicals and fuels industries. It is also used widely in industrial processing from metallurgy to foods. It can be used to improve efficiencies and enable the use of new energy sources.

1. Electric Utility Applications

Hydrogen can be used by electric utilities to match their electrical production capability to the demands of their customers. Electricity can be used to produce storable hydrogen which is later used in fuel cells or combustion-driven generators to produce electricity. Research and development are required to establish the feasibility of this application. Research in fuel-cell technology and other high-efficiency energy-conversion cycles, e.g., hydrogen-oxygen turbines, is also required. Hydrogen storage systems such as hydrides, organic compounds, cryogenic systems, high-pressure systems, and underground storage require further work. High-pressure electrolyzers are an important part of electric utility peaking systems. Some of this work is already being funded by the utility industry itself. In addition, significant developments in the production of hydrogen and subsequent energy conversion will be easily transferable to other sectors of the energy economy when needed.

2. Transportation Uses

In the transportation sector, it is expected that the earliest potential role for hydrogen is to provide the fuel for air transportation. Studies thus far have identified both the opportunities and problems that hydrogen affords the air transport industry. Further work is required now to establish possible implementation modes. In addition, logistics questions regarding hydrogen delivery and handling must be studied.

The use of hydrogen as a transportation fuel for other than air transport is not projected before the year 2000. A reason for the delayed entry of hydrogen into all transportation sectors is its high cost relative to synthetic fuels as well as the lack of adequate storage and distribution systems. Hydrogen cannot compete with synthetic liquid fuels as long as coal is available for their production. Therefore, research dealing with hydrogen as a fuel in surface transportation could be given low emphasis for a number of years.

3. Fuels Production

Crude petroleum is refined and processed with the addition of hydrogen which is normally obtained from a portion of the feedstock material. There are possibilities that merchant hydrogen from coal could extend petroleum resources. Desulfurization processes might be modified to recycle the hydrogen used, thus economizing on consumed feedstocks. Creative investigations in the area of refining fossil fuels have the potential for significant benefits and are continually funded by the petroleum industry.

Specific systems studies should be carried out to evaluate the potential technical difficulties in substituting new merchant sources of hydrogen for traditional captive hydrogen supplies. The assumed feasibility of supplanting current hydrogen feedstocks with coal-derived or electrolytic hydrogen should be verified at an early date. Questions related to energy demands, materials compatibility, and generation of by-products require detailed understanding before the captive-to-merchant hydrogen transition can be projected.

4. Other Hydrogen Uses

Other potential uses of hydrogen have been identified. Hydrogen as a producer of industrial process heat is a distinct future possibility. Natural gas may initially be supplemented and eventually be replaced by hydrogen as the residential and commercial fuel gas. It would appear that a rich field of creative opportunities is available in each of these areas of hydrogen use. It is concluded, however, that work in these areas should be deemphasized in favor of the other work above because: (1) the work required appears to be mostly developmental in character, technically straightforward and stated goals should not be difficult to achieve; (2) the results of such work are not expected to be required until after the turn of the century.

C. GENERAL

There are several areas of general research and technology to be undertaken that require no hardware development but are needed to provide data for important technological decisions. Before significant changes in the overall methods of supply and demand of hydrogen occur or are seriously advocated, the more significant environmental and institutional issues should be identified and resolved.

Systems analyses of the coal production and delivery processes should be performed in order to determine what must be done to permit coal to become the prime energy source in the period before the year 2000. An analysis of petroleum refineries to determine the feasibility of providing both process heat and hydrogen from nonfossil sources must be made. Systems studies concerning the possible roles of hydrogen in military ground transportation and civil rail transportation would also be valuable.

Continuing efforts in the area of supporting research and technology should be encouraged. A handbook (manual or guidebook) for the researchers, technologists, and others involved with handling hydrogen or designing hydrogen systems and devices, is needed. Long-term research of hydrogen-related materials problems is required. Similar continuing efforts in the area of hydrogen safety should be supported.

D. URGENCY

Levels of urgency can be tentatively assigned to the activities cited in these conclusions on the basis that certain activities must be undertaken at the outset and that not all of the activities can be begun at first.

The first level of urgency must be accorded to the completion of general implementation planning and to the development of partial oxidation processes using coal and heavy oil to produce hydrogen.

Development of electrolysis technology and other elements of utility energy storage, fundamental research on other water-splitting hydrogen-generating processes, and work toward aviation applications are second level.

Merchant-hydrogen system studies and assessments of hydrogen-technology impacts need to be conducted early, to a first order. Their completion, in-depth, must await the availability of a more complete data base. Surface-transport applications will not be generally competitive for some time.

E. PROGRAM PLANNING

It would be most prudent and cost effective to develop a coordinated national research and technology program involving both government and the affected industries cooperatively striving toward recognized goals through complementary and non-duplicative activities. Very large savings in feedstock costs are possible through the development of processes having improved efficiencies. Short-term goals of the program would emphasize production of hydrogen from the most abundant fossil fuels. Long-term goals would emphasize new energy-efficient uses of hydrogen and water-splitting production methods.

The Federal government should take the lead in formulating this plan, since the economic well-being of the nation is intimately tied to future energy supplies and the form in which energy will be delivered. Factors which need to be considered in the plan development include:

Determination of cost- and risk-reduction benefits to the nation to be derived from Federal government support of specific items of hydrogen technology.

Evaluation of alternative program options to arrive at the most cost-effective approach.

Determination of the degree of Federal government and industry participation required.

Interaction with related Federal programs in energy storage transportation, and synthetic fuel development from fossil fuels.

PART TWO
SUPPORTING DATA

N76-18659

CHAPTER VI

HYDROGEN UTILIZATION AND ALTERNATIVES*

This chapter describes the historical uses of hydrogen and identifies potential new uses which could develop as a result of the diminishing supply of conventional fossil fuels such as natural gas. A perspective view of hydrogen, both as a chemical feedstock and as a fuel, is necessary to understand its relationship to the overall national energy projections. These projections, which show energy usage in terms of use sectors, forms of energy and sources of energy, do not specifically identify hydrogen as a component of the energy system. By superimposing the traditional roles upon the new opportunities for hydrogen on the energy projections, the role of hydrogen and future projections can be developed within the context of the national energy projections. Use, supply and other factors affecting application are of course interrelated. Supply and other factors are discussed elsewhere in this report, but the implications of supply and other factors were employed in the logic process used to develop the concepts presented here.

This material relies heavily on the published work of a number of researchers and therefore only summary accounts of the many technical aspects are given. A few areas which are not discussed thoroughly in the literature are expanded upon to provide a deeper technical base.

A. HISTORICAL USES OF HYDROGEN

At the start of this century, relatively little hydrogen was produced. Small quantities of pure hydrogen were produced by electrolytic means for some specialty applications. Impure hydrogen gas was also produced as a fuel for gas lights. The successful synthesis of ammonia in 1913, together with the demands of World War I, caused a rapid surge in hydrogen production. The steady growth of hydrogen demand up through World War II was encouraged by the reduced cost of hydrogen because of improved technology and the use of low cost natural gas as a raw material.

1. World Production and Present Markets

The world production of hydrogen has increased sharply over the past 35 years. In 1938, the estimated production was 7.1×10^{7} m^3 feet (2.5 billion cubic feet), and by 1973 it had climbed to about 2.5×10^{11} m^3 (9000 billion cubic feet). Most of this hydrogen is produced very close to its point of consumption, so that it does not appear to the "man in the street" as a very evident raw material, as does oil, natural gas, and coal. At today's hydrogen selling prices, this commodity is worth more than 9 billion dollars annually.

Hydrogen production from World War II through 1973, from Bureau of Mines (1974 preliminary) is shown in Table VI-1. Table VI-1 shows that over 93% of the total hydrogen produced at the present time is used as a chemical intermediate in chemical processes to produce hydrogen-containing products such as ammonia, methanol and refined petroleum fuels and chemicals. This portion of the hydrogen production is usually produced and consumed on site and is called "captive" hydrogen (see Fig. VI-1). The remaining 7% is used for a variety of applications, including reduced atmospheres and reducing agents, chemical hydrogenation, and clean combustion applications. Many industries are dependent on obtaining this unique material, which is used for the manufacture of glass, electronic components, food and drug products, reduction of heavy metal oxides, metallurgical finishing processes, and even in the manufacture of synthetic gems. These relatively small users of hydrogen represent the present "merchant" market potential for hydrogen sold as industrial gas. This market is represented by the miscellaneous category of Table VI-2. About 10% of this market potential is currently met by merchant hydrogen sales [Dept. of Commerce, 1974].

Further, as shown in Fig. VI-2, the production of industrial gases involves hydrogen in a major way [Henglein, 1969]. The chain leading from raw materials to industrial gases to end products is illustrated. For example, the chain from natural gas to CO + H_2 mixtures for methanol and gasoline synthesis is shown. The role of hydrogen in production of industrial gases is primarily captive. However, the electrolysis and the metal-metal oxide-steam pathways for producing hydrogen indicate a potential merchant hydrogen pathway for ammonia synthesis (where nitrogen would be extracted via liquefaction of air).

Figure VI-3 shows the present markets for hydrogen. The following five general categories of hydrogen are utilized:

> Hydrogen in mixtures with nitrogen and/or carbon monoxide used to produce ammonia or methanol.
>
> Refinery waste-hydrogen, which is usually available as cat-cracking effluents in concentrations of 60-95%. These gases are run through refinery operations, reducing the hydrogen content to 50-75% — at which point, it is burned as a fuel.
>
> Low-purity hydrogen gas, which is used to produce chemicals and treat metals.
>
> High-purity hydrogen gas, used to produce chemicals, hydrogenate fats and oils, treat metals, and in the electronics and drug industries.
>
> High purity liquid hydrogen now used primarily as a rocket fuel.

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*By R. Manvi, R. Caputo and T. Fujita, with support from the NASA Working Panel, Appendix A.

Table VI-1. Hydrogen production 1945-1973

World Production	10^9 m^3 (billion scf)							
	1945	1962	1964	1965	1968	1971	1972	1973
U.S.	2.0 (72)	23.0 (814)	27.5 (970)	32.7 (1155)	58.3 (2060)	76.8 (2712)	81.6 (2880)	86.7 (3057)
Rest		38.8 (1370)	42.5 (1500)	44.6 (1576)	84.8 (2995)	84.8 (4174)	125.0 (4400)	170.0 (6000)
Total	2.0 (72)	61.8 (2184)	61.8 (2470)	77.3 (2731)	143.1 (5055)	143.1 (6886)	206.1 (7280)	256.2 (9047)

Table VI-2. Recent United States hydrogen production and consumption in 10^9 m^3 (billion scf)

End Use	1964	1968	1971	1972	1973	Average growth rate, % 9 yr (5 yr)
Ammonia	14.0 (495)	24.5 (865)	28.3 (1001)	30.7 (1084)	31.3 (1104)	9.3 (5.0)
Refinery operations	7.6 (270)	22.2 (783)	37.8 (1334)	38.8 (1370)	40.6 (1434)	20.4 (12.9)
Methanol	2.83 (100)	4.11 (145)	5.41 (191)	6.4 (226)	8.58 (303)	13.1 (15.9)
Hydrogenation of oils	0.28 (10)	0.31 (11)	0.34 (12)	0.40 (14)	0.42 (15)	4.6 (6.4)
Miscellaneous*	2.69 (95)	7.25 (256)	4.93 (174)	5.27 (186)	5.69 (201)	8.7 (-4.7)
Total:	27.5 (970)	58.3 (2060)	76.8 (2712)	81.6 (2880)	86.7 (3057)	13.6 (8.2)
Energy Equivalent	0.334 (0.316)	0.707 (0.670)	0.931 (0.882)	0.988 (0.936)	1.047 (0.992)	(10^{15} Btu) 10^{18} J

*Electronics and electrical, space, other industrial, and other chemicals for example, hydrogen peroxide, alcohols.

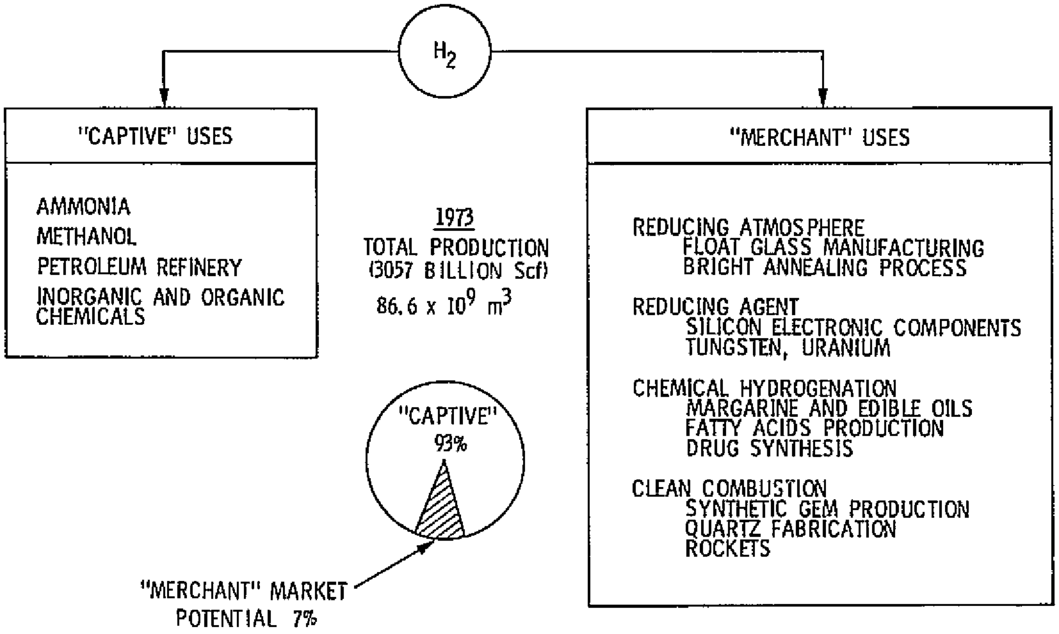

Figure VI-1. Hydrogen utilization

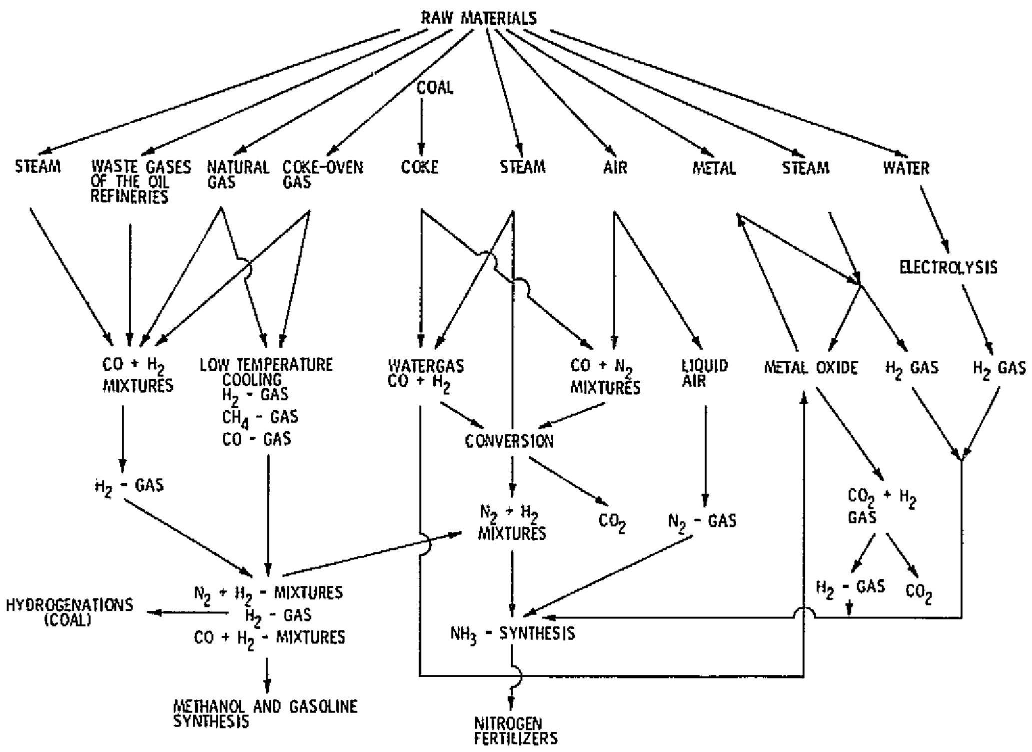

Figure VI-2. Hydrogen's role as an industrial gas

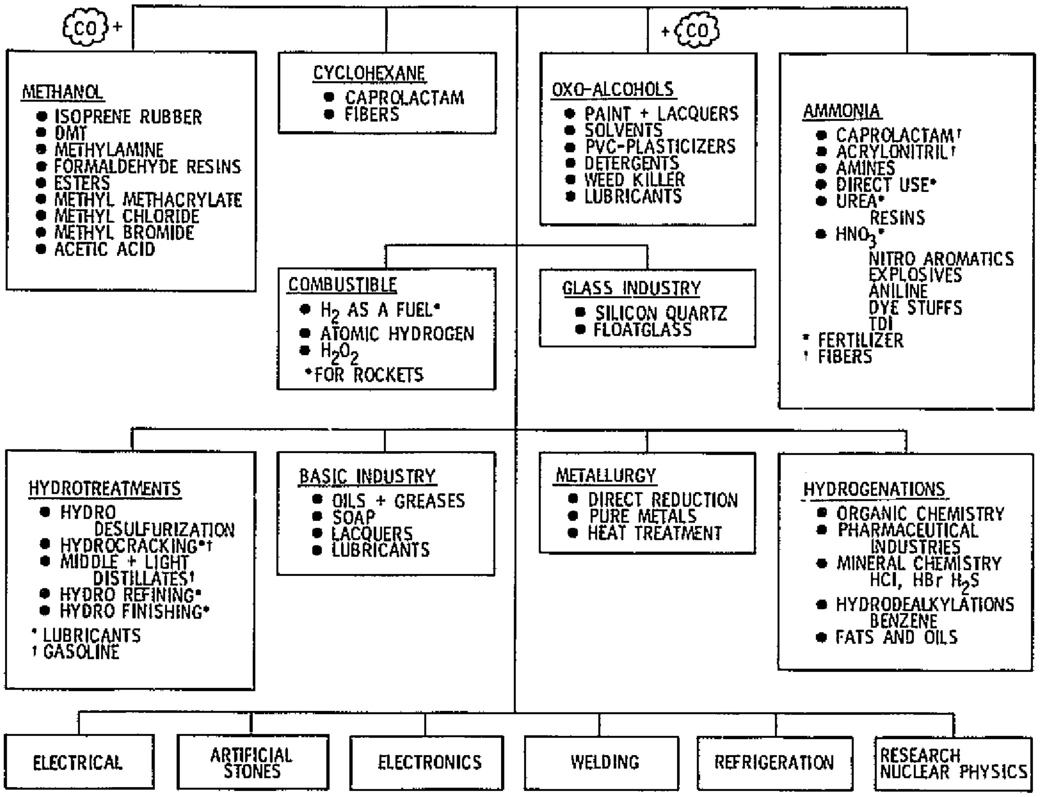

Figure VI-3. Present markets for hydrogen

2. Domestic Consumption and Unit Industrial Requirements

Table VI-2, based on data from the Bureau of Mines, shows the past 9-year consumption of hydrogen in the United States. The typical industrial hydrogen requirements are indicated in Table VI-3. Domestic demand for hydrogen, excluding plant fuel use, increased at an average rate of approximately 13.6% annually since 1964. At the present time, the oil refining industry is the largest producer and consumer of captive hydrogen, followed closely by synthetic anhydrous ammonia manufacturers who are the second largest producers and consumers of captive hydrogen. More than 98% of hydrogen produced is low purity (less than 99.5% pure). The remainder, referred to as high-purity hydrogen is 99.5% to (virtually) 100% pure.

Domestic consumption of hydrogen is essentially equal to production, which is mostly by steam reforming of hydrocarbons and some partial oxidation of hydrocarbons. There are no imports of hydrogen, and exports (high purity bottled gas) are a small part of total output. Stocks of elemental hydrogen also are a minor part of total hydrogen supply. Only NASA stocks some liquid hydrogen for its uses.

It is noted that Table VI-3 also provides hydrogen requirements for future markets such as coal and shale oil conversion. These values are given here for purposes of comparison and will be referred to in following sections.

B. POTENTIAL USES OF HYDROGEN

The future uses of hydrogen impact all sectors of society as illustrated in Table VI-4, which indicates that industrial uses are relatively firmly entrenched whereas uses in other sectors are less firm. In addition to its present primary role as a chemical feedstock, hydrogen can be used as a gaseous or liquid energy carrier created from a primary energy source. In particular, this new role has major ramifications in all energy use sectors.

The energy carrier role of hydrogen is not constrained to depletable primary energy sources but can be used with future sources such as solar energy and nuclear fusion. Thus, a continuing potential role for hydrogen is delineated in an eventual time frame when fossil fuels become severely depleted. The time period called "eventually" is defined as the time when fossil reserves are no longer used as a fuel. Fossil materials will become too scarce or expensive to burn for heat. When "eventually" occurs can only be imprecisely estimated, but recent studies [Hoffman, 1975] predict that this era will start in about 2020-2025. There are several energy carriers in addition to hydrogen and it is likely that each will fulfill roles for which it is particularly suited. Electricity would probably continue to supply energy for lighting and home appliances, steam and hot water could be recirculated for industrial heating, and synthetic fuels such as substitute natural gas (SNG) and methanol are candidates for residential heating. In the absence of conventional fossil fuels, the manufacture of synthetic hydrocarbon fuels will require hydrogen from water plus a carbon source such as limestone or carbon dioxide from air. Thus, "eventually" the entire synthetic hydrocarbon fuel technology will rely on hydrogen production.

Between the present and "eventually", conventional highly-developed fossil fuel-based technologies will play a strong but gradually diminishing role. Hydrogen, in this context, will continue in its traditional unique chemical role, undergo development for its energy systems role, and expand gradually into new roles. Quantitative judgments regarding the magnitude of hydrogen usage as a function of time are given in later sections. The present section will provide background information regarding major potential roles including:

Continuation of historical uses

Manufacture of synthetic fuels

Utility applications

Reducing agent

Gaseous or liquid fuel

The present study includes both captive and merchant uses of hydrogen since it is oriented toward delineating technology requirements, particularly including technology concerned with production of hydrogen. Generally, improvements in production technology will be applicable to both captive and merchant uses. Further, the decision of whether to use captive or merchant hydrogen in any given process or industry depends primarily on an economic analysis which will be largely influenced by production costs as governed by technology advances, the quantity required especially in the context of economy of scale and plant siting with regard to transportation costs of raw materials and energy transmission costs. Thus, captive markets can shift toward merchant markets as discussed in Chapter III.

1. Continuation of Historical Uses

The outlook for hydrogen during the 1975-2000 period is for continued growth in almost all uses listed in Fig. VI-3. The strong growth pattern of hydrogen usage in chemicals and for miscellaneous purposes as shown in Table VI-2 is expected to continue since these uses involve growth industries such as fertilizers, and plastics where there is essentially no substitute for hydrogen.

a. Unique Chemical Feedstock. Historical and present uses of hydrogen are primarily as a unique chemical. This is the most important current use and projections indicate that this category will continue to dominate in the 1975 to the year 2000 time frame. Major uses within the category include ammonia manufacture, methanol manufacture, petroleum refining, and the hydrogenation of fats and oils.

Ammonia is a particularly vital chemical due to its usage in fertilizers. Food production to meet anticipated demands is expected to be a critical problem in the period of 1975 to the year 2000 [Oil and Gas Journal, 1974, and Harre et al., 1974]. Methanol is primarily used as a solvent and a precursor for manufacturing plastics,

Table VI-3. Typical industrial hydrogen requirements

Use	m^3 (scf)	Unit of Product
Ammonia synthesis	2.18-2.50 (70,000-80,000)	kg (ton) of NH_3
Methanol synthesis	1.62-2.34 (52,000-75,000)	kg (ton) of CH_3OH
Hydrogen peroxide	0.75-2.18 (24,000-70,000)	kg (ton) of H_2O_2
Butanol	0.325 (10,500)	kg (ton) of butanol
Decyl alcohol	0.140 (4,500)	kg (ton) of decyl alcohol
Ethylene glycol*	2.6 (84,000)	kg (ton) of ethylene glycol
Petroleum refining (av)	109 (610)	m^3 (bbl) crude oil)
Hydrotreating		
Naphtha	9 (50)	m^3 (bbl)
Coking distillate	134 (750)	m^3 (bbl)
Hydrocracking	267-623 (1,500-3,500)	m^3 (bbl)
Coal conversion to*		
Liquid fuels	784-1,514 (4,400-8,500)	m^3 (bbl) "synthetic" oil
Gaseous fuel	44 (1,560)	28 m^3 (1,000 scf) "synthetic" gas
Oil shale conversion to*		
Liquid fuel	232 (1,300)	m^3 (bbl) "synthetic" oil
Gaseous fuel	34 (1,200)	28 m^3 (1,000 scf) "synthetic" gas
Liquid fuel from tar sands	303 (1,700)	m^3 (bbl) "synthetic" oil
Iron ore reduction*	0.624 (20,000)	kg (ton) of iron
Process heat*	82.3 (3,070)	GJ (10^6 Btu)
	or	
	169 (2,700)	10^3 kg (10^3 lb) process steam
Hydrogenation of fats and oils	0.109 (3,500)	kg (ton) of product

*Future markets

Table VI-4. Future markets for hydrogen utilization

	Industrial	Residential and Commercial	Transportation	Electric
Unique chemical	Assured			
Gaseous fuel	Probable	Probable	Possible	Probable
Synthetic fuel	Assured	Possible	Probable	Possible
Reducing agent	Assured			
Others	Assured	Possible	Possible	Assured

resins, and organic chemicals. It is, thus, an important constituent of major industrial sectors which are expected to remain in existence and grow at least through the year 2000.

Hydrogen processing for petroleum refining [Mason and Tolberg, 1973] is used to upgrade crude oil to refined products such as gasoline and lubricating oil and to remove sulfur via hydrodesulfurization in compliance with environmental laws (e.g., sulfur content <0.5% for fuel oils in the United States). Hydrogenation of fats and oils is extensively used in food processing, particularly in the manufacture of margarines and shortenings. The use of hydrogenation since 1900 revolutionized the oils and fats industry by allowing the upgrading and hence wider use of specialty oils [Kent, 1962].

The list of unique chemical uses for hydrogen (Appendix D) is extensive. The major examples briefly mentioned above are characteristic of the essential role of hydrogen, i.e., there is no viable substitute for hydrogen. Thus, this category constitutes a base level or minimum requirement for hydrogen and is classified as a use within the industrial sector (see Table VI-4).

b. Collected Small Quantity Uses. Most of the major users of hydrogen purchase their own hydrogen production plants. Small users purchase hydrogen from suppliers such as Linde/Union Carbide, Airco, and Air Products. Some major uses of hydrogen such as food hydrogenation mostly involve in-plant hydrogen production, but small food producers still purchase hydrogen. Some small users also obtain hydrogen as by-products of other processes via mechanisms such as inter-plant transfers.

The category of collected small quantity uses has been defined as those uses which employ relatively small quantities of purchased hydrogen. This is essentially the merchant hydrogen market identified in Fig. VI-1. Descriptions of many of the small uses for hydrogen are given in Appendix D. In most instances, there are no immediately available viable substitutes for hydrogen and the continued growth of hydrogen usage in the sector is anticipated.

2. Manufacture of Synthetic Fuels

The manufacture of usable gaseous and liquid fuels from sources such as coal, shale, and tar sands all require hydrogen. Utilization of these sources for synthetic fuels is quantified in the selected energy scenarios described in Chapter III. Thus, hydrogen requirements consistent with these scenarios can be directly determined: i.e., the scenarios contain an implied amount of hydrogen for synthetic fuel production.

For the time period of 1975 to 2000, the energy scenarios still assume that substantial quantities of petroleum and natural gas are available for use. As a consequence, this results in relatively low usage of inherently more costly synthetic fuels. However, at some point beyond the year 2000, petroleum and natural gas will become less available and use of synthetic fuels will probably grow at a rate sufficient to at least fill the void. Hydrogen requirements for making these synthetic fuels should then grow at a proportional rate.

This role of hydrogen in the manufacture of synthetic fuels constitutes a major application for hydrogen that will rapidly grow in importance, as feedstocks such as coal are implemented to a greater extent. In the transportation sector, for example, synthetic gasoline derived from coal liquefaction is a strong contender for replacing petroleum-based gasoline [Kant, 1974], due particularly to its compatibility with the existing distribution system. Hydrogen requirements for producing liquid fuels from coal range from 784-1514 m^3/m^3 (4400 to 8500 scf per barrel) of synthetic fuel (Table VI-3). Using the FTFB projection of Table IV-1, the transportation sector will consume 26 GJ (25 x 10^{15} Btu) in the year 2000, which corresponds to about 6 - 8 x 10^8 m^3 (4 to 5 x 10^9 barrels) of liquid fuel. If all the transportation needs were to be met by liquid coal-derived fuels, the quantities of hydrogen required would range from about 5 - 11 x 10^{11} m^3 (16 to 40 trillion scf). Since hydrogen consumption in 1973 was only about 8 x 10 m^3 (3 trillion scf) Table VI-1, the potential for an order of magnitude increase in hydrogen consumption exists just for transportation needs.

Use of coal-derived substitute natural gas (SNG) is similarly a primary candidate for replacing natural gas since it can be used in existing distribution systems and end use devices without any modification to equipment. About 0.045 m^3 (1.6 scf) of hydrogen is required for each m^3 (scf) of SNG produced (Table VI-3). The FTFB projection for the year 2000 projects about 36 x 10^{18} J (34 x 10^{15} Btu) or 9.6 x 10^{11} m^3 (34 trillion scf) for natural gas consumptions (Table III-1). In the period after the year 2000 when natural gas is no longer available, this level of usage could be supplied by SNG and this would require about 1.5 x 10^{12} m^3 (54 trillion scf) of hydrogen.

Although relatively small quantities of synthetic fuels and correspondingly small quantities of hydrogen for manufacture of synthetic fuels in forecast prior to the year 2000, the potential requirement in this application area reaches major proportions as traditional petroleum and natural gas feedstocks are depleted.

3. Utility Applications [Salzano, 1974a; Michel, 1973; Hord, 1975]

Hydrogen can serve as a fuel for electric power generation. Its use results in low air-pollution and high efficiency in conversion devices such as fuel cells and turbines. Its use is predicated on energy storage for peaking power generation and energy transmission in gaseous pipelines. The energy storage application is based on using base-load equipment to generate and store energy during low-demand periods for use during high peak-demand periods. This allows base-load equipment to operate at a higher load factor and this improves overall plant economics.

a. Energy Storage for Electrical Peaking Power Generation.* There is an immediate requirement for economical energy storage for electrical utilities [American Chemical Society, 1974]. Since petroleum distillate and natural gas for peaking and intermediate-power are becoming very costly, there is strong economic incentive to employ large-scale energy storage so that off-peak baseload power can be stored and used for intermediate and peak load demands. The base-load power systems are generally comprised of larger, more efficient equipment which operate from less costly fuels. Thus, if low-cost storage can be provided, the base-power-storage combination for peak power demands could be economically advantageous.

Hydrogen energy storage concepts are being considered for their potential applicability within the utility industry. Hydrogen is of interest to utilities as a method of energy transmission and storage, as a marketable product, and for use in electrical peak-leveling systems [Burger, 1975; Fernandes, 1975; Parrish, 1975]. Recent considerations of hydrogen energy storage systems for electrical peaking power generation by Brookhaven National Laboratory and NASA-Lewis have shown that several hydrogen storage concepts are operationally and economically competitive with other major candidate systems.

(1) Hydrogen Peaking Concepts. Figure VI-4a illustrates the elements of a hydrogen energy storage system for electrical peaking power generation. The hydrogen systems discussed here presume the use of electrolytically generated hydrogen as the most viable process of production. A portion of the nuclear or fossil fuel base-plant off-peak power production is subjected to power conditioning where voltage step-down and rectification are accomplished. The low voltage dc is then fed to the electrolysis cells where hydrogen and oxygen are evolved. The pressure and temperature operating levels of the cell are not yet established. Regardless, hydrogen gas, and perhaps the oxygen gas, will be cooled, dehydrated, and stored for later use in a power conversion system. The various hydrogen peaking power systems are differentiated primarily by the methods of storage and power conversion.

The hydrogen storage and power conversion system permutations are illustrated in Figure VI-4a. In Figure VI-4b, hydrogen is used to generate electricity by using a hydrogen-air fuel cell or a hydrogen-air turbine and generator. For a hydrogen-air turbine, compressed air is introduced and mixed with fuel in the reaction chamber. Air is also mixed with the combustion products as a diluent to lower the temperature to a safe operating level in the turbine. For systems using hydrogen-air power conversion elements, only the hydrogen generated by the electrolysis cells is stored; the oxygen is vented or sold as a by-product. Hydrogen can be stored either as a gas, optimally at high 16.5 MN/m^2 (24000 psi) pressures, or as a hydride. Cryogenic storage for utility peaking power applications does not appear to be cost competitive. For gas storage, a set of manifolded pressure bottles would be required. In hydride storage, hydrogen is stored in chemical combination with a metal. While requiring further development, hydride storage permits safe storage at high densities. In both gas and hydride storage, conditioning prior to and after storage is required, with hydride storage requiring a more complex conditioning system (e.g., methods to heat the hydride material to evolve the hydrogen).

Other hydrogen peaking concepts employ both hydrogen and oxygen in their power conversion systems. These concepts are illustrated in Figure VI-4c. Hydrogen and oxygen generated by the electrolysis cells are conditioned and stored — the hydrogen as either a gas or hydride, the oxygen as a high pressure gas. Again, cryogenic storage does not appear to be cost competitive. The stored gases would be used to generate electricity by using a hydrogen-oxygen fuel cell or a hydrogen-oxygen turbine and generator. In a hydrogen-oxygen turbine, gases are burned stoichiometrically and water is used as a diluent downstream of the burning zone to lower the vapor temperature for use in the turbine. The resulting stream is then expanded through a conventional steam turbine.

(2) Alternate Peaking Systems. Figure VI-5 illustrates the functional elements for various types of alternate (non-hydrogen) existing and proposed peaking power generation concepts. The conventional gas turbine peaking system is shown in Figure VI-5a. Ambient air is compressed and mixed with fuel, and then burned in a combustor for subsequent expansion through a turbine-generator to produce peaking power when required. A compressed air-fuel peaking system is shown in Figure VI-5b. This a variation of the gas turbine system, which utilizes direct electric power from a base plant during off-peak periods to drive a compressor producing high pressure air, which is then stored underground. Potential underground storage sites include natural or excavated caverns, depleted fossil fuel reservoirs, aquifers, or even perhaps pressure vessels. A hydrostatic head may be added to the storage site to maintain constant pressure, thereby simplifying system design and aiding system efficiency. During peaking operation, the stored air and auxiliary fuel are introduced into a combustor/turbine to drive a peaking generator. A general class of peaking systems, which utilize storage of electrical energy directly from a base plant and subsequent direct conversion into electricity, with no requirement for auxiliary fuels, is shown in Figure VI-5c. In these concepts, off-peak electrical power is stored in electrochemical (batteries, redox) or mechanical (flywheel) devices, in magnetic fields (superconducting inductive coil), or in water reservoirs above or below ground. During peak demand periods, this stored energy is reconverted and introduced into the utility network for peaking electrical power.

The concepts shown in Figure VI-5d and VI-5e store energy thermally. Here, thermal energy from the base plant heat source is stored during off-peak periods in the form of sensible,

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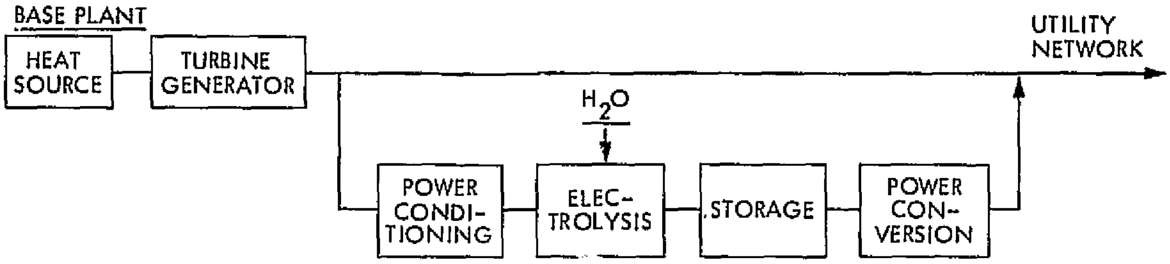
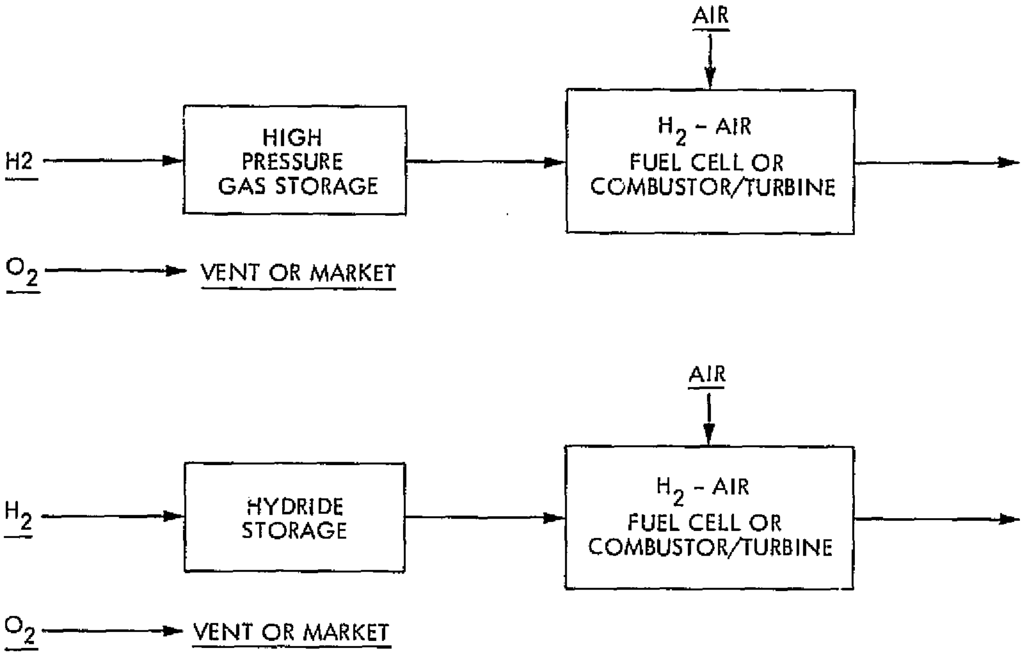
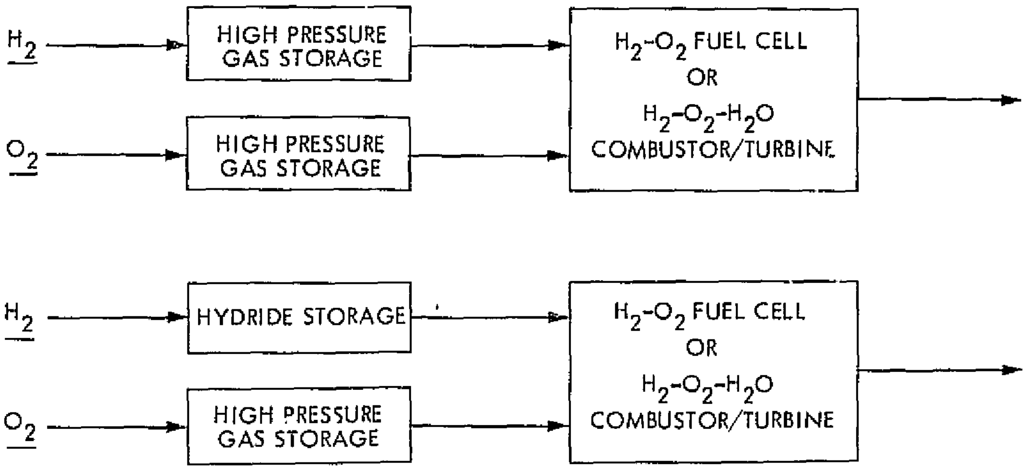
*By W. J. Masica, NASA-Lewis Research Center



a. Basic hydrogen peaking power system

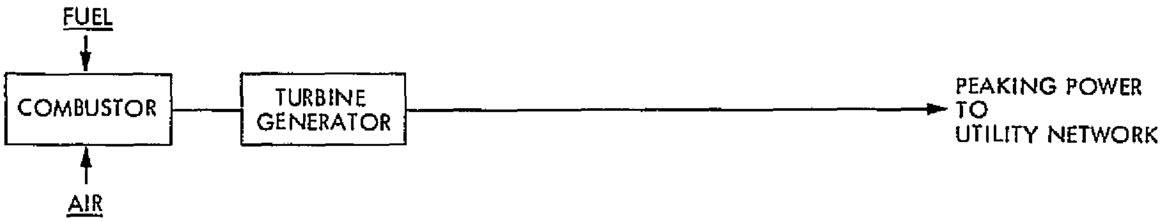


b. Hydrogen-air power conversion variations

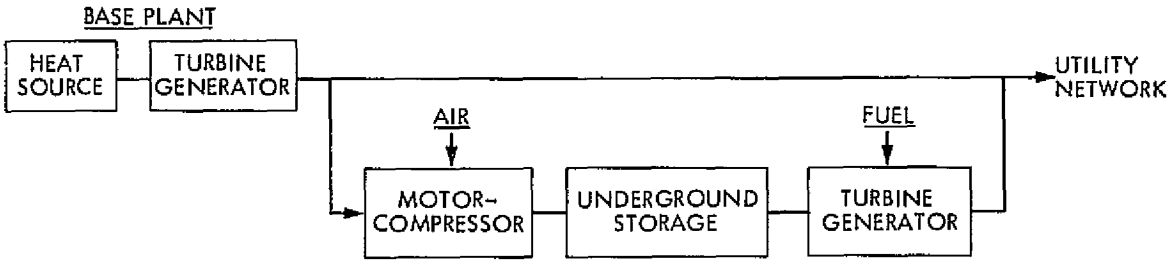


c. Hydrogen-oxygen power conversion variations

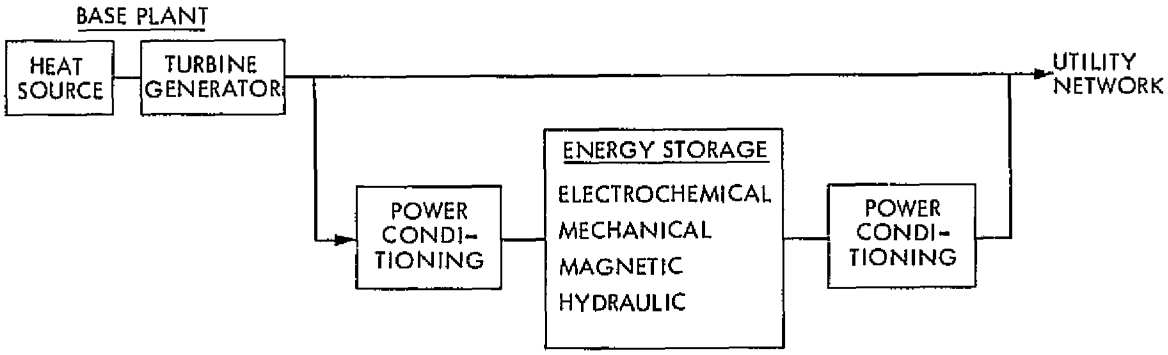
Figure VI-4. Hydrogen Peaking Power System



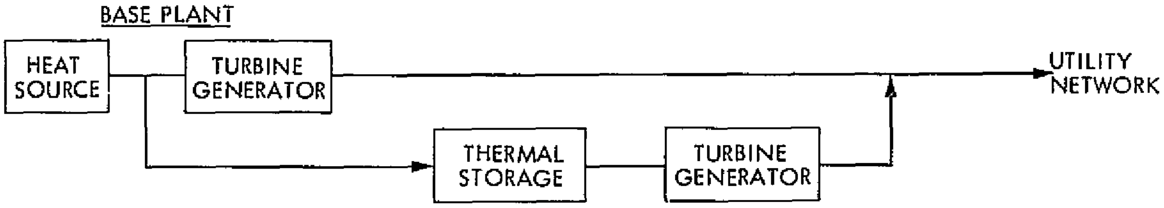
a. Gas turbine



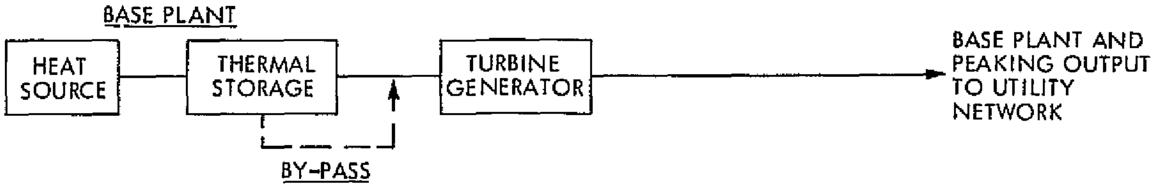
b. Compressed air-fuel



c. General electrical energy storage systems



d. Thermal storage with separate power conversion system



e. Integrated thermal storage system

Figure VI-5. Alternate Peaking Power Systems latent, or perhaps chemical heat. Potential storage media include steam, salt eutectics, hydrocarbons and hydrides. During peaking power demand, the stored thermal energy is used either in a separate power conversion system or to heat the increased working fluid flow in the base plant.

(3) Comparative Summary. These storage concepts represent generalizations of the serious contenders. Various comparative assessments of these concepts have been made; e.g., American Chemical Society Study, 1974; Ricci, 1975; NASA-LeRC, 1975. Other in-depth ERDA studies are currently in progress. The summary results of one such study are shown in Table VI-5. Despite some conflicting technical characteristics and projected cost estimates, a number of summary qualitative conclusions can be noted:

Technology Status – Gas turbine and pumped hydro systems are available today. The compressed air peaking system is the prime near-term contender. Lead-acid battery systems, at a high cost, could also be available in the near-term. Thermal energy storage systems are relatively simple and can be considered almost near-term, but they do require integration with the base load plants, a feature that might involve some degree of difficulty with certain utility systems. They are also probably limited to integration with new base load plants rather than being suitable for retrofit of existing base plants. Also relatively near-term might be the H_2-air gas turbine or H_2-O_2 steam turbine systems. Fuel cell, redox, and advanced battery systems represent technology requiring a longer development period. Flywheel systems and superconducting magnets are most likely the systems most removed into the future.

Table VI-5. Projected Characteristics of Major Electrical Energy Storage Systems

System	Maximum efficiency, %	Capital costs*		Development stage	Potential applications
		Cp, $/kW	Cs, $/MJ ($/kW hr)		
Mechanical Pumped-Hydro	70	60-90	1.2 - 3.3 (6-12)	Commercial	Central storage for peak shaving and load leveling
Compressed Air	75	90-100	0.8 - 5.6 (3-20)	First commercial system recently announced	Central storage for peak shaving and load leveling; reserve capacity
Flywheels	90	30-50	14 - 21 (50-75)	Initial development	Distributed storage; power factor correction; emergency capacity
Chemical Hydrogen (electrolysis plus fuel cell)	60	200-250	0.7 - 2.8 (2-10)	Advanced development of subsystems	Central storage with localized generation; combined gas/electric system
Electrolysis** (plus H_2-O_2/H_2O generator)	55	170-200	3 - 7 (10-25)	Conventional system ready for demo; high temperature requires advanced development	Storage for peak shaving and load leveling; reserve capacity
Batteries Lead-Acid	75	80-100	5.6 - 11 (20-40)	Examining possibility of advanced technology	Distributed storage; emergency capacity
Redox	75	100-200	1.4 - 2.8 (5-10)	Conceptual and laboratory studies	
Electromagnetic Superconducting Magnets	95	30-50	97 - 111 (35-400)	Initial development	Central storage

*Total capital costs = Cp + tCs where t = average hours per day of energy delivery from storage.

**NASA-LeRC assessment, 1975.

Source: Chemical Engineering, February 1975. Data from Brookhaven National Laboratory, Electric Power Research Institute, and Public Service Electric and Gas Company, New Jersey.

Fuel Requirements – Gas turbine systems and compressed air systems will require liquid or gaseous fossil-type fuels for their operation. This may restrict their ultimate application and use because of the attendant availability and cost uncertainties of these fuels.

Site Requirements – Pumped hydro, compressed air, and to a lesser degree superconducting magnet systems, may be restricted in their usage due to unique siting requirements. Thermal energy storage systems, by their nature, must be located at the base plant. The other systems appear capable of being sited closer to the load centers, thus not only being flexible in their application but also providing a transmission credit. Such a credit would, of course, require a more detailed economic analysis for a specific utility system.

Efficiency – The hydrogen systems, as a group, appear to have the lowest overall efficiency. Compressed air systems appear to be the best. Thermal energy storage systems have a range of efficiencies dependent on the available base plant temperature. Other system efficiencies are dependent on projected technology advances.

Modularization – The hydrogen systems, electrochemical systems (batteries and redox), and flywheel systems appear to feature the capability of modularization. Thus, large-scale commitments by a utility system would not be necessary at the beginning of an extensive program to add energy storage. Rather, smaller units could be installed, near urban load centers, as desired and feasible.

Costs – As might be expected, the advanced systems exhibit considerable cost spread because of development uncertainties. The gas turbine, compressed air, pumped hydro, and several electrochemical systems appear to have potential for overall minimum cost. In general, hydrogen storage concepts are cost competitive. Hydrogen combustion-turbine systems using high pressure gas storage are near-term contenders. If projected technology advances in hydride storage and fuel cells occur, hydrogen systems employing these elements would be cost competitive with other advanced systems.

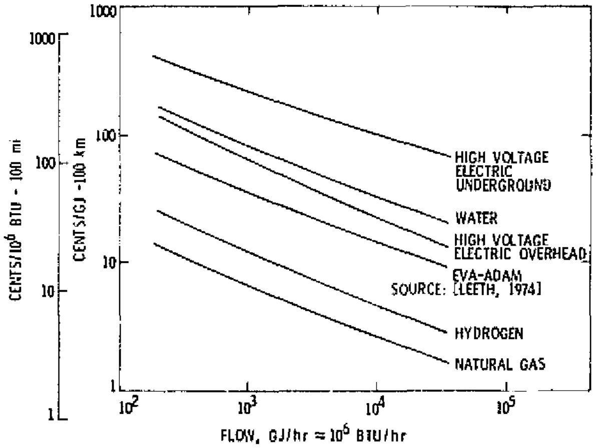
With the present state of technology in large-scale energy storage, it is difficult to establish which of the various systems are the most economically and technically attractive. Each system has rather unique duty cycle, operational, and application advantages. The dispatching of generated power by an electrical utility system is dictated by economic and security considerations. The objective of dispatching with energy storage is to supply total load at minimum cost and maintain adequate reserves to enable the system to withstand disturbances while anticipating daily, weekly, perhaps even seasonal, load demands and storage and peak leveling commitments. Specific conditions, appropriate to individual utilities but impossible to incorporate in comparative assessments, will ultimately determine the development and purchase of actual systems. Hydrogen systems do appear, however, to have a combination of features which make them attractive for further study.

b. Energy Transmission. Since hydrogen is not a primary energy source, it must be derived from other energy sources and raw materials. One of the major factors which could justify a step involving hydrogen generation is energy transmission characteristics. Gaseous pipeline transmission of energy, particularly large blocks of energy 3×10^{10} watts (10^{10} Btu/hr) in large diameter pipes .76 - 1.01 m (30-in./40-in. diameter) is a low-cost form of energy transmission as compared to both electrical overhead and underground transmission [Gregory, 1972].

Several authors [Konopka and Wurm, 1974; Reynolds and Slager, 1974; and Behgi, et al, 1974] addressed the problem of delineating an optimum system for pipeline transmission of hydrogen. One author [Leeth, 1974] projected costs to a 1985 timeframe and showed similar trends. His results are shown in Figure VI-6 to illustrate relative comparisons.

In order of decreasing unit transmission costs, the systems shown on Figure VI-6 are comprised of high voltage underground cables, hot water pipelines 422°K 827 kN/m^2 (300°F, 120 psi), "Eva-Adam" chemical heat pipe, hydrogen pipeline and natural gas pipeline. The magnitude of energy flow or throughput is seen to be a major parameter, since sizeable reductions in cost occur for all the systems as the energy throughput increases.

In the context of assessing the level and rate of implementing hydrogen energy transmission systems in the 1975-2000 timeframe, the primary alternatives are expected to be well-established systems; i.e., electrical and natural gas transmission. The present preliminary report will focus on these comparisons, since they bear on estimates of hydrogen demand.



SOURCE: [LEETH, 1974]

Figure VI-6. Energy transport costs (1985 dollars)

For transmission of power from central stations, [Gregory, 1972]indications are that transmission via hydrogen pipelines would be less expensive for long-distance transmission >322 km (>200 miles) even if the cost of electrolysis generation of hydrogen were included. Further indications are [Johnson Space Center, 1973] that even if hydrogen were reconverted to electricity at the use center, the cost could still be lower than conventional overhead electric transmission at distances over 1931 km (1200 miles.)

Costs of conventional ac overhead transmission tend to increase with distance due to requirements for reactive compensation. Recent advances in dc transmission, particularly the use of solid state ac-dc conversion equipment at the terminals of the high voltage dc line, indicate that dc transmission will be less costly than ac for distances of roughly 483 km (300 miles) or more [Bell, 1973] . When compared to dc transmission, the cost advantage of hydrogen pipeline transmission is largely offset by the equipment needed to (1) generate hydrogen (electrolysis) and (2) to reconvert hydrogen back to electricity (e.g., fuel cells). In fact, indications are [Bell, 1973] that hydrogen transmission will be more costly under some circumstances.

c. Fuel Cells.* In the context of an available supply of hydrogen, fuel cells can logically be considered for applications, such as urban central station, urban dispersed generation or rural. Inherent modularity plus a relative invariance in operating efficiency with cell load are the two characteristics which are the basis of the fuel cell's flexibility in generator size and siting location.

In large urban power networks, fuel cells could be installed at or near a hydrogen depot or terminal to provide efficient generating capacity with a minimum amount of gas distribution. On the other hand, if the capital cost and right-of-way problems commonly associated with urban transmission are the predominant factors in urban siting, fuel cells dispersed throughout the network could provide a viable system.

In rural electric systems, the excursions of the daily load profile can be expected to be much more pronounced than for urban systems because of a general lack of industrial load in these areas. Faced with this situation the rurals have the option of either purchasing high-cost peak power or operating at low, inefficient load factors with their own equipment. Also, the loads in rural areas are widely dispersed and thus the penalty paid for transmitting power from a central station over long transmission lines is high. Small fuel cell generator units dispersed throughout a rural net could impact both of these problem areas.

A block diagram schematic of a typical present technology fuel cell system is shown in Figure VI-7. The three major components of a fuel cell power plant are a fuel processor, the fuel cell, and the power processor. The fuel processor converts a fossil fuel such as natural gas or naphtha into a hydrogen-rich stream. The processed hydrogen reacts with oxygen from air in the fuel cell, converting chemical energy into electricity. The power processor converts the dc power to ac power at the desired frequency and voltage level. Direct use of hydrogen would impact both the fuel processor and fuel cell portion of this basic system. First, the fuel processing segment would be simplified or ultimately eliminated. It would be simplified for the situation in which coal were available to be gasified and in effect hydrogenated to form gases such as synthetic Methane which could in turn be supplied to an advanced technology fuel cell. It would be eliminated for the case in which electrolytic hydrogen and oxygen are generated for direct use in the fuel cell.

The use of fuel cells would be enhanced by the availability of pure hydrogen and oxygen reactants which can be expected to provide a significant improvement in cell performance. For example, an advanced technology molten-carbonate-cell operating on hydrocarbon fuels and pure hydrogen is expected to show a thermal efficiency of 46% at both full rated and 25% load for operation on hydrocarbons, while an efficiency of 50% is projected at full rated load and 56% at 25% load for operation on pure hydrogen.

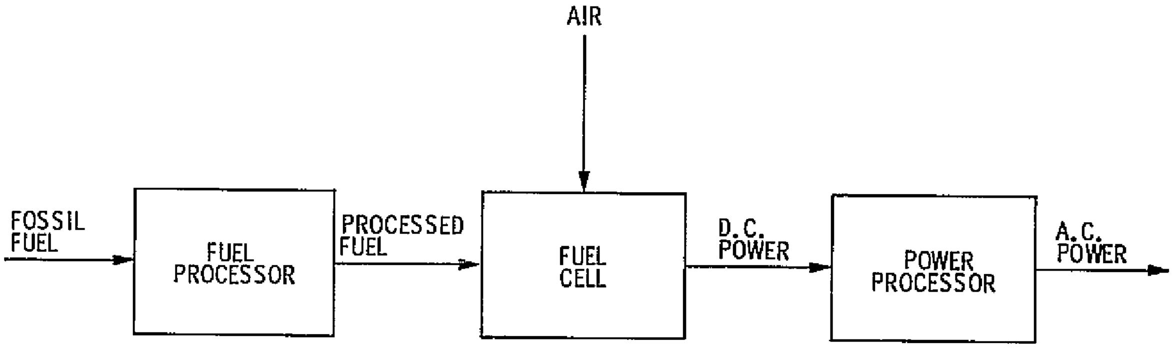


Figure VI-7. Schematic diagram of fuel cell power plant

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*Contributions from M. Warshay and P. Prokopius, NASA, LeRC

First in the classical energy storage scenario, off-peak power is used to generate electrolytic hydrogen and oxygen which are stored and then consumed in a fuel cell in a load-leveling or peak-shaving function (see Figure VI-8). For example, a Nuclear-Electrolysis path uses off-peak nuclear energy as the primary energy source supplying both heat and dc power to the water electrolysis unit. The electrolysis plant dissociates the water into hydrogen and oxygen which are stored for future use. Hydrogen could be stored by techniques similar to those used for natural gas; namely, bulk underground storage in mines or depleted wells, or cryogenically.

In addition to nuclear energy, many of the other primary energy sources expected to be in future use such as geothermal, solar, and wind would fit into the electrolysis energy storage scenario. For example, the solar path could either employ solar cells followed by electrolysis or the combination of solar collectors and a conventional vapor cycle to produce the required power for the electrolyzer. Since wind energy is available as shaft power, one route for wind-energy storage would be the electrical-electrolysis path. Geothermal energy could also fit into the electrolysis energy storage scenario.

Another possible electrolysis-fuel cell scenario lends itself to rural power application. In this case, electrolytic hydrogen and oxygen would be stored where they would be always available to be drawn upon by rural fuel cells. The primary source of this power would probably be a mixture of off-peak and baseload.

(1) <u>Technology Status</u>. Fuel cells for terrestrial applications can be arbitrarily categorized by operating temperatures: ambient to 473°K (200°C); 473°K-973°K (200°C to 700°C), and above 973°K (700°C). The low temperature range includes cell technologies such as the low temperature alkaline electrolyte, solid polymer electrolyte, and phosphoric acid electrolyte. The first generation of commercial terrestrial fuel cells will operate in this temperature range. The problems most common to the various cells which fall into this category are in the area of electrocatalysis.

In the intermediate temperature category fall the molten carbonate and molten alkaline electrolyte technologies. The major advantages to be realized by going to higher temperatures are: (1) decreased use or elimination of noble metal catalysts, (2) higher operating efficiency, (3) less stringent fuel processing requirements. The major problems to be reckoned with are of a materials nature; basically, to develop the materials which could assure long cell life in the severe conditions of high temperature and corrosive environment.

Solid oxide electrolyte cells comprise the high-temperature category. The advancement of this technology could provide the greatest payoff in terms of cell cost and operating efficiency; however, it can be assumed that the materials problem will be more difficult to overcome than for the intermediate range.

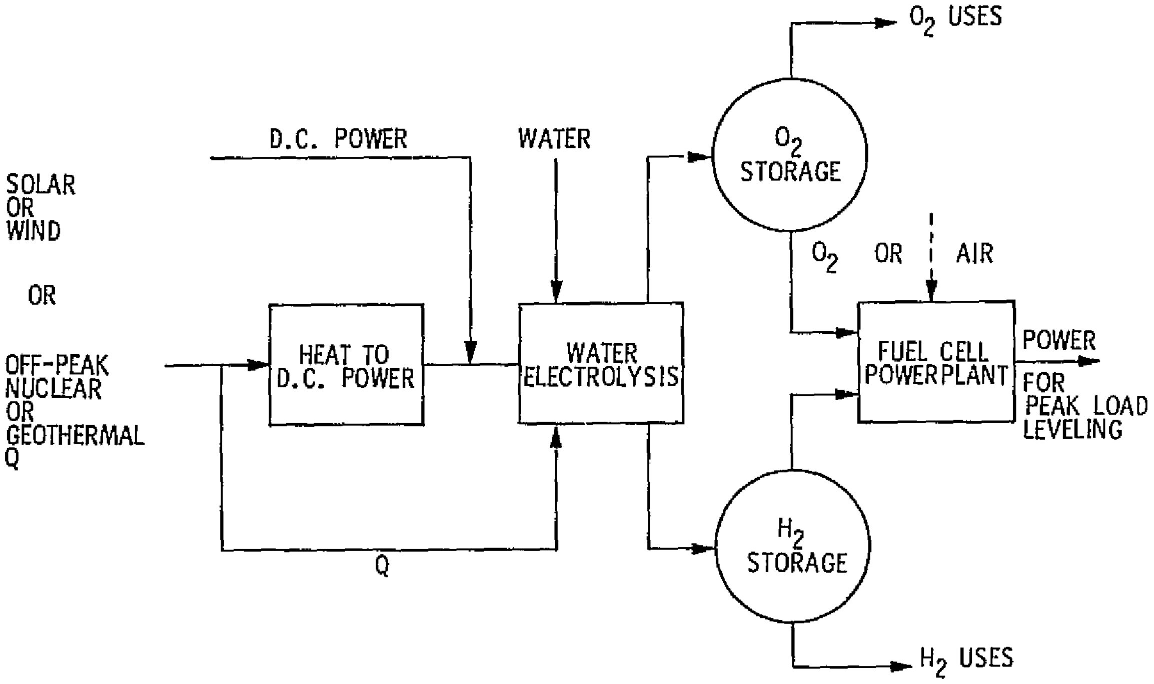

Figure VI-8. Energy storage concepts involving electrolysis and fuel cell

(2) Technology Requirements. All current fuel cells as well as all advanced fuel cells considered for utility applications will operate on pure H_2, and usually with better performance. So the problem is not developing a fuel cell that will run on H_2, but rather developing fuel cells to the point of commercialization where they become an integral part of the utility powerplant industry. To be sure, some fuel cell systems will be helped to a greater extent than others by the availability of pure H_2. A case in point for present generation fuel cells would be the alkaline fuel cell which has a greater initial performance than the acid fuel cell, but suffers severe degradation due to carbonation resulting from the CO_2 in the reactants. Avoiding CO_2 by use of pure H_2 and O_2 would therefore more greatly enhance the alkaline fuel cell. Among the advanced fuel cell systems, probably the molten carbonate fuel cell will be helped more by a pure H_2 fuel than the high temperature solid oxide fuel cell which, in most implementation scenarios, is integrated with a low Btu coal gasifier.

To fully realize the potential of fuel cells as an efficient energy conversion mechanism for use in hydrogen energy systems, it is necessary to strongly attack problem areas of electrocatalysis and materials problems.

d. Hydrogen-Fueled Gas Turbines.* Use of hydrogen as a fuel in highly developed gas turbine systems will greatly enhance its role in electric utility applications. Thus, a study was made to determine the characteristics of hydrogen-air fueled gas turbine power plants with ranges of power output from 10 MW to 200 MW.

A computer program available at LeRC was utilized for the purpose of screening a range of parameters and to determine power plant sizes and efficiencies. Three turbine inlet temperatures, two recuperator sizes, single shaft and dual shaft machines, were investigated. The results were then compared with those of a methane air gas turbine.

The results indicate that except for the combustor there are only negligible differences in the gas turbine machinery. Efficiencies for hydrogen-air will be slightly higher than for methane-air (or natural gas-air). For example, a comparative computer analysis was made for two 50 MW power plants, one fueled by hydrogen-air, the other by methane-air, both for 1478°K (2660°R) turbine inlet temperature TIT. The results are shown in Table VI-6. Hydrogen-air shows one-half percentage point higher efficiency and a small advantage in specific output. The two machines are nearly identical.

The technology for burning hydrogen efficiently is well in hand from experiences gained (1) in developing hydrogen-oxygen burning rockets and APUs and (2) more limited, but directly applicable, experience in developing hydrogen-air aircraft gas turbines. Materials data generated for the Space Shuttle program indicate that hydrogen embrittlement will not be a problem with the excess nitrogen present in the working fluid.

It would appear then, that the conversion of a natural gas turbine to a hydrogen-air turbine involves only the redesign of the combustor, and

Table VI-6. Comparison of Hydrogen-Air with Methane-Air

50 MW Power Plant
(2660°R) TIT
1478°K

Design Parameters	Hydrogen-Air	Methane-Air
Compressor stages	17	17
Compressor inlet diameter – (ft) m	1.33 (4.35)	1.34 (4.40)
Turbine stages	4	4
Turbine exit diameter – (ft) m	2.24 (7.35)	2.24 (7.36)
Air flow, (lb/sec) kg/s	150 (330)	152 (336)
Fuel flow, (lb/sec) kg/s	0.844 (1.86)	2.2 (4.8)
Turbine exit temperature, (°R) °K	908 (1635)	941 (1641)
Recuperation exhaust temperature, (°R) °K	682 (1228)	682 (1228)
Overall efficiency, percent	41.8	41.3
Heat rate (Btu/kWhr) J/J	2.396 (8171)	2.421 (8254)
Machine size, kW/(lb/sec)	152	148

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*Contribution from H. Camerson, NASA, LeRC.

the cost of either type of machine should be nearly identical. Therefore, in determining the viability of a hydrogen-air power plant, the economics of production, storage and transmission of hydrogen remains as the pivotal issue.

(1) Working Fluid Considerations. Hydrogen and air combine stoichiometrically at a weight ratio of 1 to 34.2. The products of combustion are mostly nitrogen, steam and some dissociated products. The combustion temperature is in excess of 3033°K (5000°F).

When practical turbine inlet temperatures are considered, excess air must be supplied. For the peak temperature of 1589°K (2400°F) used in these studies, the H_2/air ratio goes to 1/139 and to 1/200 for the lowest turbine inlet temperature of 1366°K (2000°F) considered here.

At these latter conditions, the combustion products and therefore the turbine working fluid are 75% nitrogen, 16% oxygen, 7% steam and 2% miscellaneous other gases such as argon, CO_2. At these temperatures, NO and NO_2 are a negligible 0.2% and 0.01%, respectively. The actual fuel air ratio is not only influenced by the turbine inlet temperature but also by the compression ratio and the regenerator effectiveness. The compression ratio enters into it because of the adiabatic heating which lowers the hydrogen requirements.

(2) System Studies. The power systems studied consisted of a compressor, one or two turbines, an exhaust gas recuperator, a combustor and a generator. Systems with two turbines are so-called two-shaft or two-spool machines in which the first turbine only drives the compressor. The exhaust of the first turbine is fed into the second turbine which drives the load. A portion of the exhaust energy of the load turbine is extracted in the recuperator and transferred to the compressor effluent before it flows into the combustor. A typical system schematic is shown in Figure VI-9. The system could be refined by adding compressor intercoolers, turbine reheat, and extracting additional energy from the exhaust, still at high temperature but atmospheric pressure. However, such refinements have not been considered in these studies.

In order to keep the analysis to manageable proportions, the initial analysis was made on two-spool machines. Two significant yardsticks in this economic-technical analysis are overall system efficiency and machine size (specific power). These were evaluated against each other with compressor pressure ratio and recuperator effectiveness and temperature as independent variables. Figure VI-10 plots percent efficiency versus specific power in kW/J/kg (lb/sec). Specific power is an index of machine utilization; the higher the better, consistent with good efficiency. Recuperator effectiveness of 0.7 results in a loss of overall system efficiency between 1 to 2 percentage points. Recuperated gas turbines currently in production incorporate exhaust gas recuperators with an effectiveness of 0.80. Experience indicates that effectiveness greater than 0.80 results in a disproportionate increase in recuperator size (i.e., cost) while a decrease does not result in any substantial saving. As can be seen, pressure ratios between 10 and 12 afford near peak efficiency without sacrificing greatly on specific power.

e. Hydrogen-Oxygen MHD Generators[*] [Seikel et al., 1974]. Magnetohydrodynamic (MHD) generators are advanced technology energy conversion devices that offer potential for high efficiency, particularly when used as a topping cycle for steam power plants. An investigation of hydrogen's compatibility with this advanced system was therefore undertaken.

This effort [Smith, et. al., 1974] was directed toward evaluating the potential performance of hydrogen-oxygen combustion-driven MHD power generators. Hydrogen was chosen because it possesses the highest energy content per unit total mass (fuel and oxidizer) of available fuels. It is therefore especially attractive for mobile applications where the operating time is sufficiently long that the fuel weight is large compared to the dry weight of the system. Hydrogen is also attractive for stationary power plants since it is relatively cheap coal derived clean fuel which is easily transported by gas pipe. It also possesses adequate power density when burned with oxygen and requires the least amount of O_2 per unit heat release of available fuels.

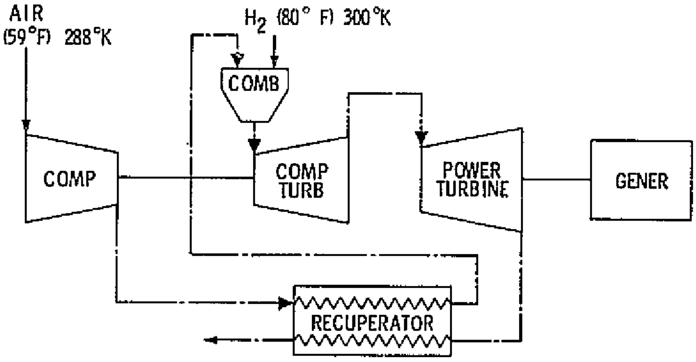

Figure VI-9. Typical hydrogen-air turbine power system schematic

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[*] Contributions from G. Seikel and J. M. Smith, NASA, LeRC.

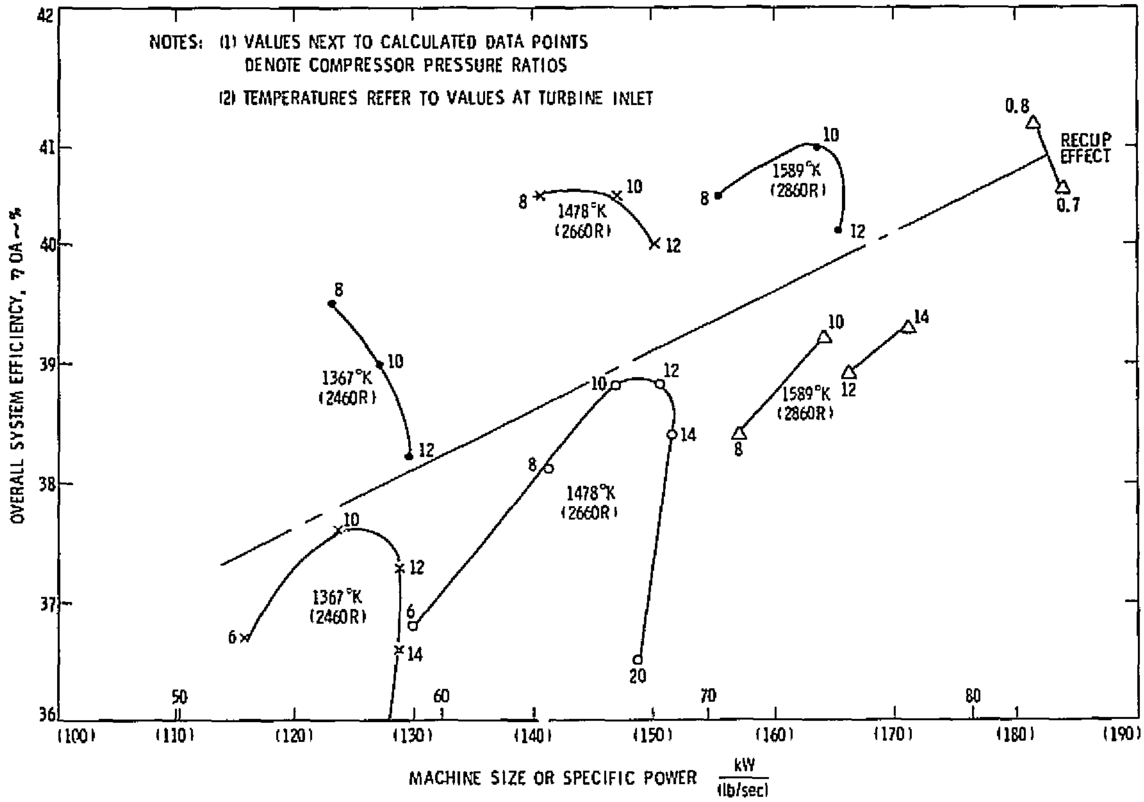

Figure VI-10. System efficiency versus machinery size for a 50 MW output using hydrogen-air working fluid-open cycle two-spool machine

Another advantage is that its combustion product, i.e., steam, is condensible and easily mated with existing steam power plants. A further feature of H_2-O_2 combustion is that it is pollution free.

Although hydrogen is an attractive fuel from a systems standpoint, it has some undesirable features for an MHD generator. The main undesirable feature is the lower electrical conductivity of the combustion products as compared to that of the higher C/H ratio hydrocarbon fuels. This is due to lower flame temperature, large electron collison cross section of water vapor, OH reaction with alkali metal seed material, and the formulation of (OH) ions. However, these limitations are partially offset by the lower molecular weight of the hydrogen combustion products which results in a higher flow velocity for a given Mach number. This higher velocity generates a higher Faraday voltage for a given magnetic field strength. This higher voltage may be particularly important in small mobile power plants where the large electrode and boundary layer voltage drops, 100-400 volts (see [Wu, 1973]), are a significant fraction of the total voltage generated. Unless these drops can be eliminated through more advanced MHD generator designs, hydrogen-fueled generators may have a significant advantage.

The H_2-O_2 steam MHD generator can be easily integrated into cycles using steam turbines. Figure VI-11 shows one such cycle. Four options for this power plant cycle were examined [Seikel et al., 1974]. In option 1, the H_2 O_2 and the steam diluent to the combustor are preheated to the steam bottoming plant temperature (839°K), the flow is expanded to a total pressure of .1 MN/m^2 (1 atm) in the MHD generator. In options 2, 3, and 4, 1500°K preheat is assumed and the expansion is to a total pressure of 0.1, 0.05, 0.01 MN/m^2 (1, 0.5, and 0.1 atm) respectively. All options except option 4 use a low pressure turbine to expand the flow to a pressure of 0.01 MN/m^2 (1/10 atm) before the steam is condensed. In Fig. VI-11 it should be noted that the re-pumped steam diluent is shown passing through a separate high-pressure steam turbine prior to the preheater. In reality this steam would be bled at the appropriate pressure from the steam bottoming plant. Likewise the exhaust steam from the MHD generator would be fed back to the steam plant after the seed recovery stage so that the low temperature and pressure steam turbine shown in Fig. VI-11 is an integral part of the steam bottoming plant.

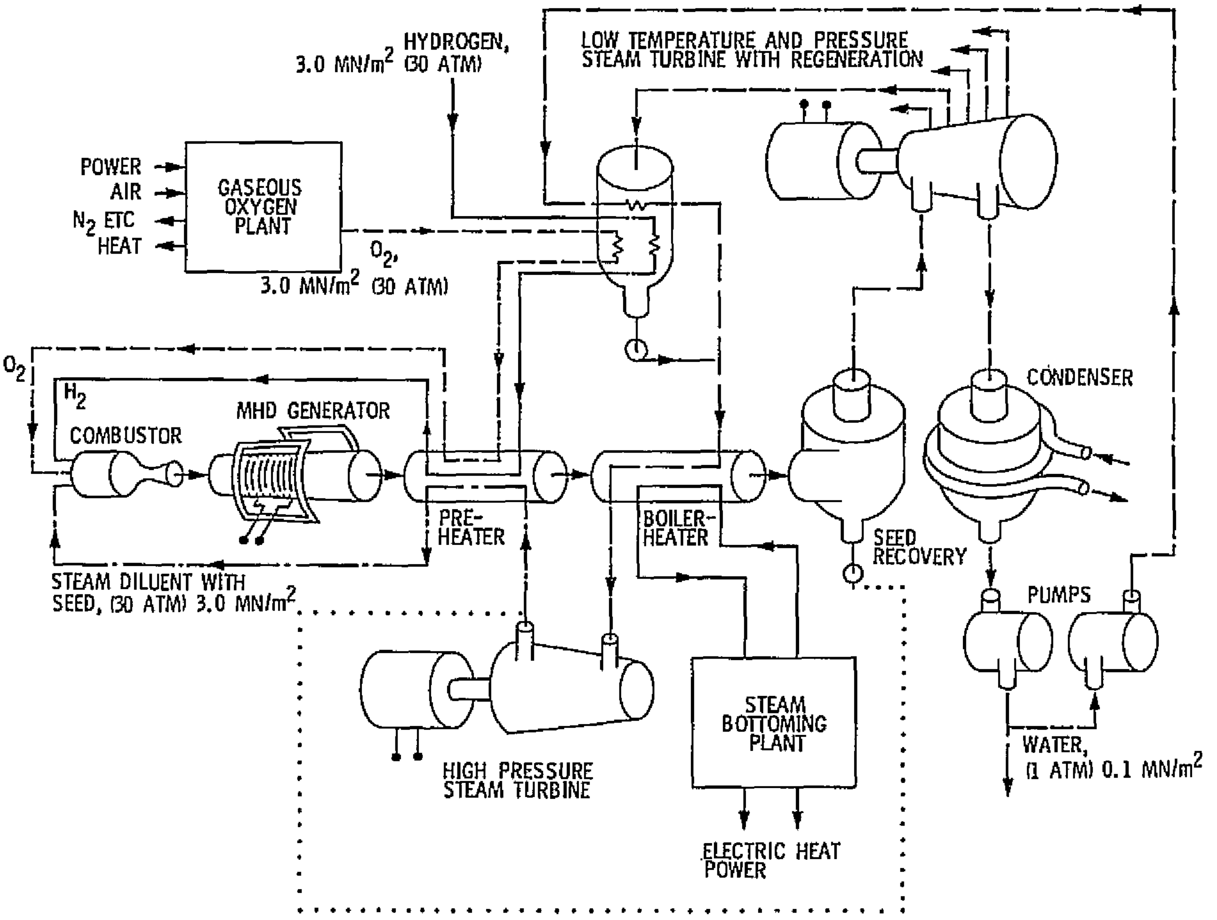

Figure VI-11. H_2-O_2 combustion steam MHD power plant

In all options the combustor is operated stoichiometrically at 3.0 MN/m^2 (30 atm) and 3468°K. To maintain this combustion temperature for the two different preheat temperatures the steam diluent flow is varied from 17% to 30% of the total MHD hydrogen and oxygen mass flow. The main purpose of the steam diluent is to increase the cycle efficiency by recycling more of the high quality MHD generator exhaust heat back through the MHD generator rather than dumping it as low quality heat into the steam bottoming plant. If the hydrogen and oxygen are preheated, the cycle efficiency is increased more by recycling water through the high pressure recuperative-boiler and turbine than by increasing the combustion temperature. As shown in Table VI-7., the gross efficiency of the high MHD expansion ratio cycle is 70% (using the higher heating value) for a preheat temperature of 1500°K. Thus, this steam MHD cycle has the potential for obtaining a net efficiency of over 60% after subtraction of the power required for oxygen production. Even without preheat the high expansion ratio steam MHD topped cycles offer the potential of over 50% efficiency.

f. Hydrogen/Oxygen-Water Turbine System.* Environmental restraints and the shortage of fossil fuels have forced the combustion engineer to concentrate on non-polluting, high-efficiency engines. From the basic combustion equations it can be easily shown that the ultimate non-polluting combustion process is one free of the oxides of nitrogen (elimination of air). Similarly, it can be shown thermodynamically (Carnot efficiency) that as the combustion temperature of an engine is increased the theoretical efficiency is also increased. The reaction of hydrogen and oxygen at high pressures produces combustion temperatures of approximately 3589 °K (6000 °F) and a sole exhaust product of steam (water). Consequently, a hydrogen-oxygen engine appears to be a logical energy conversion concept to explore in an attempt to satisfy the environmental restraints and fossil fuel shortage. Because this concept is not well developed in the open literature, it will be discussed in greater depth here.

A conversion concept as envisioned for electrical production is shown schematically in Figure VI-12, hydrogen/oxygen-water system

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*Contributions from L. Gordon and H. Cameron, NASA, LeRC.

Table VI-7. MHD power plant characteristics

Characteristics and Costs	Hydrogen-Oxygen Steam MHD				Coal-Air MHD Topped Steam
	Option 1	Option 2	Option 3	Option 4	
Combustion chamber					
Temperature, °K	3468	3468	3468	3468	2836
Pressure (atm) MN/m^2	3.0 (30)	3.0 (30)	3.0 (30)	3.0 (30)	0.8 (8)
Preheat temp, °K	839	1500	1500	1500	1473
MHD generator					
Expansion ratio	30	30	60	300	6.7
Max. magnetic field, T	6	6	6	6	6
Enthalpy extraction, %	31	31	37	47	23
Av. power density, MW/M^3	76	76	40	8.4	18
MHD power/net power	0.74	0.82	0.89	1.04	0.63
Steam power/net power	0.48	0.38	0.30	0.12	0.56
O$_2$ plant power/net power	0.21	0.20	0.18	0.17	—
Compressor power/net power	—	—	—	—	0.19
High temp preheater Thermal power/net power	0	0.31	0.27	0.26	0.52
NET EFFICIENCY, %	48	51	55	60	50

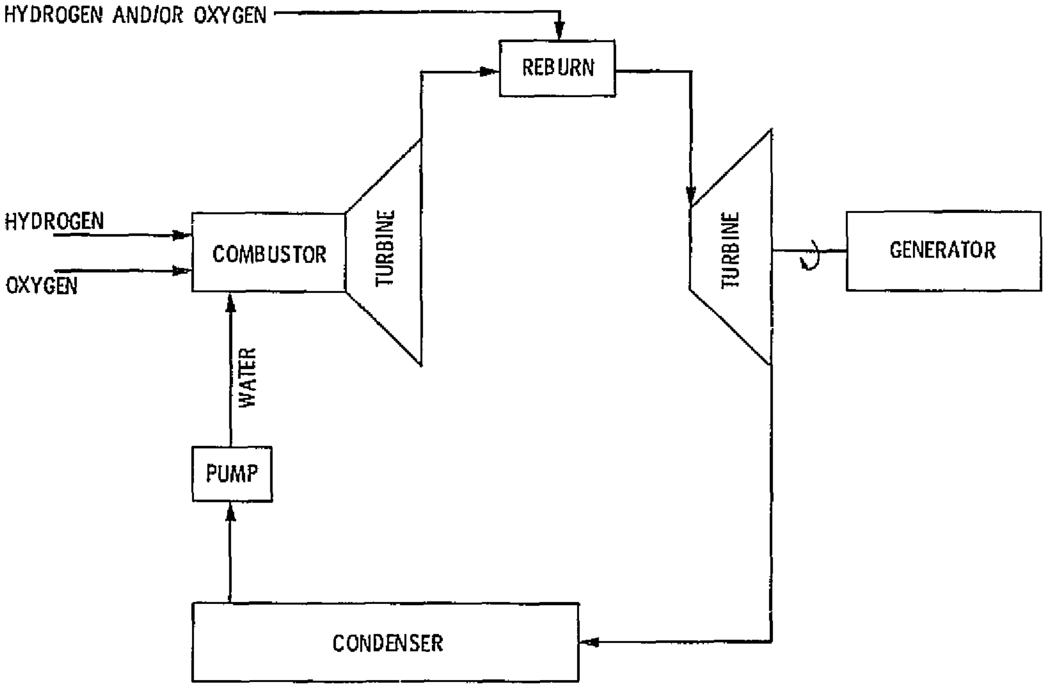

Figure VI-12. Hydrogen/oxygen-water system schematic

schematic, and involves the generation of steam by the stoichiometric combustion of hydrogen and oxygen [Hughes, 1969].

Water, as a diluent, is injected downstream of the combustion process to lower the combustion temperature to compatible turbine inlet conditions. This conditioned stream drives a conventional steam turbine (or advanced high temperature concepts) and generator to produce electric power. As this is a closed thermodynamic cycle, the hydrogen/oxygen-water system lends itself to another unique method of increasing performance. The system (Fig. VI-12) depicts a reburn at stoichiometric hydrogen/oxygen conditions rather than the conventional reheat method used by the utilities.

The use of a system similar to the above has many advantages, but also several questionable areas (possibly disadvantages) arise. As previously stated this concept is non-polluting and has the capability of high (≈55%) thermodynamic efficiency. In addition, the combustor is not a tube type heat exchanger (e.g., steam boiler) but a compact, direct heat input component. Estimates have been made [Skyline Magazine, 1972] which predict the present day 6-story fossil fuel boiler could be replaced by a hydrogen/oxygen-water combustor the size of an average living room. Workers in the area of a H_2/O_2-H_2O would also be pleasantly surprised as to the quietness of the overall system compared to the conventional coal grinders, the boiler furnace, etc.

The primary questionable areas are controls and combustion. The ability of the control system to maintain stoichiometric conditions and to follow the flow demand is not insurmountable but challenging. The combustor must insure that no non-condensables as well as temperature striations remain in the resulting (turbine inlet) flow field.

Overshadowing both the advantages and possible disadvantages is the overall cost of the conversion system. However, as can be readily seen, the hardware and materials of construction are not expensive, unique items. The important dollar factor in the cost breakdown would be the basic reactants; i.e., cost of hydrogen production.

(1) Applications. Specific applications of this concept for electrical production cover both continuous as well as intermittent power production. In other words, the hydrogen/oxygen-water system could be used as a baseload electric power system and/or a peaking electric power system. The concept is also potentially feasible for an unpredictable intermittent system such as solar-wind energy conversion (electric). In addition to the above, a potential market exists in the East and Mid-West States for boiler replacement units. Many of the utilities have equipment dating back to the early 1920s and 30s. In these units the boilers must continually be repaired, but the turbine-generators seem to be ageless. Consequently, by matching the turbine inlet conditions, a simple substitution of boiler for hydrogen/oxygen-water combustor could be made.

Applications of this concept could encompass more than electrical power production. Many non-electrical applications are feasible with the hydrogen/oxygen-water system. Shaft power as the output can be used for trains and other forms of transportation. The exhaust steam can be used for space heating of large building complexes. The high temperature and pressure exhaust could also be used to extract high viscosity oil (residual in most wells ≈300 billion barrels in U.S.) and/or entrapped oil in shale. Again, the compactness of the system lends itself to being lowered into existing wells.

(2) Component Discussion. As previously stated, combustor technology is one of the areas where experience and expertise exist. This is substantiated by the aerospace rocket technology programs [Calhoun et al., 1973]. Nevertheless, the primary function of the combustor is to maximize the energy release from the stoichiometric combustion process and then uniformly dilute the combustion product (H_2O) to compatible turbine inlet conditions.

A high energy release efficiency is difficult because now each oxygen atom must be combined with the two hydrogen atoms present. No oxygen-rich or fuel-rich conditions exist as was prevalent in the aerospace rocket engines. After this is successfully completed the diluent must be introduced to first cool the hardware, secondly, vaporize to cool the exhaust and thirdly, result in a uniform flow field. Geometry perturbations can solve the cooling and the uniformity problem. Common materials of construction can be assumed in all cases.

The degree of success of the above processes is represented by how closely the theoretical condition (Fig. VI-13), can be approached.

Preliminary H_2/O_2 combustor tests at LeRC have been made to establish the most promising avenues of approach to solve the above. However, another problem resulted during these tests - start transient effects. Severe temperature spikes during ignition could seriously damage downstream hardware such as turbine buckets, temperature control sensors, etc. Combustion problems, although minor in nature (no great hardware risk, etc.) must be successfully resolved before this system can be justly compared.

The present trend in turbine technology is to higher pressures and temperatures. As shown in Fig. VI-14, Turbine Pressure and Temperature Profiles, pressure has climbed more rapidly than temperature because of the inability of present steam-power plants to go to higher tube temperatures, the resulting limiting efficiency being approximately 40%. However, higher gas turbine inlet conditions are the state of the art and hence, a closed cycle hydrogen/oxygen-water combustor could directly generate the desired high temperatures. Some turbine designers advocate water cooled blades to permit higher inlet temperature. The compabitility of water cooling with this concept is obvious. Again, transient effects, turbine warm-up, and start-up specifications must be

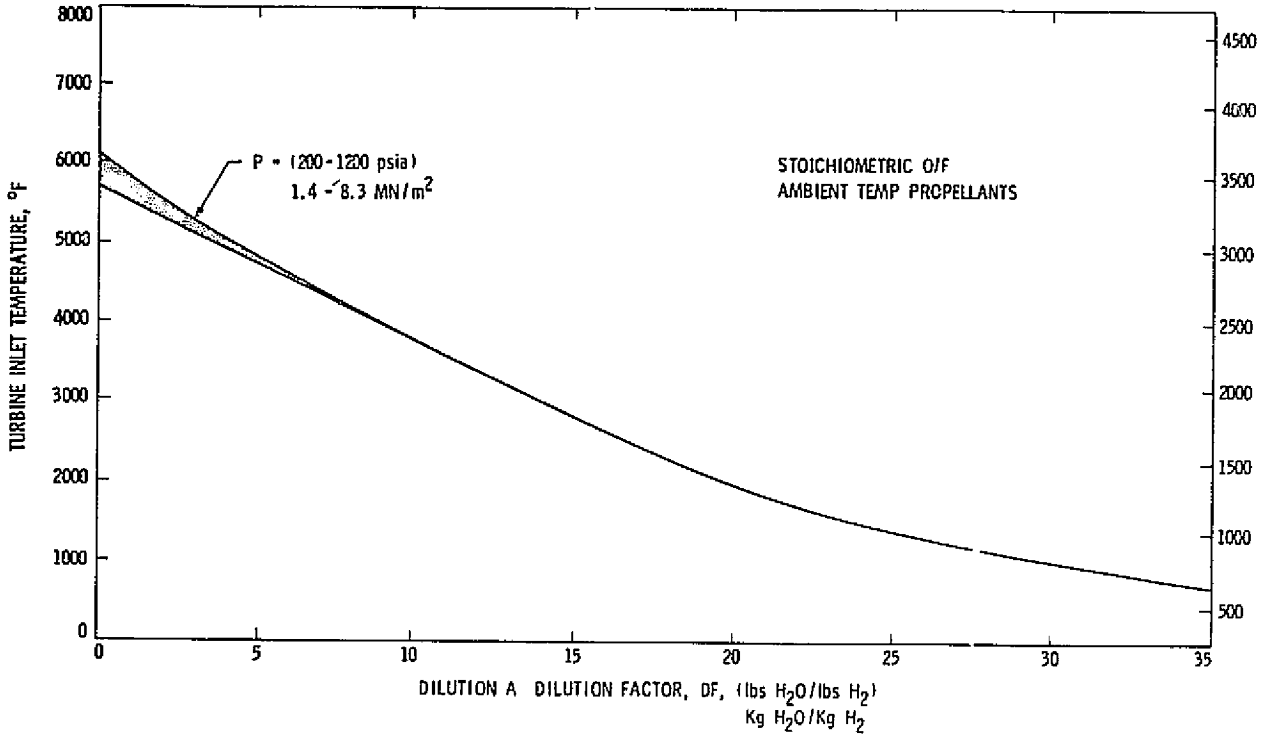

Figure VI-13. Theoretical performance of hydrogen/oxygen-water combustion

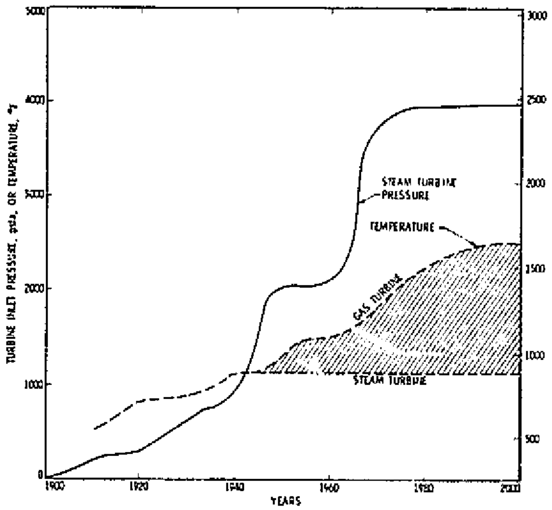

Figure VI-14. Turbine inlet temperature/pressure trends considered, but it is reasonable to believe that the turbine will not be a pacing item in this conversion concept for electrical production.

Similarly, the conventional ac generator is not expected to be a pacing technology item. It is interesting to note that generators are presently cooled by recirculating hydrogen gas. This relieves some of the hydrogen handling problems, etc. which the electric production companies would have to address with the subject system.

The control of a hydrogen/oxygen-water system will be complicated by the many feedback loops as well as the low-hydrogen flow rates in some applications. Turbine inlet pressure and temperature must be sensed and the corresponding control function made. Control similar to this has been done quite successfully in APU systems. However, these were small systems (≈300 kW) with a predominant hydrogen flow (oxidizer to fuel ratio = 0.67).

Combustion induced stabilities could possibly be induced by flow controlled shifts while attempting temperature control. Many of the control problems can be minimized prior to operation; however, there is no reason to believe that this control system will be any different from previous ones - considerable debugging, instability, etc. This again reinforces coupling control problems as the most troublesome; i.e., the type to be expected and solved in a prototype or systems demonstration.

(3) Fuel Requirements. Figure VI-15 graphically illustrates the trade-off between turbine inlet temperature and exhaust pressure versus overall thermodynamic cycle efficiency. This study was made at a turbine efficiency level of 80%. As previously stated, the overall efficiency (assuming a generator efficiency = 85%) dictates the fuel requirements shown in Fig. VI-16, Propellant Consumption vs. Power Output. Entering this graph for the proper efficiency level and the desired output, the amount of hydrogen and oxygen can be determined. This is necessary information for costing comparisons as well as storage capacity. The chosen turbine inlet temperature can be used in conjunction with Fig. VI-13 to estimate the diluent flow rate.

(4) Cost Discussion. A detailed cost analysis of this system has not been performed. However, it is anticipated that for all of the components (turbines, pumps, condensers, generators) the present day costs and projected increases as presented by utilities will be unchanged. For a 4 MW Steam Generator (LeRC test configuration) and the necessary controls, the cost estimate varies from \$20-\$35/kW generated. This is approximately 10% of the cost for conventional boilers. As stated previously, the real impact on this system is the cost of the fuel.

(5) Present Technology Areas of Concern. The technology areas of most concern are:

Reactant energy release and diluent mixing efficiency

Compatible turbine inlet conditions

Start up transient effects

Flow and temperature control

Hydrogen embrittlement

These items have been discussed in detail throughout the previous subsections; however, the hydrogen embrittlement area could be of concern.

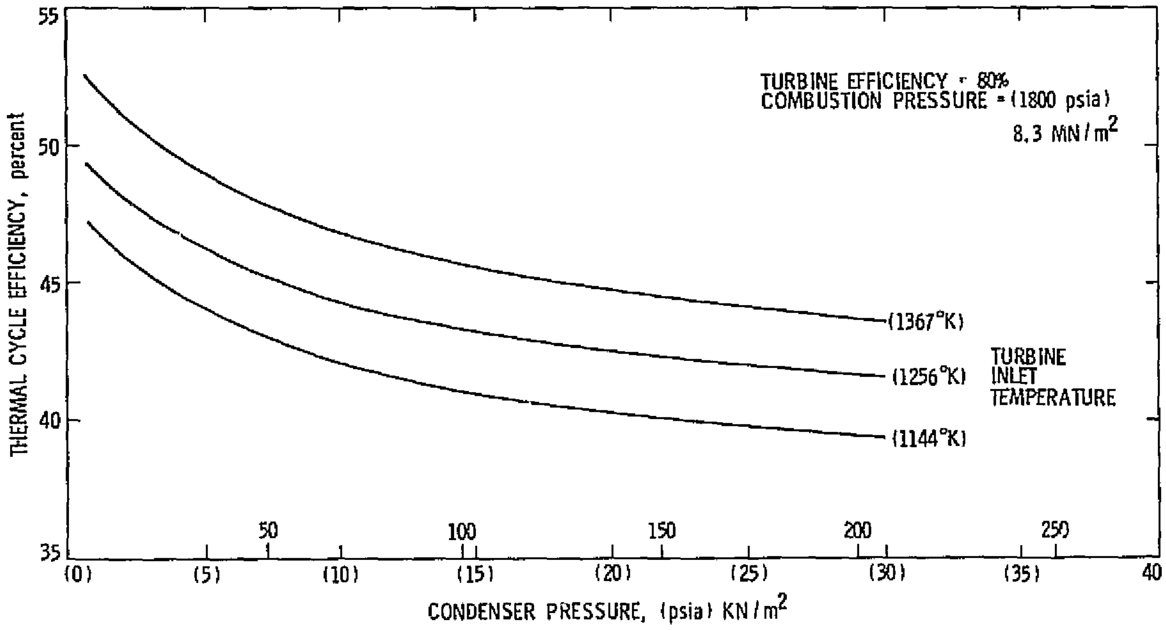

Fig. VI-15. H_2/O_2-H_2O cycle efficiency

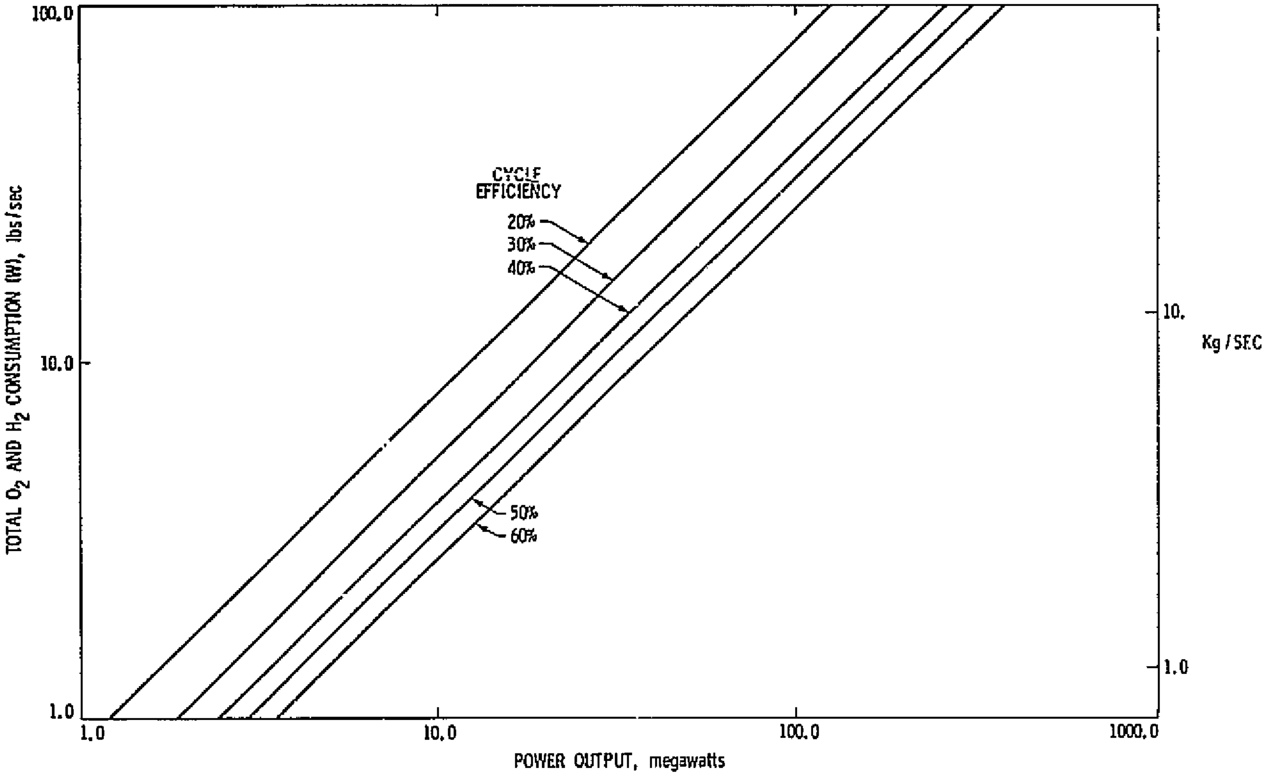

Figure VI-16. Reactant consumption vs. power output

Embrittlement is known to be a strong function of hydrogen purity (see Chapter VIII). The water diluent will certainly tend to eliminate embrittlement problems downstream of the combustor. Nevertheless, depending on the hydrogen production method (purity control) upstream feedlines may be weakened by hydrogen embrittlement. A more detailed discussion of materials not susceptible to embrittlement, etc. as well as more background information can be found in Appendix H.

(6) Future Component Uprating. What is the trend that is foreseen for turbine inlet pressures temperatures and efficiency? Figure VI-20 shows the past as well as the predicted trend derived from many sources. The important aspect of the trend is that turbine temperatures will be increasing (based on gas turbine technology), and pressures will be remaining at their present high level. The end result will be an increase in overall efficiency. Certainly this is consistent with energy conservation. The use of H_2/O_2-H_2O to produce these high temperatures can be done easily and within the environmental confines. Consequently, the use of this hydrogen energy conversion system for electrical production can be initiated without any serious technical obstacles such as no available material for specific component, etc., or the development of its associated turbine equipment.

(7) Technology Program. The interest in hydrogen-oxygen-H_2O combustion is rapidly gathering momentum as evidenced by recent stoichiometric experiments (MHD) and joint utility-aerospace projects for compact heat exchangers (Rocketdyne-Commonwealth Edison Co.).

The potential for large scale hydrogen usage that we are addressing perhaps will not appear as an economical and viable solution to the energy problems for some 10, 20, or even 30 years from now. However, the R&D for such a system could and should be undertaken now.

The research and technology program as presently envisioned consists of two parts. First, a basic research program is needed to explore the critical technology areas stated above. Then, consideration should be turned toward a subscale conversion system demonstration.

4. Reducing Agent [Industrial Heating, 1974; Blickwede, 1974; Shaver, 1975]

Hydrogen can serve as a reducing agent and the most prominent application appears to be iron ore reduction using mixtures of hydrogen and carbon monoxide. The usage of direct reduction methods is growing for the following reasons:

Economical operation in small sized plants (45×10^6 kg/year) (50,000 ton/year).

Avoids use of high grade coal or coke.

Process can use wide range of fuels including low-grade coals or natural gas.

Cost savings via use of lower cost fuels.

Improves output and economics of electric furnaces.

Reduced iron from process is easily stored, handled and transported.

Hydrogen can also be used alone for iron ore reduction in such processes as "H-Iron." These processes are not in general use, however.

Based on an analysis of the iron-steel industry involving factors such as facility costs, raw materials availability, and other complex interrelationships, the Futures Group [Fein, 1972] estimated requirements for hydrogen in iron ore reduction. These estimates are used in later sections as a basis for developing scenarios and projecting demands for hydrogen.

Other smaller reducing agent uses of hydrogen are discussed in earlier sections dealing with continuation of small quantity uses and industrial process heat. These uses include, e.g., metal reduction involving tungsten carbide and uranium oxide as well as reduction of silicon compounds by hydrogen in the manufacture of solid state components for the electronics industry.

5. Gaseous or Liquid Fuel

Primary potential uses of hydrogen as a gaseous or liquid fuel are:

Process heat for industrial applications.

Residential and commercial needs.

Energy for vehicular transportation.

a. Process Heat. The industrial sector is the largest energy user in the U.S., accounting for over 40% of the total primary energy consumed. This sector includes many diverse activities ranging from small consumer-oriented business to giant petrochemical complexes. Process needs are met in a variety of ways such as steam, direct furnace heat, electricity and fossil fuel feedstocks. The largest component of industrial energy is consumed in the form of steam, accounting alone for 17% of the total national energy use. The fuel requirements of industry are currently being supplied by natural gas (51%), oil (27%) and coal (22%). The significance of process heat requirements and sources has inspired many recent industry appraisals [Kinderman and Kopelman, 1974] over the past 10 years.

Because of certain advantages such as reduced steam generator sizes, minimum pollution control equipment, and possibilities of integration of power plants with process units industries would find special advantages in the reaction of hydrogen with oxygen for process heat (steam) if it were readily available at costs comparable to fossil fuels. Clean combustion of hydrogen could warrant a price premium above alternative fuels because of the advantages mentioned above.

However, there would be reluctance on the part of industrial users to switch to hydrogen for process heat needs in the absence of firmly committed supply at prices equal to or at most slightly above what they are willing to pay for traditional sources. Hence, it is unlikely that as long as fossil fuel sources are used for hydrogen production, hydrogen would be used as a gaseous fuel for process heat needs. In addition, to attract the process steam market, a ready supply of oxygen is also required.

Even though there are no significant technical restrictions to the use of hydrogen combustion as a source of industrial process heat, i.e., modifications of burners, etc., its use for this sector is primarily a question of supply and cost. In our "Reference" use projections, we have considered hydrogen's use for process heat and steam needs unlikely before the year 2000. Nuclear and solar heat can be used directly for process heat, and any energy supply scenario employing these primary energy sources would emphasize direct application of such sources. Since heat from these would be cheaper than hydrogen, alternatives to hydrogen such as utility steam systems, chemical heat pipes (EVA-ADAM) [Leeth, 1974], and others are likely to be more attractive for process heat and steam requirements.

b. Residential and Commercial Needs.* The combined residential and commercial usage of energy accounted for 30.6% of the total United States energy demand in 1970 [Johnson Space Center, 1973]. These results are further supported by 1972 data [National Petroleum Council, 1974] showing that 33% of the nation's energy (including allocated electric utility losses) was consumed in the residential/commercial sector. Primary end users in this category in order of decreasing usage are space heating, water heating, air conditioning, refrigeration, lighting and cooking. The residential sector accounts for 19.6% or approximately two-thirds of the combined residential and commercial usage [Johnson Space Center, 1973]. Residential demands have historically grown at the rate of 2.7% per annum. For the residential sector space heating, water heating, and air conditioning account for 88% of the energy demand. Energy sources for residential demands are comprised of fossil fuels (85%) and electrical (15%). It is unlikely that the electrical portion of the demand for lighting and electrical appliances will be supplanted by any alternative, at least in the 1975 to 2000 timeframe.

Technologically, hydrogen is implementable for residential use in any capacity requiring heat. It is suitable for air conditioning (by means of absorption cycles), heating, production of hot water, and cooking. Further, hydrogen can be used for lighting either directly using improved mantle design or by conversion to electricity through the use of fuel cells. The existence of the well-developed electrical distribution system, however, makes hydrogen an unlikely contender for light production

Since they are clean, quiet, possess no moving parts, and have reasonably high efficiencies, fuel cells are potentially suitable for production of electricity from hydrogen in the residential sector However, they presently require electrodes using critical materials, such as platinum, palladium, rhodium, or nickel. Further, they produce direct current and thus require a converter to produce alternating current for compatibility with the

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*Contributions from W.R. Downs, NASA, JSC and W.D. Powers, NASA, MSFC.

present electrical distribution system and appliances. Thus, it is unlikely that fuel cells will be used in large quantities in the residential area unless electrode technology produces breakthroughs in materials and cost, and low-cost converters of high capacity and reliability are developed [Austin, 1967].

Aside from presently used fossil fuels, there are other alternatives to hydrogen which could fulfill at least a portion of the demand. These are coal-derived synthetic natural gas (SNG) methanol from coal or industrial process by-product, electricity from coal and nuclear energy or solar energy. SNG could be used in existing natural gas systems, and methanol could be used in liquid petroleum systems with minor modifications. Solar energy systems appear to be viable particularly in the South and Southwest for at least a portion of the demand.

As present fossil fuels are phased out, the relative costs of these options in relation to hydrogen will determine hydrogen's role. The choice could depend on the local availability and price of coal, availability of low cost hydroelectric power, and level of solar insolation. This suggests that a mixture of energy systems could be used to meet the demand, with the decision resting on regional economic comparisons.

Space conditioning systems are compared in Table VI-8. The comparison is based on projected technology expected to be available in the year 2000. The technology projection encompasses [Davitian, 1974]:

> Electrical generation efficiency of 50% via coal-fired combined cycle power plants or nuclear HTGRs.
>
> Production efficiency of 65% for hydrogen, methane, and methanol from coal via advanced processes.
>
> Energy efficiency of 90% for advanced electrolytic production of hydrogen at elevated temperatures with external heat supplying part of the energy input.
>
> Efficiency of 70% for hydrogen-air fuel cells for stationary power based on development of alkaline fuel cell systems.
>
> Efficiency of 55% for fuel cell-reformer systems operating on methane or methanol.

For each of the systems, the assumed or projected component efficiencies are also shown in Table VI-5. For example, the component efficiency of catalytic combustion of hydrogen for heating is shown to be 90%. This value is based on recovery of about one-third of the latent heat of vaporization via use of condensing surfaces.

For the heat pump systems, the term "electric heat pump" refers to the conventional electric motor driven units. The term "gas heat pump" denotes a system where the electric motor is replaced by an engine fueled by either hydrogen or methane. The "fuel cell/electric heat pump" system involves supply of hydrogen or methane to a fuel cell which in turn produces electrical energy to drive an electric heat pump. It is felt that the gas heat pump would probably be more efficient and no more costly than absorption type heat pumps and for this reason absorption units are not included in Table VI-8.

The values reflected in Table VI-8 are sensitive to technology projections and other assumptions. However, the results are indicative of a future potential role hydrogen systems.

Although hydrogen systems can offer efficiency and operating cost advantages as compared to SNG in some cases, these advantages may not be sufficient to overcome the difficulties in implementing a hydrogen distribution network if SNG is also available. These difficulties are primarily economic because of large conversion costs necessary to change an already existing distribution and use network. Due to hydrogen embrittlement and other materials compatibility questions, some modifications of existing gas transmission and distribution systems will probably be required for hydrogen service. Additionally, end use devices such as water heater and cooking stove burners will have to be replaced.

Due to the considerations, it appears likely that hydrogen can only be introduced in a gradual manner with initial emphasis on new residential and commercial areas where the added cost and inconvenience of replacing existing equipment can be availed. A probable near-term implementation may be to follow the suggestion [Casazza, 1974] that up to 8% (by volume) of hydrogen can be mixed with natural gas without necessitating equipment alterations. This could stretch existing natural gas supplies or provide a means for overcoming seasonal shortages.

c. Vehicular Transportation. Vehicular transportation systems encompass a broad spectrum which has been subdivided into ground systems such as automobiles and trains; water systems including ships and barges; and air systems involving both subsonic and supersonic aircraft and space vehicles [Hord, 1975 and Singh, 1975]. Potentially, hydrogen in gaseous or liquid form can be used in all of these systems [McAlevy et al, 1974]. However, alternative fuels can also be used and the assessment of hydrogen's role must be conducted in this context.

One option among the alternatives is to produce a hydrocarbon fuel from coal that can essentially replace gasoline without changing the vehicle or powerplant. This approach preserves the large capital investment in the transportation sector and utilizes the existing established technological foundation [Dixon et al, 1974]

According to the recent studies [Meltzer, et al, 1974 and Kant, et al, 1974] the technology and cost of generating synthetic gasoline from coal appears to be reasonable and about the same as producing methanol from coal which is a developed process. Substantial quantities of hydrogen are required in the manufacturing

Table VI-8. Efficiency and operating costs of space conditioning systems [Source: Davitian, 1974]

System	Heating		Cooling		Component Efficiency* (%)			
	Net Efficiency (%)	Relative Operating Costs§	Net Efficiency (%)	Relative Operating Costs§	Primary Conversion	Fuel Cell	Heating Unit	Cooling Unit
Hydrogen								
Catalytic Combustion	e‡ 37 c‡ 53	2.70 1.40			electrolytic 45 coal 65		90	
Gas Heat Pump	e 60 c 88	1.60 0.80	40 58	2.40 1.30			150	100
Fuel Cell/Electric Heat Pump	e 85 c 120	1.10 0.60	85 120	1.10 0.60		70	300	300
Electricity								
Resistance Wire	45	3.0 6.1†			50		100	
Electric Heat Pump	135	1.00 2.00	135	1.00 2.00	50		300	300
Substitute Natural Gas (from coal)								
Combustion	44	1.60			65		75	
Gas Heat Pump	88	0.70	58	1.10	65		150	100
Fuel Cell/Electric Heat Pump	100	0.70	100	0.70	65	55	300	300

*Transmission/Distribution efficiency of 90% assumed in all cases.

†Underground distribution of electricity.

‡e = Electrolytic production, c = coal production.

§Relative cost of energy to transfer 1 GJ (1 M Btu) into (heating) or out of (cooling) dwelling. For comparison purposes electric heat pump is taken as the reference.

process and this will be discussed in a following section dealing with hydrogen's use in the manufacture of synthetic fuels.

The costs of manufacturing synthetic fuels are not firmly established and more in-depth studies are required. As the cost picture becomes clarified, more detailed trade-offs can be made among the various candidate fuels. It is quite conceivable that several of the synthetic fuels could be adopted for transportation depending on the application.

(1) Ground transportation. In assessing various alternate fuels for ground transportation it is essential to compare the fuels on the following basis:

Cost, availability, and production efficiency (see Chapter VII).

Economic and logistic compatibility with existing vehicle power plants and fuel distribution systems.

Effect on engine thermal efficiency.

Onboard storage characteristics as related to overall vehicle performance and cost.

Environmental aspects.

Overall safety considerations.

The alternate fuels considered herein are hydrogen, synthetic gasoline, methanol, methane, ammonia and hydrazine. Electrochemical batteries and fuel cells are also considered.

Commercial operation of trucks fueled by hydrogen was demonstrated over 50 years ago [Erren and Campbell, 1933]. Growing concern for the environment, coupled with the onset of gasoline shortages, has prompted a recent rebirth of interest in hydrogen-fueled ground transportation. As shown by recent automotive conversions to hydrogen fuel, there are no insurmountable technical problems in adapting ground transportation powerplants to hydrogen. Aside from the question of fuel availability, the major problems are onboard fuel storage and fuel distribution and refueling systems that would be required to implement hydrogen on a large scale. In making a decision on the use of hydrogen vis-a-vis other possible fuels it is important to first have knowledge of the parameters that affect their comparable performance.

When comparing alternate fuels, a most meaningful parameter is the efficiency of converting chemical fuel energy to work. Comparing the performance of hydrogen with conventional gasoline in similar engines provides a basis for assessment although such results are biased against hydrogen [McAlevy, et al, 1974] in that most comparisons involve only minor modifications to existing gasoline engines and hence they are still gasoline engines optimized for gasoline and not for hydrogen.

Recent data, comparing the automobiles fueled first with gasoline and then with hydrogen, are summarized in Table VI-9. The hydrogen fueled automobile had an efficiency of from 44 to 58 percent better when using hydrogen rather than gasoline. This stems partially from the wide flammability limits of hydrogen, which allows operation of the hydrogen-fueled engines at equivalence ratios far below stoichiometric conditions. Though, there is a loss in power associated with the lower equivalence ratios a great deal of normal driving is done at conditions of low power requirements, i.e., cruising. In a model described [Hord, 1975] sixty percent of the driving time is spent cruising.

The alternate fuels are compared in Table VI-10. Three methods are considered for storing hydrogen fuel onboard an automobile. They are: (1) as high pressure gas, (2) as a cryogenic liquid, and (3) as a metal hydride.

The first U.C.L.A. hydrogen car [Finegold, et al, 1973] utilized two compressed gas cylinders for hydrogen storage. Each cylinder weighed 136 kg (300 pounds) and held 1.4 kg (3 pounds) of hydrogen when pressurized to 41 MN/m^2 (6000 psi). The cylinders replaced the back seat of the car and the 2.7 kg (6 pounds)

Table VI-9. Efficiency comparison of hydrogen and gasoline fueled automobiles

Reference	Operating Conditions	$\frac{\text{Mi. per Btu } H_2}{\text{Mi. per Btu gasoline}}$ $\frac{\text{km/J} H_2}{\text{km/J gasoline}}$
Finegold, et al, 1973	GMC Proving Grounds	1.44*
	Average Operation (Grades up to 7%)	1.58
	Cruise 18 m/s (40 mph)	

*Gasoline mileage not measured, assumed 6376 km/m^3 (15 miles per gallon of hydrogen fuel gave the car a range of about 97 km (60 miles) — just enough to enter the 1972 Urban Design Vehicle Competition. (The U. C. L. A. car was declared "Overall Winner — Class I: Internal Combustion Engines".) Table VI-10 shows the relative weight and volume of various fuels and storage systems. The three hydrogen storage schemes are compared to a tank holding 0.07 m^3 (20 gallons) of gasoline. From the standpoint of both weight and volume it appears that vehicular storage of hydrogen in the form of a high pressure gas may be precluded with the exception of very specialized applications.

Onboard storage of hydrogen as a liquid has been demonstrated [Stewart, et al, 1974] and [Underwood and Dieges, 1971]. Since liquid hydrogen is a cryogenic, fuel tanks must be designed to minimize boiloff and the boiloff must be disposed of in a safe or useful manner. For a tank holding 3.8 kg (8.3 pounds) of hydrogen, it was found that if the internal pressure was allowed to rise 34-517 kN/m^2 (5-75 psi) as boiloff occurred the tank could remain unvented for two days [Billings, 1974].

Another study [Stewart et al, 1974] found that the boiloff was about one percent per day. Here, fabrication diffulties precluded the use of a high strength aluminum in the tank construction and internal pressure was limited to 207 kN/m^2 (30 psi). The authors indicated that use of high strength aluminum, allowing an internal pressure of 345 kN/m^2 (50 psi) would extend the tank lockup time to more than seven days. Venting boiloff from a liquid hydrogen tank is not only costly and inefficient, but potentially dangerous when vented in a garage. However, viable solutions appear to exist; e. g., a catalytic device could be added to the fuel tank whereby the boiloff could be oxidized into water vapor [Billings, 1974]. U. C. L. A. has demonstrated such a system.

A prototype vehicle (Billings)utilizes both a liquid hydrogen fuel tank and a metal hydride tank, where the liquid hydrogen tank boiloff is transferred to the hydride tank for storage and later use.

The hydride storage method, in which hydrogen is chemically bonded to metal atoms is

Table VI-10. Vehicular storage requirements of fuels

Basis: Energy equivalent of 7.6 x 10^{-2} m^3 (20 gal) gasoline 2.40 GJ (2.27 x 10^6 Btu) without end use efficiency considerations.

	Fuel Alone		Fuel + Container	
	kg (lbs)	m^3 (ft^3)	kg (lbs)	m^3 (ft^3)
Gasoline	54 (119)	0.0073 (2.59)	61 (134)	0.078 (2.76)
H_2 (gas) at 20.68 MN/m^2, 300°K (3000 psi, 80°F)	19.9 (43.9)	1.15 (40.6)	1021 (2250)	1.87 (66)
H_2 (liquid) at 0.1 MN/m^2 (1 atmos)	19.9 (43.9)	0.289 (10.2)	160 (353)	0.289 (10.2)
H_2 as MgH_2(a)	262 (577)	0.187 (6.6)	216 (697)(a, b)	0.334 (11.8)(b)
H_2 as $MgNiH_2$(c)	569 (1254)	0.396 (14.0)	649 (1430)(b)	0.544 (19.2)(b)
Methane (gas) as 20.68 MN/m^2, 300°K (3000 psi, 80°F)	47.9 (105.5)	0.351 (12.40)	227 (500)	0.782 (27.6)
Methane (liquid) at 0.1 MN/m^2 (1 atmos)	47.9 (105.5)	0.115 (4.06)	109 (240)	0.456 (16.1)
Ammonia (liquid) at 300°K (80°F)	129 (284)	0.203 (7.16)	206 (455)	0.379 (13.4)
Hydrazine	153 (338)	0.153 (5.40)	166 (367)	0.171 (6.05)
Methanol	118 (261)	0.149 (5.26)	129 (285)	0.161 (5.70)

(a) Assumes theoretical yield of hydrogen, density MgH_2 1.4 gms/ml.

(b) Includes 2.2 kg and 0.03 m^3 (5 lbs and 1 ft^3) allowance for heat exchange means and ancillary equipment to charge and discharge MgH_2 or $MgNiH_2$.

(c) Based on data from [Hord, 1975].

(d) Sources: [Kant, et. al., 1974], except for notes (b) and (c) above.

the most compact method known for storage of hydrogen. All the air is removed from a tank containing a suitable powdered or granulated metal, and then hydrogen, under moderate pressure is allowed to enter the tank and combine with the metal to form a hydride. The fueling process is exothermic and it was suggested that cooling ducts be attached to the tank for heat removal during refueling. Heat must then be added to the endothermic process of driving the hydrogen out of the tank when it is needed. It has been suggested [Billings, 1974] that the use of exhaust or cooling system heat to supply the thermal energy is needed for the process.

The hydride system would avoid the energy and added cost associated with liquefaction and would appear to be a feasible method for hydrogen storage. (The magnesium hydrides, though theoretically attractive from the standpoint of weight require additional research on basic feasibility regarding safety aspects of a severe crash and fire.) As stated, [Hord, 1975] hydride storage does not have an extensive history of development when compared to high pressure gas and liquid storage. Additionally, the ability to supply heat for liberation of the hydrogen, without compromising overall operational efficiency remains a moot question.

Two unanswered questions concerning hydride storage are whether or not sufficient heat at adequate temperature will be rejected from the engine to supply the necessary dissociation energy and how well the hydrides will perform after repeated use.

A detailed analysis of alternative automotive power systems (AAPS) and fuels has been conducted and reported recently by the Aerospace Corporation under EPA contract [Meltzer, et al, 1974]. Their results are summarized in Tables 11 and VI-12. In evaluating the potential of alternative non-petroleum based fuels for transportation, the energy source from which they are derived is a prime consideration. Sources available in the future will be coal, oil shale, tar sands, nuclear energy, and solar energy, while liquid petroleum and natural gas will be in continued short supply.

Assuming that the technical aspects of onboard hydrogen storage are within the grasp of future technology, the major obstacles to implementation of hydrogen fuel for automotive needs are fuel availability and the requirement of replacing the existing gasoline distribution and refueling system. From this standpoint alternate fuels such as gasoline derived from shale oil or syncrude from coal seem more logical at this time. However, when petroleum and coal become scarce and costly, hydrogen is a prominent alternate fuel for the following reasons:

> It can be made to produce essentially no air pollution except possibly for a very low level of oxides of nitrogen (combustion with air).
>
> It can be produced from water (essentially unlimited supply) and can be used as a substitute for nearly all fuels.
>
> It can be generated using almost any primary energy source (nuclear, solar, geothermal, etc.).

Thus, there is a large potential benefit for using hydrogen systems. To realize these potentials, further analysis and design or hydrogen fueled engine systems must be pursued. Development activity directed toward establishing viable on-board storage systems, fuel handling and distribution techniques applicable to the public sector, etc., is also warranted. Then, as petroleum and coal are phased out (some time after the year 2000), hydrogen can be implemented as appropriate. Unforeseen developments in the national energy picture could drastically alter the timing of this implementation.

Hydrogen technology is, however, involved in a potential interim solution to automobile engine problems of pollution and efficiency. This application, in which relatively minor modifications are made between the gasoline tank and the internal-combustion engine [Hoehn et al, 1974 and 1975; Jet Propulsion Laboratory, 1975] provides hydrogen associated advantages in combustion without the complications in fuel cost, supply logistics, and on-board hydrogen storage. Part of the gasoline fuel stream is catalytically converted to a hydrogen rich gas mixture which is fed into the engine with air and gasoline, permitting very lean combustion and reduced engine temperature. This results in improved fuel efficiency and drastic reductions in the emission of oxides of nitrogen and other pollutants.

Battery and fuel cell systems are possible future developments. Present batteries (lead-acid) are hampered by both low specific power (power/weight) and low energy density (energy/weight). This limits their usage to special purpose vehicles. Development of advanced batteries such as sodium-sulfur and lithium-sulfur can greatly expand the utility of electric vehicles and such development activity is underway.

Battery systems which operate at high temperatures (e.g., 673°K (400°C) for lithium-sulfur batteries) are presently being researched regarding materials problems (corrosion), thermal insulation and temperature control, etc. Thus, it is not expected that these batteries will be available for large-scale implementation prior to 1985.

Batteries for ground transportation appear to be possible by the year 2000. However, a wide-scale conversion will require major capital investments and changes in vehicular manufacturing practices. Thus, if synthetic gasoline is available, economic considerations would favor its use with existing technology. Electric propulsion could compete with hydrogen as a low pollution alternative for congested urban areas and other special purpose application.

Fuel cell powered vehicles have also been investigated by companies such as GMC and Union Carbide [Busi and Turner, 1974]. These systems employ fuels such as ammonia, hydrazine, and hydrogen. Use of exotic noble metal catalysts have resulted in high costs in relation to other automotive options and eventual viability will depend on development of less costly and less

Table VI-11. Summary of availability and suitability of alternative nonpetroleum-based automotive fuels [Meltzer, et al. 1974]

Fuels	Present Energy Source	Future Energy Source	Fuel Available in Limited Quantity (Near-Term Energy Source)	Fuel Available in Significant Quantity (Future Energy Source)	Future Suitability for Automotive Use	Research Gaps in Engine Application	Factors Inhibiting Fuel Use
Synthetic gasoline and distillate hydrocarbon	Liquid petroleum	Coal, oil shale	Pre-1985	Post-1985	Excellent	More engine data	Major factors identified
Methanol[a], Ethanol	Natural gas, liquid hydrocarbons	Coal, possibly solid waste	Pre-1985	Post-1985	Good, Fair	More engine data	Cost, performance, compatibility factors
Methane (CNG or LNG)	Natural gas	Coal, possibly solid waste	Pre-1985	Post-1985	Fair	More engine data. Resolve storability problem	On-board storage, distribution network
Propane, Butane (LPG)	Natural gas, liquid hydrocarbons	Coal	Pre-1985	Post-1985	Fair	More engine data	More expensive than synthetic gasoline and similar fuels
Hydrogen	Petroleum, gas, coal, water (by electrolysis)	Coal, nuclear (electrolysis)	Post-1985	Post-2000	Fair to poor	More engine data. Resolve storability problem	On-board storage, distribution network, safety
Ammonia, Hydrazine	Same as hydrogen	Same as hydrogen	Post-1985	Post-2000	Poor	Not worth pursuing	Toxicity, safety, cost
Reformed fuels	Liquid hydrocarbons	Coal, oil shale	Post-1985	Post-1985	Fair	More engine data. Development of fuel reforming	Cost and complexity

[a] Possible application when mixed with gasoline (methanol blend).

CNG = compressed natural gas
LNG = liquid natural gas
LPG = liquid petroleum gas

Table VI-12. Logistic factors for use of alternative nonpetroleum-based automotive fuels [Meltzer, et al, 1974]

Fuel	Est. Relative Cost at Pump $\$/10^9$ J ($\$/10^6$ Btu)[a]	Vehicle Storage	Toxicity	Safety	Compatibility with Petroleum Fuels	Status of Distribution to Consumer
Gasoline	1.0 (from coal) 0.83 (from shale)	Excellent	Medium	High fire hazard	--	Existing
Distillate	0.79 (from coal) 0.63 (from shale)	Excellent	Low	Low fire hazard	High	Existing
Liquid Hydrogen	2.22 (from nuclear electrolysis) 1.5 (from coal)	Poor	Low	High fire and explosion hazard	Low	Major development and investment required
Ammonia	2.42 (using hydrogen from electrolysis)	Fair	High	Moderate fire hazard	Low	Some experience in farm distribution. Major expansion required with emphasis on safety
Hydrazine	6.34	Good	High	High fire and explosion hazard	Low	Major modifications to existing gasoline system in areas of materials compatibility and safety
Methanol	1.07 (from coal)	Good	Medium	Moderate fire hazard	High if water contamination controlled	Existing gasoline system could be used with modifications to prevent water contamination and corrosion
Ethanol	2.48 (from organic waste)	Good	Low	Moderate fire hazard	High if water contamination controlled	Same as Methanol
Methane	1.20	Poor	Low	High fire and explosion hazard	Low	About the same problem as for Hydrogen
Propane	Greater than 1.20 (from coal liquefaction)	Fair	Low	Moderate fire hazard	Low	Limited availability at present. Requires extension

[a] Estimated relative cost per unit of energy for the Post-1985 Period, with gasoline from coal as the reference. Data are primarily from [Kant, et al, 1974].

poison-prone catalysts. Large-scale implementation by the year 2000 is not expected, due to major costs of converting existing technology as was the case with advanced batteries.

(2) Water transportation [Berkowitz et al, 1974 and Carhart et al, 1971]. Water vehicles generally operate away from heavily congested areas. Thus, air pollution will not be a strong factor in causing a shift to low-polluting fuels such as hydrogen. Water vehicles will generally be less sensitive to volume and weight problems as compared to automotive ground vehicles. However, a shift to alternate fuels will require large capital investments in terms of ship modifications and the establishment of a suitable fuel distribution network at harbors. Thus, petroleum and substitute synthetic fuels from coal or shale oil appear to be likely choices at least through the year 2000.

There are special purpose categories, such as military supply logistics, which could result in implementation of synthetic-fueled ships. Berkowitz, et al, recently conducted a study for the U.S. Navy at General Electric – TEMPO, Center for Advanced Studies in Santa Barbara, California. The objective of this study was to determine the effects that the use of hydrogen, and synthetic fuels derived from hydrogen, would have on the design and performance of Navy Ships and Aircraft in assigned missions. The concept studied entails:

> A factory ship or transportable, forward-based manufacturing complex which produces synthetic fuels such as hydrogen, ammonia, etc., from some primary energy sources, for example, nuclear, solar, etc.
>
> Operation of a spectrum of Navy ships using synthetic fuels generated by the transportable manufacturing complex.

The ships which have been selected for this study represent a range of types which might be found in use by the Navy between the present and the end of this century. They include hydrofoils, a surface effect ship, and displacement type hulls ranging from 2.3-559 x 10^5 kg (230 to 55,000 long tons) in weight. The aircraft include a vertical-, or short-, take-off and landing (V/STOL) type as well as a carrier-based attack (VA) type. Helicopters and other Navy types of aircraft have not been investigated in detail, but their estimated fuel requirements have been included in the analyses of those ship types which carry aircraft. The ships and aircraft modeled in the study represent generic rather than specific designs. The primary emphasis is on the comparison of fuels rather than ship designs.

The synthetic fuels considered in the study encompassed,

	Lower Heating Value	
	10^6 J/kg (Btu/lb)	MJ/m^3 (Btu/ft^3)
o Hydrogen (H_2)	120 (51, 600)	8524 (228, 600)
o Ammonia (NH_3)	19 (8, 000)	12, 892 (340, 800)
o Hydrazine (N_2H_4)	17 (7, 200)	16, 940 (454, 300)
o Methane (CH_4)	50 (21, 500)	20, 762 (556, 800)
o Methanol (CH_3OH)	20 (8,600)	15, 937 (429,400)
o Mixed Methylamines (MMA)	35 (15,100)	23,480 (629,700)
o Diesel fuel, Marine (DFM)	42 (18,200)	37,997 (1,019,000)

Usage of hydrogen and methane is based on their storage in the form of cryogenic liquids.

Since most of the synthetic fuels have lower volumetric heating values and lower densities, baseline vehicle size was enlarged to maintain operational performance characteristics. The degree of structural enlargement of the synthetically fueled ship is most concisely expressed as the relative volume of the modified ship compared to the baseline diesel fuel marine (DFM) fueled version. The gross weight was held constant by allowing the increased structural weight from the size increase to be offset by the reduced weight of the synthetic fuels. Ramification of increased size (e.g., higher hydrodynamic and aerodynamic drag) were accounted for in fuel consumption calculations. Performance level in terms of cruise speed was held constant.

The primary military objective in considering use of synthetic fuels via the concept of G.E. TEMPO Study is improved mobility. The following two basic factors affect mobility:

> Unrefueled range.
>
> Time required for refueling.

The unrefueled range is a function of ship design and fuel type whereas refueling time is governed mainly by the logistics of the fuel resupply system.

The findings of the study are summarized [Petzrick, 1975] as follows:

> Ships modified to operate on hydrogen, methane, or methylamines achieve ranges comparable to those of the same ships operating on DFM.
>
> Ships modified to operate on hydrogen, methane, or methylamine achieve approximately twice the range of the same ships modified to operate on methanol, ammonia, or hydrazine and consequently would have to be refueled only half as often.
>
> The dynamic lift ships, hydrofoils, and surface effects ships achieve a greater

range performance when using hydrogen than for DFM or any of the other synthetic fuels.

For displacement hulls in the 2.7-5.4 x 10^6 kg (3000 to 6000 ton) class, the ships modified to operate on hydrogen and methane achieve approximately the same range performance as that of the DFM-fueled ship.

For the 12.7 x 10^6 kg (14,000-ton) and a new concept 50 x 10^6 kg (55,000-ton) aircraft-carrying ships, greater range performance is achieved for the DFM-fueled and methane-fueled ship than for the hydrogen-fueled ship.

For the 36 x 10^6kg (40,000-ton) amphibious assault support ship, the range performance is approximately the same for the ship operating on either hydrogen, DFM, or methane.

Carrier-based aircraft modified to operate on hydrogen and methane, and assuming steady, level flight, would be expected to suffer approximately a 10% range degradation for hydrogen and a 5% degradation for methane. The use of the other synthetic fuels would result in greater degradation.

The results of this investigation indicate that liquid hydrogen and liquid methane used in dimensionally modified ships and aircraft are potentially equivalent to conventional fuels in mission performance capability. However, if the carbon to produce methane must be transported from a continental land base to the factory ship as coal, this logistic burden is within 15% of DFM tonnage required for direct use. Therefore, liquid hydrogen remains as the most promising synthetic fuel alternative.

The study leaves unanswered, however, the question of whether optimum design from first principles would result in significantly different vehicle designs and performance parameters. The research and development areas found to be critical to the improved potential of cryogenically fueled naval vehicles are fuel storage and handling and overall system design.

In the area of fuel storage, the metal hydrides appear to impose too great a weight penalty for beneficial application to naval vehicles. In addition, the dissociation rates may not be acceptable for application in power systems with high demand rates.

Liquid hydrogen appears to be the most desirable form for storing hydrogen although its requirement for a high performance insulation is a disadvantage for naval designers. Unlike the aircraft application where relatively short mission times at high consumption rates permit the use of less efficient solid insulations, shipboard applications will require the low-, or no-loss storage of large quantities of liquid hyrogen for extended periods of low consumption rate; this requires the application of higher efficiency vacuum-type insulations. These not only add to the volume disadvantage of hydrogen, but also require additional structure which invokes a weight penalty. Consequently, more development of better insulation systems and structural designs for the weight-critical dynamic-lift ships will be required.

The hazards of hydrogen are fairly well known as the result of investigations undertaken for aerospace programs of the 1960s. However, the combat environment imposes new unknowns which must be studied in greater depth before militarily-effective, hydrogen-fueled systems can be designed. For example, the storage of hydrogen in the hull of a ship can bring together all of the undesirable conditions of leakage, sources of ignition, and confinement under which hydrogen will detonate. When the risks of hostile weapons effects are added to this, the design of hydrogen systems for the combat environment becomes formidable.

Much further study of military logistics and the possible role of synthetic fuels is necessary before definitive conclusions can be drawn. Nevertheless, possible military advantages could result from some partial conversion of water transportation to hydrogen.

(3) Air transportation*. Air transportation systems that can potentially use hydrogen as a fuel encompass essentially the entire spectrum including subsonic aircraft, supersonic aircraft, and hypersonic aircraft. Hydrogen has a lower heating value of about 120 x 10^6 J/kg (51,600 Btu/lb) as compared to about 43 x 10^6 J/kg (18,600 Btu/lb) for fossil fuels such as jet fuel. This factor of 2 to 3 improvement in energy density results in lighter fuel loads for a given mission and overall vehicle weight savings, which translates into improved performance for airborne systems.

In general, the technology for hydrogen-fueled airplanes is available. The major deficiency identified so far is the lack of a suitable fuel tank insulation. The insulations that now exist would not be serviceable for the long life expected of commercial airplanes. Engine manufacturers have reported little need for research on hydrogen-burning engines, and that the development of hydrogen-fuel engines could proceed. NASA undertook a series of studies of liquid-hydrogen-fueled airplanes in 1971. These involved parametric calculations to establish broad trends and more detailed examinations of particular aircraft, most of the latter being done under contract. The most recent detailed results applicable to subsonic airplanes were obtained under contract for NASA Langley [Lockheed California and Georgia Co, 1975]. Passenger and cargo aircraft were studied but for brevity only the passenger designs will be discussed. The passenger aircraft designs selected in the Lockheed study are shown in Figure VI-17. The nearer of the two configurations shown represents the most

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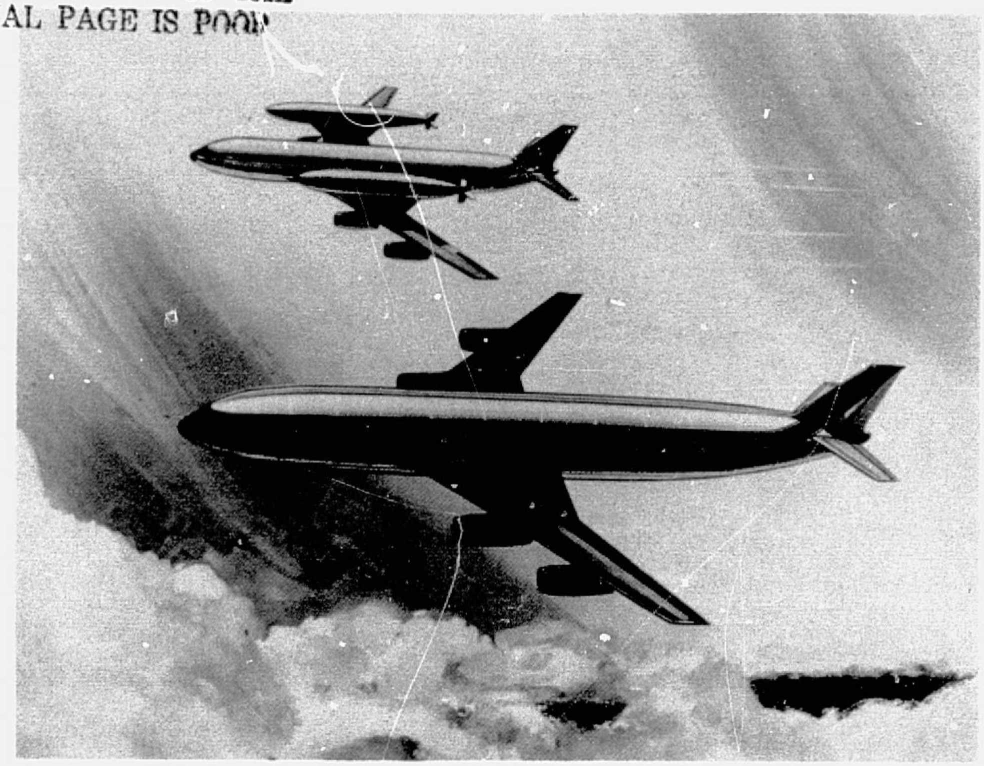

Figure VI-17. Subsonic liquid hydrogen airplane concepts
(Source: Lockheed California Company)

efficient design, which, however, has the disadvantage that the fuel is carried within the fuselage. The close proximity of the fuel to the passengers may be undesirable from a safety point of view. The vehicle in the background was found to be the most attractive of several configurations considered to eliminate this feature. It is, however, appreciably heavier and consumes 15% to 25% more fuel than the more conventional configuration in the foreground. The major characteristics of these two airplanes are compared with a jet-fueled airplane sized for the same mission in Table VI-13.

The conclusions of the <u>subsonic</u> airplane studies to date may be summarized as follows:

> The gross weight and fuel weight of hydrogen-fueled airplanes are much less than for conventional airplanes, with the differences increasing with range.
>
> Hydrogen-fueled airplanes use slightly less mission energy per seat km (mile), but the total energy consumed, considering the energy required for producing the hydrogen is greater. Again, for extremely long ranges (for which no detailed conceptual designs have been made) the parametric studies show the probability of overall energy savings.

A recent industry-funded study [Carline, 1975] indicates, however, that for a short-range liquid hydrogen-fueled aircraft of the DC9-30 class, the mission energy per available seat km (mile) is about 15% greater for the hydrogen fueled airplane than for the JET-A fueled airplane.

Studies, of varying depth, have been done on LH_2 fueled supersonic aircraft. A detailed study, done under contract for NASA, Ames, also by Lockheed Aircraft Corporation [Brewer, 1974] has assessed the potential for hydrogen-fueled supersonic transports. The aircraft design studied is shown in Figure VI-18. A comparison of the characteristics of two advanced supersonic transports, one using conventional JET-A-1 fuel and the other using liquid hydrogen, and having the same speed, payload and range, are shown in Table VI-14. Of particular interest are the following items:

> The takeoff gross weight of the hydrogen fueled SST is 50% of that of the JET A-1 fueled SST.
>
> The hydrogen fueled SST has a 13.3% payload fraction compared to 6.5% for the JET A-1 fueled SST.
>
> The hydrogen fueled SST requires only 70% as much energy as the JET A-1 SST to accomplish the same

Table VI-13. LH_2 configuration comparison [Lockheed, 1974]

(Range = 10,186 km (5,500 nmi) Mach = 0.85 400 passengers)

		External Fuel	Internal Fuel	Jet A Fuel
Gross weight	kg (lb)	198,100 (436,800)	177,700 (391,700)	237,273 (523,100)
Fuel weight	kg (lb)	37,000 (81,000)	27,900 (61,600)	86,500 (190,700)
Operating empty weight	kg (lbm)	121,500 (267,800	109,800 (242,100)	110,900 (244,400)
Wing area	m^2 (ft^2)	338 (3,640)	312 (3,360)	389 (4,190)
Sweep	degrees	30	30	30
Span	m (ft)	52.1 (171)	53.0 (174)	59.1 (194)
Fuselage length	m (ft)	60.0 (197)	66.8 (219)	60.0 (197)
F.A.R. T.O. field length	m (ft)	1,615 (5,290)	1,902 (6,240)	2,435 (7,990)
F.A.R. landing field length	m (ft)	1,771 (5,810)	1,771 (5,810)	1,588 (5,210)
L/D (cruise)		13.4	16.1	17.9
SFC (cruise) (mg/s)/N	$\left(\frac{lb}{hr}/lb\right)$	5.64 (0.199)	5.64 (0.199)	16.5 (0.582)
Thrust/engine	kN (lb)	172.4 (38,760)	127.6 (28,690)	145.4 (32,690)
Energy/seat mi.	J/seat km (Btu/AS NM)	931.6 (1.634)	706.4 (1.239)	789.0 (1.384)
Airplane price	$\$10^6$	30.2	26.9	26.5
DOC*	¢/seat km (¢/ASn mi)	0.689 (1.277)	0.583 (1.079)	0.545 (1.01)

*(LH_2 fuel cost = \$2.84/GJ = \$0.34131/kg (\$3/10^6 Btu = 15.48¢/lb, based on LHr))

(Jet A fuel cost = \$1.89/GJ = \$0.081/kg = \$65.52/m^3 (\$2/10^6 Btu = 3.68¢/lb = 24.8¢/gal))

task. It must be pointed out again that this energy does not include the energy required to produce the fuels.

In a recently completed study [LTV Aerospace Corp., 1975] a hydrogen-fueled Mach 2.7 SST (supersonic transport) carrying 292 passengers approximately 7593 km (4100 nautical miles) required 95% as much energy as its JET-A counterpart. This major difference is due to some extent to the difference in design philosophy of the studies.

Liquid methane, liquid hydrogen, and conventional jet-fueled supersonic transports, having a range of 7408 km (4000 nautical miles) and carrying 250 passengers are compared in Whitlow et al, 1973. The liquid methane SST used 88% as much fuel (Btu) as the conventionally fueled SST and the liquid hydrogen fueled SST used 80% as much as the conventionally fueled SST.

A comparison of the direct operating cost (DOC) of the subsonic and supersonic airplanes, which includes the cost of the flight crew, fuel and oil, insurance, depreciation of the aircraft, and maintenance, is shown in Figure VI-19 (Subsonic) and Figure VI-20 (Supersonic) as a function of fuel cost. The data in Figure VI-19 indicate that airlines using subsonic aircraft could afford to pay 42¢/GJ (44¢/10^6 Btu) more for LH_2 than for Jet-A without incurring an increase in their direct operating costs. For supersonic airplanes (Figure VI-20) they could afford to pay \$1.65/GJ (\$1.75/10^6 Btu) more for LH_2 than for Jet-A.

Liquid hydrogen fuel is essential to the hypersonic transport [Witcofski, 1972a and 1972b] because of the aerodynamic heat load associated with hypersonic transports. As illustrated in Figure VI-21, the heat-sink capacity of hydrogen fuel could make possible the active cooling of the airframe of a M = 6 transport, and permit the use

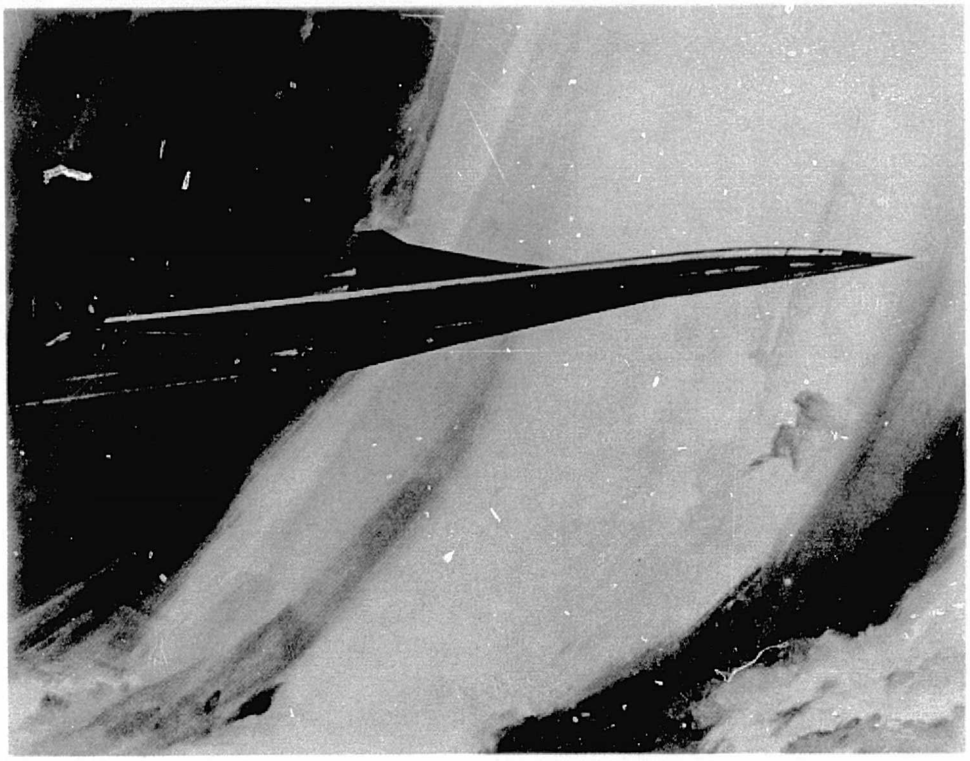

Figure VI-18. Supersonic liquid hydrogen airplane concept
(Source: Lockheed California Company)

Table VI-14. Comparison of jet A and LH_2 supersonic transport aircraft [Brewer, 1974]
(Range = 4200 nmi Mach = 2.7 234 Passengers)
7778 km

	LH_2		Jet A	
Gross Weight kg (lb)	166,900	(368,000)	340,000	(750,000)
Operating Empty Weight kg (lb)	101,200	(223,100)	140,500	(309,700)
Block Fuel Weight kg (lb)	36,940	(81,440)	147,800	(326,000)
Thrust per Engine kN (lb)	205	(46,000)	398	(89,500)
Span m (ft)	32.2	(105.6)	40.4	(132.5)
Height m (ft)	11.4	(37.5)	10.6	(34.8)
Fuselage Length m (ft)	100	(328)	90.5	(297)
Wing Area m^2 (ft^2)	639	(6880)	1005	(10,822)
L/D (Cruise)		6.99		8.5
SFC (Cruise (mg/s)/N $\left(\frac{lb}{hr} / lb\right)$	15.9	(0.561)	42.8	(1.51)
Aircraft Price ($\$10^6$) $\$10^6$		48.0		67.3
Energy Utilization kJ/seat Km (Btu/Seat nmi)	2437	(4274)	3479	(6102)

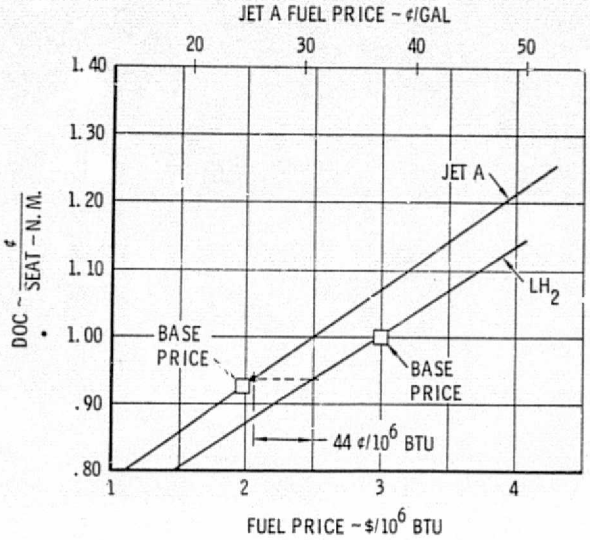

Figure VI-19. DOC vs. cost of fuel — subsonic airplanes (Lockheed Corporation, 1974) (all costs in 1974 dollars)

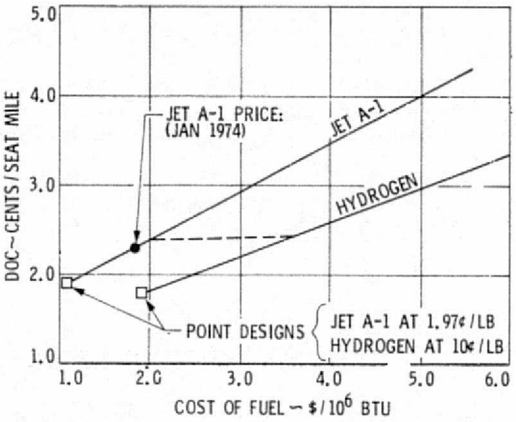

Figure VI-20. DOC vs. cost of fuel — supersonic airplanes (Lockheed Corporation, 1974) (all costs in 1974 dollars)

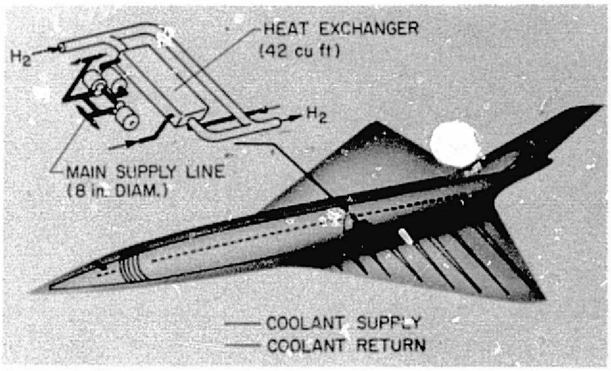

Figure VI-21. Hypersonic aircraft cooling system of conventional light-weight aircraft construction materials in place of heavier, high-temperature materials associated with a "hot" structure. This would also give designers more freedom to shape the airplane for aerodynamic excellence and the aerodynamic heat transferred to the fuel would also improve engine performance slightly. Calculations indicate that these structural insulation weight savings, when combined with increased engine performance, could yield a 70% increase in payload fraction for the actively cooled airplane, compared to a "hot" structure airplane.

C. REFERENCE HYDROGEN USE SCENARIO

The selected and well-established overall energy scenarios of Chapter III provide a framework within which a hydrogen use scenario can be formulated. This section presents such a "reference" hydrogen use scenario based on the FTFB energy future which is comprised essentially of continuing traditional and established uses of hydrogen as supplemented by hydrogen usage for synthetic fuel production (based on production estimates given in the FTFB energy scenario).

Potential or future uses of hydrogen presented in previous sections are examined in the context of alternatives to assess likely implementation. In general, energy futures showed continued primary usage of conventional, established energy sources through the year 2000 and this essentially defers large-scale implementation of hydrogen for new energy applications until after the year 2000.

The FTFB energy scenario and hence the counterpart hydrogen use scenario do not extend beyond the year 2000. Thus, the "reference" use scenario does not include future large scale new applications and in this sense constitutes a reference or baseline for hydrogen usage. Barring catastrophic occurrences, the usage indicated by the reference use scenario is considered to be a safe level, particularly since it is based mainly on applications where hydrogen is uniquely required.

The reference use scenario is basically formulated by establishing criteria for assessing the growth of traditional hydrogen applications as a function of each of the selected FTFB energy future. Then, new applications are examined by delineating a rationale for comparison with alternative systems.

1. Traditional Uses and Synthetic Fuel Production

The current uses of hydrogen are almost without exception primarily for unique chemical feedstock uses. As shown in Table VI-2, nearly half of the hydrogen consumption is in refinery operations while approximately one-third is for ammonia production. The remaining consumption is for a multiple of uses as shown in Fig. VI-3.

The reference scenario is simply based on determining the hydrogen which is implied in the selected FTFB energy future. This is the hydrogen used for which there appears to be no substitute at this time. For instance, each barrel of oil refined for use in this country requires a certain amount of hydrogen for desulfurization and other purposes. To project that so many quadrillion Btu equivalent of oil will be used implies that a certain amount of hydrogen will be needed. Thus, for each such category the hydrogen requirements are implicitly given by the chosen energy scenario.

The overall growth rate of all uses of hydrogen has ranged from 8.2% to about 13% in the recent past. If hydrogen used for petroleum refining is excluded, which grew at 20%, the remaining hydrogen uses grew between 4% and 8% or at a nominal rate of about 6%. This is about twice the overall growth of energy during this same time period.

The expected growth rates of future hydrogen uses are shown in Table VI-15 in a qualitative manner. Ammonia synthesis, which is the major nonpetroleum refinery use of hydrogen, is presently considered to have slow to modest growth due to near term market conditions but more rapid growth could occur in the long term due to anticipated use of fertilizers [Harre, 1974]. According to Table VI-2, ammonia consumption grew at a rate that varied between 5 and 9.3% based on the last 5 years or the last 9 years.

The approach taken in establishing the reference scenario is to estimate hydrogen consumption in all these varied uses and quantity hydrogen consumption in terms of uses specified or inherent in the scenario. This is done by separating current and projected uses of hydrogen into four broad categories:

Petroleum refining.

Other unique chemical uses:

- Ammonia, methanol, etc.
- Inorganic and organic chemical.

Synthetic fuel production:

- Coal processing to SNG (substitute natural gas).
- Coal processing SNC (synthetic crude).
- Shale oil processing to liquids.
- Tar sands processing to liquids.

Miscellaneous collected small uses.

The amount of hydrogen typically used for varied applications was previously shown on Table VI-3. These unit consumption values were used to assess hydrogen consumption implied by the selected FTFB scenario in each major area.

Table III-1 presents the amount of coal for synthetic fuels, shale oil, tar sands and the oil consumption that is built into each energy future. Using the data in Table III-1, the rate at which hydrogen will be used in each major area of synthetic fuel production is determined. The long

Table VI-15. Expected growth of current hydrogen uses
(Source: Articles in Chemical Engineering Journal)

Product	Precursor	Future
Ammonia synthesis	Nitrogen	Slow to modest growth
Methanol synthesis	Carbon monoxide and carbon dioxide	Modest to rapid growth, synthetic fuel
Hydrogen peroxide	Isopropanol; auto-oxidation	Modest to rapid growth
Benzene	Toluene	Benzene growth strong; this route favored
Naphthalene	Methyl naphthalene	Slow growth
Oxo chemicals	Olefin + CO + H_2	Strong growth
Aniline chemicals	Nitro chemical	Slow growth
Glycerol	Propylene	Slow growth
Cyclohexanone Cyclohexonal	Phenol	Modest growth
Adiponitrile	Butadiene	Rapid growth
Hexamethylene-diamine	Adiponitrile	Rapid growth
Cyclohexane	Benzene	Rapid growth
HCl	Chlorine	Modest growth, but byproduct will supply most of growth
Aliphatic amines	Ammonium salts of fatty acids	Steady growth

list of hydrogen uses in Unique Chemical and Miscellaneous Collected Small Use categories is assumed to grow at twice the overall energy use rate. This seems to be the recent historical experience (past 9 years). This is done rather than breaking out each of the multiple uses and estimating separate growth rates. The approach taken thus relates hydrogen use to overall energy growth. Therefore, using the growth rate specified in each energy scenario, the corresponding hydrogen usage is determined.

This is rather straightforward, but requires some interpretation for the FTFB model. In this model, the historic growth rate (over the past 20 years) of 3.4% is used. Energy conservation 69 x 10^{18} J (65 x 10^{15} Btu by year 2000) is anticipated and the actual energy used is the historic growth minus conservation. Therefore, the actual (net) energy growth is about 2% which is significantly less than the 3.4% historical growth. The Ford Energy Policy Project maintains that the effective use of energy is at the 3.4% level as far as the gross impact on the economy. The increasing of end use efficiencies is responsible for the conservation. Based on this logic, the effective growth rate of the Ford model is considered to be 3.4%.

The hydrogen used in petroleum refining is directly related to the FTFB energy scenario by using 53 m^3/m^3 (300 scf for each barrel) of crude used. This particular value is less than the 109 m^3/m^3 (610 scf) of hydrogen suggested in Table VI-3. This is based on the actual amount of hydrogen used over the past 9 years for petroleum refining. This number varied from about 14 m^3/m^3 (76 scf of hydrogen per barrel) in the mid 1960's to as much as 58 m^3/m^3 (328 scf of hydrogen per barrel) in the early 1970's. This composite number does not represent a particular type of crude in a specific refining process; but the average amount of hydrogen used on an annual basis in oil refining. The value of 53 m^3/m^3 (300 scf of hydrogen per barrel) is used as a good average over the last 5 years or so and is considered to be appropriate for the future.

2. New Energy System Applications

To assess and project the role of hydrogen energy systems, it is necessary to delineate alternatives and then compare these alternatives with the appropriate hydrogen system. This was done in the major application areas discussed previously. It is emphasized that these applications embrace new potential large scale uses for hydrogen. The present industrial unique chemical role for hydrogen is expected to grow at rates projected from historical trends. However, the viability of new uses, and the rate and timeframe of probable implementation will depend strongly on a comparison of hydrogen with other alternative systems.

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The basic groundrule adopted for comparing optional systems is economic competitiveness, i.e., decisions will be predicated on selecting the most economically viable or lowest cost option over the projected life of the system. Further, each option must be environmentally and socially acceptable and provisions to meet these criteria (e.g., emission controls, siting restraints, etc.) will be embodied in costs. Future projections of acceptable conditions, etc., are of course somewhat subjective and the assumptions used will be given where appropriate.

The selected economic groundrule tends to favor existing and well-established systems for the 1975 to 2000 timeframe, as long as they are viable in terms of resource availability. Further, energy systems must be well developed and thoroughly demonstrated prior to large-scale (nationwide) implementation and the twenty-five year period to the year 2000 is not very long in this context. Thus, even if significant implementation by the year 2000 does not appear probable for some new applications, it is understood that research and demonstration programs would be required if large-scale implementation beyond the year 2000 is contemplated.

a. Energy Transmission. Based on efficiency and cost considerations described previously, hydrogen transmission from power stations will probably not be warranted unless a substantial portion of the hydrogen is used directly for purposes such as industrial processes or commercial and residential applications. This would partially avoid the costly step of reconverting hydrogen back to electricity. In the period from 1975 to 2000, the FTFB energy scenario infers substantial usage of petroleum-derived fuel and natural gas for industrial and commercial applications. If these established fuels are available to operate existing well-developed equipment, the economic rationale infers that these existing systems will be used due to economic leverage in terms of existing capital investment and lesser technological risks.

A small quantity of synthetic usage is projected in the FTFB energy scenario. The main synthetic gaseous fuel alternative to hydrogen appears to be substitute natural gas (SNG). As evident from Fig. VI-6, natural gas (and/or SNG) is less expensive to transmit via pipelines. However, SNG is more difficult and will require more capital to manufacture from coal (primary source of synthetic fuels assumed in the FTFB scenario).

The basic logic inherent in the FTFB energy future is that synthetic fuels will be introduced gradually as they become economically viable in terms of the scarcity and increased cost of natural gas. SNG has the advantage of being a direct replacement for natural gas. Existing distribution networks and utilization equipment (furnaces, water heaters, etc.) can be used without modification.

Use of hydrogen will, in general, require some modification of equipment. Further, more research is required to establish conditions under which natural gas pipeline materials can be used for hydrogen service. A potential "hydrogen environment embrittlement" problem exists. There is evidence that this problem can probably be overcome by techniques such as oxide coatings, composite pipes, and addition of small quantities of impurities (e.g., oxygen) which tend to ameliorate materials problems.

As previously noted, hydrogen has the advantage of lesser air pollution and potential for greater efficiency via use in catalytic burners. It is also directly useable for industrial applications such as iron ore reduction, manufacture of ammonia, synthesis of other fuels from coal, etc. Further, after the year 2000 the depletion of fossil fuels (including coal) and/or the development of low-cost hydrogen production from water via advanced methods would make hydrogen a very viable option (in terms of present knowledge) for industrial and commercial/residential applications. At this point in the future, large-scale energy transmission via hydrogen pipeline systems appears to be a reasonable possibility.

For reasons given above, it is concluded that, in the context of the selected FTFB energy future, large-scale hydrogen pipeline transmission systems will not be implemented prior to the year 2000 and no accounting for this potential new application has been taken in the reference use scenario.

b. Energy Storage. Utility storage of energy via an electrolysis-hydrogen storage-fuel cell or turbine system is among the possible candidates being pursued. As discussed previously, there is an immediate requirement for efficient low-cost energy storage systems to more effectively utilize existing electrical generating capacity. Thus, it is conceivable that utility usage of hydrogen for storage would be implemented on a significant level prior to the year 2000. However, the extent of usage is uncertain and many viable candidates exist. Thus, in the framework of a safe or reference level of implementation, no note is made of hydrogen usage in utilities for storage.

c. Process Heat. Following the rationale that well-established techniques will continue to be used as long as they are economically viable, it follows that industrial process heat requirements will be met by conventional equipment using fuel oils, natural gas, and coal until these sources become unavailable or overly costly. Processes which now use natural gas (in shortest supply) may switch to fuel oil when and if natural gas becomes sufficiently costly that a change can be economically justified. When fuel oil becomes scarce and costly, coal or coal-derived fuels will be used.

Hydrogen is one of several synthetic fuels that can be derived from the reaction of coal and water (coal gasification). Substitute natural gas (SNG), low Btu gas, etc., are other gaseous fuel options. Hydrogen appears to be easier and less costly (lower capital investment) to produce in comparison to SNG, but it is more costly to transmit and existing developed equipment for natural gas may have to be modified. Hydrogen generally produces less air pollution and would probably have a cost advantage in terms of reduced requirements for pollution control devices.

Hydrogen can be produced from nuclear energy via water electrolysis. Advanced thermochemical methods, biological methods, etc., are also possible future methods for producing hydrogen. Thus, hydrogen can be supplied even in the absence of fossil fuels. If the economic trade-off between hydrogen and synthetic fuels from coal is close, the flexibility in supply options would favor hydrogen. Of course, if the non-fossil fuel options were developed to the point of being less expensive than coal-derived fuels, these options would be used instead of coal processing [Johnson Space Center, 1973].

In the context of relatively abundant coal availability in the 1975 to 2000 timeframe and the development effort presently being directed toward producing SNG via coal gasification, it is unlikely that hydrogen would completely supplant SNG or other synthetic fuels from coal. Thus, for industrial process heat applications, no credit for hydrogen usage is assumed since this would maintain a safe level for the reference scenarios. As noted previously present use of hydrogen for process heat is insignificant.

d. Residential and Commercial Needs* [Johnson Space Center, 1973]. Hydrogen and other synthetic fuels are potential candidates for the bulk of the energy (85%) presently being supplied for residential and commercial needs by fossil fuels such as natural gas, fuel oil, etc. However, as long as present fossil fuels remain in reasonably good supply, economic factors will probably dictate their continued use for the bulk of the demand. The reference hydrogen scenario is formulated on this premise. Due to assumed primary reliance on petroleum and natural gas (and nuclear energy-electricity in the NEE projection), only a relatively small quantity of synthetic fuels is projected in the year 2000.

It is felt that space conditioning of buildings using hydrogen as a fuel may become viable after the year 2000. If and when hydrogen is used on an extensive scale in industrial process applications, there will be pipeline systems and sufficient production to warrant commercial and residential applications.

Until hydrogen can be justified for wide, scale industrial heating applications, it is unlikely to be justifiable for commercial and residential uses where the barriers to implementation are far greater. Since the energy scenarios indicate that the role of synthetic fuels (including hydrogen as inferred above) is relatively small in the period from 1975 to 2000, it follows that the use of hydrogen for commercial and residential applications will be very small, and thus no contribution is assumed in the reference scenario which ends in the year 2000.

When fossil fuels become unavailable and extremely costly, presumably some time after the year 2000, the use of nuclear or solar energy sources to generate hydrogen for commercial and residential uses appears to be a reasonable possibility in terms of presently known options. Hydrogen is superior in terms of air pollution [Gregory, 1972b] and can be used in efficient catalytic burners. An alternative to hydrogen in this distant timeframe might be electrical energy from nuclear or solar sources or possibly even a hydrocarbon fuel (e.g., methane) synthesized from hydrogen derived from water and carbon from a source such as limestone. However, based on presently available technology, hydrogen appears to be a competitive future option which can be implemented without major technological breakthroughs.

e. Transportation. As noted previously, hydrogen can serve as a low pollution fuel for the transportation sector. At present, the transportation sector is supplied almost exclusively by petroleum-derived fossil fuels. However, it appears likely that well-established petroleum fuel-based systems will continue to dominate as long as petroleum is available in reasonably good supply.

The energy scenarios are based on substantial petroleum availability through 1985. Further, the FTFB scenario indicates substantial petroleum usage through the year 2000. This implies that a large scale shift to alternate fuels for transportation is unlikely by the year 2000.

As discussed in preceding sections, a strong candidate for replacing petroleum-derived fuels is coal-derived fuels encompassing synthetic gasoline, methanol, etc. Recent studies [Kant, et al, 1974, Pangborn and Gillis, 1974 and Meltzer et al, 1974] indicate that fuels can be produced and distributed at costs ranging from about \$1.79-\$2.84/GJ (\$2 to \$3/10^6 Btu) in the year 2000. These costs are of course subject to revision or refinement as more detailed studies are conducted and it is important to understand or interpret them in this light.

The primary advantage of these coal-derived fuels is that they can be implemented with essentially no changes in present vehicles. Further, the existing distribution networks can be employed. This economic incentive of using the large capital investment in present systems favors fuels which can be used as direct substitutes for present petroleum fuels.

According to the FTFB scenario, coal will be available in substantial quantities at least through the year 2000. Thus, it is unlikely that major shifts in the transportation sector will occur prior to the year 2000. Shifts to other alternatives such as electric propulsion or hydrogen will require substantial capital investments which mitigate against their use in the context of availability of coal-derived fuels that are compatible with existing vehicles and fuel distribution systems.

(1) Ground vehicles. As discussed in earlier sections, the major technical difficulty

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*Contributions from R. Downs, NASA, JSC and W. Powers, NASA, MSFC.

with using hydrogen as a fuel in ground vehicles is storage. In gaseous form, compressed gas tankage volume and weight require compromises which would limit range to the order of 161 km (100 miles). Cryogenic liquid storage entails additional cost and handling complexity while lightweight hydride storage systems for long range operation have not yet been developed.

Also, a large hydrogen fuel distribution network must be provided if hydrogen is to be used on a large scale. Since this requires large capital expenditures, it is likely that hydrogen usage in the ground vehicle sector would be at best accomplished in a gradual manner. For reasons of improved air pollution or other special purposes such as fork lifts in buildings, some small usage of hydrogen is possible. However, for purposes of formulating a solid reference level of usage, no contribution in the ground vehicle sector is included.

(2) Water vehicles. Conversion of ships to hydrogen will require large scale re-fueling provisions to be provided at harbors. For transoceanic ships, this implies establishment of international re-fueling stations which somewhat complicates implementation. The vast bulk of water shipping occurs away from heavily populated areas where air pollution is not a critical or immediate health hazard problem. Thus, there is less pressure of a special purpose nature that would cause conversion of ships to hydrogen.

From these overall considerations, it follows that if ships convert to hydrogen, this conversion will probably occur somewhat later than ground vehicles. As discussed previously, there may be military applications which could result in conversion of ships to hydrogen. For the reference scenario, no credit has been taken for this possibility.

(3) Aircraft and space vehicles. As noted previously, for both subsonic and supersonic aircraft, cryogenic liquid hydrogen provides potential performance advantages. Basically, hydrogen has a much higher energy content per unit weight as compared to jet fuel. This results in a lighter fuel load and an overall weight savings which provides performance advantages in airborne vehicles.

These factors indicate that conversion to hydrogen fuel will be economically viable for aircraft sooner than for ground or water vehicles. Further, aircraft fueling and maintenance is performed by highly trained technical crews and this will facilitate introduction of a cryogenic hydrogen fuels technology.

However, development time and cost of the new aircraft system and the establishment of an airport hydrogen refueling network on a worldwide basis are factors which militate against immediate wide-scale conversion. Factors such as performance advantages for military missions or even requirements for reduced air pollution near airports could stimulate hydrogen airplane development, but in the context of the reference scenario which embraces only relatively secure uses, no contributions were attributed to hydrogen airplanes.

A key factor with regard to the probable implementation of hydrogen airplanes is the economic comparison with conventional aircraft. As indicated in earlier sections, hydrogen airplanes are presently comparable to jet-fuel airplane on a cost per passenger-mile basis. This comparison will probably shift more in favor of hydrogen with (1) development of advanced low-cost hydrogen production techniques and (2) increase in the cost of conventional and synthetic hydrocarbon fuels as fossil reserves diminish. Thus, an eventual strong role for hydrogen airplanes appears to be a reasonable possibility.

The space program has used hydrogen and will increase its requirements with the implementation of the space shuttle. The reference hydrogen scenario includes this space usage based on NASA space program projections. The quantity of hydrogen is, however, very small compared to industrial unique chemical requirements.

f. Iron Ore Reduction. The use of hydrogen or more specifically hydrogen and carbon monoxide mixtures for direct reduction of iron ores has been discussed previously. Four general types of coal based reduction processes are [Fein, 1972]:

Kiln reduction of ore.

Batch reduction and vertical retorts.

Continuous reduction of descending pellets in a shaft furnace.

Reduction of a fluidized bed or ore with a reducing gas.

Additionally, potential or future nuclear energy reduction processes can use pure hydrogen, [Blickwede, 1974].

The implementation of coal-based direct reduction has already been initiated [Fein, 1972]. Since direct reduction is already being implemented, a relatively conservative usage level is included in the reference scenario, namely a value of approximately one-third of the estimates made by Fein.

The quantitative "Reference" use projections are displayed in Table VI-16, referenced to 1973 data and extending to the year 2000. Notes to this table explain the bases of calculations. This projection is considered to represent a lower bound for hydrogen demand through the remainder of the century.

D. EXPANDED HYDROGEN USE SCENARIO

The preceding section described a reference use scenario which incorporated only a relatively certain level of hydrogen usage based primarily on continuation of established uses. The expanded hydrogen use scenario is based on the higher energy use NEE scenario and includes selected new applications. Also, for consistency with inclusion of these unestablished uses, the levels of usage for traditional unique chemical applications have been increased to reflect more optimistic growth projections.

Table VI-16. "Reference" Hydrogen Projection by end uses (HEST study projections based on FTFB scenario)*

End Use, 10^{18} J (10^{15} Btu)	1973	1985	2000	Comments*
Unique Chemicals				
Ammonia	0.379 (0.359)	0.767 (0.726)	1.828 (1.731)	Assume 6% growth[1]
Petroleum Refining	0.492 (0.466)	0.697 (0.660)	0.825 (0.781)	FTFB projections[2]
Methanol and Others	0.103 (0.098)	0.232 (0.220)	0.642 (0.608)	Assume 7% growth[3]
Hydrogenation of Oils, etc.	0.005 (0.005)	0.012 (0.011)	0.033 (0.031)	Assume 7% growth[3]
Subtotal	0.98 (0.93)	1.71 (1.62)	3.33 (3.15)	
Synthetic Fuels				
Tar Sands		NIL	NIL	
Oil Shale		0.026 (0.025)	0.106 (0.100)	FTFB projections[4]
Coal Gasification		NIL	0.535 (0.507)	FTFB projections[5]
Coal Liquefaction		NIL	1.160 (1.100)	FTFB projections[6]
Subtotal	NIL	0.026 (0.025)	1.81 (1.71)	
Direct Reduction	NIL	0.457 (0.061)	0.23 (0.22)	HEST estimates[7]
Miscellaneous, including welding, cooling, process heat,, and others	0.069 (0.065)	0.16 (0.15)	0.40 (0.40)	Assume 7% growth[3]
Space Shuttle	NIL	0.0014 (0.0013)	0.0014 (0.0013)	NASA projections[8]
TOTAL	1.05 (0.99)	1.95 (1.85)	5.79 (5.48)	Average growth rate 6.8%

*Notes for this Table are on the following page.

Thus, the expanded hydrogen use scenario is intended to reflect a somewhat more optimistic but still possible level of usage within the framework of the selected NEE energy future. In general, the expanded scenario incorporates all the uses in the reference scenario, and thus only the modifications and additions are discussed.

1. Traditional Uses

The traditional unique chemical usage of hydrogen is increased over that of the reference scenario by selecting the highest historical growth rates. For ammonia and methanol production, the accelerated growth rates of 9.3% and 15.9%, respectively, are used (see Table VI-2). These accelerated growth rates are possible since there is some historical precedent. Circumstances such as increased export of ammonia-derived fertilizers and expanded applications for methanol, could result in maintaining these accelerated growth rates.

The quantity of hydrogen required in petroleum refining is variable, depending on the type of crude and the extent of refining. In a climate of increasing requirements for hydrodesulfurization and highly refined petroleum products, it is possible that the higher unit requirement of 108 m^3/m^3 (610 scf of hydrogen per barrel) (see Table VI-3) will prevail and this value is used in determining usage levels for the expanded scenario.

For hydrogenation of foods such as margarine and shortening, increasing quantities of hydrogen consumption has resulted from use of oils having a significant portion of unsaturated fatty chains. Continuation of this trend could result in the accelerated historical growth of 6.4% (Table VI-2) and this value is therefore used. For the extensive list of collected small quantity uses, the growth for the past five years is somewhat higher than that over the nine year period, indicating accelerated growth. This recent higher

Notes for Table VI-16

(1) The questions facing fertilizer producers are diverse if not downright contradictory in some cases, and they involve both supply and demand. Demand for fertilizers is generally outpacing supply today, but isolated softness is beginning to show up. A continued growth in foreign markets for nitrogen fertilizers is unlikely because of recent cuts in the foreign aid programs. Hence, it is unlikely that the 9.3% growth rate (based on last 9 years) shown in Table VI-2 would continue. The growth rate could be closer to the past 5-year rate of 5%. Another major contributing factor to the slower growth rate of ammonia is the fact that more foreign countries, particularly those with ample sources of natural gas, oil, and coke, will become self-sufficient. We assume 6% ammonia growth rate, which is lower than that of other chemicals. Shortage of available natural gas and oil could influence the supply situation.

(2) The Ford Technical Fix Baseline (FTFB) projects the following oil supply estimates:

Oil Supply, 10^{18}J (10^{15}Btu)	1985	2000
Domestic	31.1 (29.5)	37.5 (35.5)
Imported	9.5 (9.0)	9.5 (9.0)
Oil from Shale	0.53 (0.5)	2.1 (2.0)
Total	41.2 (39.0)	49.1 (46.5)

We assume that on the average approximately 53 m^3/m^3 (300 scf of hydrogen per barrel) are required to process the crude oil.

(3) In the U.S., energy growth has been historically closely related to the growth in real gross national product. Based on this relationship, we can expect a 3.4% GNP growth rate for FTFB projections. The recent Federal Reserve Board index for Chemicals and Allied Products Production changes at about twice the rate of change of real GNP. Thus a 6.8 to 7.0% annual growth for petrochemicals and other uses could be expected through year 2000.

(4) FTFB estimates 0.5 x 10^{18}J (0.5 x 10^{15} Btu) and 2 x 10^{18}J (2 x 10^{15} Btu) equivalent oil from shale in year 1985 and 2000 respectively. See item (2) above. Approximately 232 m^3/m^3 (1300 scf of hydrogen per barrel) of crude are required.

(5) FTFB projection estimates 1 x 10^{18} J (1 x 10^{15} Btu) equivalent substitute natural gas (SNG) from coal in year 2000. Approximately 44 m^3 (1560 scf) of H_2 are required per 28 m^3 (1000 scf) of SNG.

(6) FTFB projection estimates 3 x 10^{18} J (3 x 10^{15} Btu) equivalent synthetic crude oil from coal in the year 2000. The hydrogen requirements depend on the type of coal process used to process used to produce the liquid fuel. The COED process requirement is 784 m^3/m^3 (4400 scf per barrel) of syncrude. Selective hydro-operation processes receive more hydrogen. H-coal process requirement is 1514 m^3/m^3 (8500 scf/barrel) of syncrude. In synthoil process 1069 m^3/m^3 (6000 scf H_2/barrel) is required. In the Consol synthetic fuel process, the hydrogen requirement is 1514 m^3/m^3 (8500 scf/barrel) syncrude. Since the FTFB projections do not specify the type of process, we assume in our computations that an averaged quantity, i.e., 1158 m^3/m^3 (6500 scf of hydrogen per barrel) syncrude, is required.

(7) Direct reduction is already in process. The American Iron and Steel Institute Study [Industrial Heating, Nov. 1974] indicates that direct reduction processes using a mixture of hydrogen and carbon would be of considerable interest to the steel making industry in the future. They note that if hydrogen were available at reasonable cost, the industry would be able to overcome some of the technical problems associated with direct reduction of iron ore using only hydrogen. The Future Group Study [Fein, E., Oct. 1972] estimates that in the year 1985, 11%, ~27 x 10^9 kg [~30 x 10^6 tons] and in the year 2000 about 25 to 30% ~82 x 10^9 kg [90 x 10^6 tons] of the metallic iron ore would be directly reduced with hydrogen. HEST study estimates are that in the year 1985, 3% ~7 x 10^9 kg [~8 x 10^6 tons] and in the year 2000 about 8% ~22 x 10^9 kg [~24 x 10^6 tons] of the metallic iron ore would be directly reduced. Hydrogen requirements are approximately 0.624 m^3/kg (20,000 scf/ton) of ore are required for direct reduction.

(8) NASA requirements for liquid hydrogen estimated at 12 x 10^6 kg/yr (26 million pounds/year) beyond year 1985. Basis: 60 shuttle flights per year.

growth rate was taken as a reasonable basis for the expanded scenario since new uses such as the space shuttle will probably be at least partially fulfilled via the category of purchased hydrogen.

2. New Applications

For industrial process heat applications, the reference scenario did not include any contribution for hydrogen. In the context of coal-derived synthetic fuels, hydrogen does have some advantages such as reduced pollution and potential for increased efficiency in some applications. Thus, it may be economically advantageous under some circumstances and a gross upper bound would be to divert one-half of the coal processing for substitute natural gas over to synthesis of hydrogen and this was assumed for purpose of the expanded scenario.

As discussed previously, hydrogen storage systems for electric utilities represent a viable option among several strong candidates. For the safe level of the reference scenario, no hydrogen storage system contribution was included. For the purpose of the expanded scenario, it was first noted [illegible] several of the options, including hydrogen, could be implemented in the future. It also appears unlikely that one system will completely dominate since siting and other such factors greatly influence the choice. Thus, it was assumed that hydrogen storage could be used for 25% of the peak power requirements in the year 2000.

In the transportation sector, there are special circumstances which would appear to dictate a gradual and small scale conversion to alternate options such as hydrogen fuel, and electric propulsion. These circumstances include air pollution minimization in congested urban areas, and special military advantages. Special purpose applications were used as a basis for including a limited quantity of hydrogen in the period prior to the year 2000 for the expanded scenario, whereas the reference scenario was based on a rationale that hydrogen will not be used for transportation until coal reserves become scarce and costly, which will occur some time after the year 2000.

For ground transportation, use of hydrogen in fleet vehicles and special purpose vehicles to exploit the low-emission characteristic of hydrogen would appear to be a logical starting point. The military vehicle sector is also another possible entry point for hydrogen since it would be advantageous for military vehicles to be independent of potential instabilities in the supply of petroleum fuels. Thus, for the expanded scenario, the military sector and a small 10% fraction of the total domestic usage is assumed to be supplied by hydrogen in the year 2000.

The possible role of hydrogen as a fuel for water vehicles was described previously. Much further study of military logistics and the possible role of synthetic fuels is necessary before definitive conclusions can be drawn. Nevertheless, there are indications of possible military advantages which could justify earlier conversion of ships to fuels such as hydrogen. Conversion of military ships to hydrogen was assumed by the year 2000 to provide an upper bound demand estimate.

For hydrogen-fueled airplanes, the transition would probably be gradual and could be led by the military sector where the potential performance advantage of using hydrogen fuel can be exploited for military purposes. In this context, conversion of military aircraft to hydrogen has been assumed to occur by the year 2000.

The higher energy demand NEE scenario, which provides the basis for the expanded use scenario, indicates that petroleum usage will decrease by about 30% in the year 2000 as compared to 1972 consumption. This indicates that a substantial shift to alternate fuels could occur in the transportation sector in the context of this scenario. It is likely, however, that the stationary power generating sector would find it advantageous to shift before the transportation sector since problems of fuel handling, storage, weight, and volume are less critical. This would leave more petroleum-based fuels for transportation, but a sizeable shift to alternate fuels or energy systems for transportation would still probably be required in the context of the NEE scenario.

Table VI-17 displays the quantitative "Expanded" use projections. Notes to this table explain the bases of calculations. This Projection is considered to represent an upper bound for hydrogen demand through the remainder of this century.

Table VI-17. Expanded hydrogen projection by end uses
(HEST study projections based on NEE scenario)

End Use, 10^{18} J (10^{15} Btu)	1973	1985	2000	Comments
Unique Chemicals				
Ammonia	0.379 (0.359)	1.102 (1.044)	4.181 (3.960)	Assume 9.3% growth[1]
Petroleum Refining	0.492 (0.466)	1.116 (1.057)	0.815 (0.772)	NEE Model Projections[2]
Methanol and Others	0.103 (0.098)	0.608 (0.576)	5.559 (5.265)	Assume 15.9% growth[3]
Hydrogenation of Oils, etc.	0.005 (0.005)	0.011 (0.010)	0.029 (0.027)	Assume 6.4% growth[4]
Subtotal	0.98 (0.93)	3.0 (2.8)	10.58 (10.02)	
Synthetic Fuels				
Tar Sands		NIL	NIL	
Oil Shale		NIL	NIL	
Coal Gasification		0.511 (0.484)	3.577 (3.388)	NEE Model Projections[5]
Coal Liquefaction		0.117 (0.016)	4.296 (4.069)	NEE Model Projections[5]
Subtotal	NIL	0.53 (0.50)	7.9 (7.6)	
Direct Redution	NIL	0.22 (0.21)	0.69 (0.65)	Futures Group Projections[6]
Transportation				
Space Shuttle		0.0014 (0.0013)	0.0014 (0.0013)	NASA Projections[7]
Air			0.993 (0.940)	HEST Estimates[8]
Ground			1.016 (0.962)	
Water			0.634 (0.600)	
Subtotal	NIL	0.0014 (0.0013)	2.64 (2.50)	
Residential and Commercial	NIL	NIL	NIL	No Significant Use[9]
Utilities				
Electric		0.1 (0.1)	0.897 (0.850)	Captive Use in Peaking[10]
Gas		NIL	0.248 (0.235)	Blending Up to 8% by Volume[11]
Subtotal	NIL	0.1 (0.1)	1.146 (1.085)	
Miscellaneous, including welding, cooling, process heat, and others	0.069 (0.065)	0.19 (0.18)	0.655 (0.620)	Assume 8.7% growth[12]
Subtotal	0.069 (0.065)	0.19 (0.18)	0.655 (0.620)	
TOTAL	1.048 (0.99)	3.98 (3.77)	23.7 (22.34)	

Notes for Table VI-17

(1) World's demand for ammonia for fertilizers is still steadily increasing [Oil and Gas Journal, 1974]. The U. S. may need to export large quantities of nitrogen based fertilizers to aid other countries, and also enhance foreign exchange. Hence, it is possible that U. S. production would continue its accelerated growth rate of 9.3% established over the past 9 years in order to meet domestic and non-domestic markets.

(2) The proportion of oil used for transport and conversion to chemicals will undoubtedly increase [Mason and Tolberg, 1973]. The heavier fractions will need to be upgraded, which can involve large demand for processes such as hydrocracking and hydrodesulfurization. Note the ratio of hydrogen to m^3 (barrels) of petroleum could increase from about 53 m^3/m^3 to 109 m^3/m^3 (300 scf/barrel to 610 scf/barrel) because of increasing importance of these processes.

(3) Methanol could add protein production and some motor fuel to its present chemical uses [Stanford Research Institute, 1967 and 1975]. Hydrogen peroxide may find increased uses in textile and rubber industries. Hence, these uses can continue to grow at the accelerated rate of 15.9% established during the past 5 years.

(4) Demand for shortening and margarine has shown a steady growth in the past and is expected to continue at the same rate. Soybean, fish, cotton seed, and corn oil contain high percentages of unsaturated fatty chains. These oils are stabilized by hydrogenation. Highest growth rate of 6.4% based on historical growth was employed.

(5) The use of coal to make chemicals or synthetic fuels will require large quantities of hydrogen. Separate manufacture of hydrogen would allow up to 2-1/2 times as much SNG to be produced per ton of feedstock compared with processes based solely on coal. The synthetic fuel production figures are from NEE projections. Hydrogen requirements for synthetic fuel production were calculated previously for the reference use scenarios (Table VI-16).

(6) The American Iron and Steel Institute study [Industrial Heating, Nov. 1974] indicates that one or several iron-ore direct reduction processes using hydrogen instead of coal or coke as the reducing agent looks economically attractive. The Futures Group study [Fein, 1972] estimates that in the year 1985 11% and in the year 2000 about 25 to 30% of the metallic iron ore would be directly reduced with hydrogen.

(7) NASA requirements for liquid hydrogen estimated at 12 x 10^6 kg/year (26 million pounds/year) beyond year 1985. Basis 60 shuttle flight per year.

(8) For establishing hydrogen demand in the transportation sector, it is believed that the military would have a strong incentive to switch to hydrogen in order to gain performance and logistic advantages. The armed services will have to be supplied 100% of their operating requirements for fuel at all times. In 1971, military uses amounted to about 8% of total transport, compared to 12% in 1969 and 11% in 1955. In the event of major war, military usage is much higher. The DOD energy breakdown by service in 1971 [Mutch, 1973] was:

Air Force	48%
Navy	31%
Army	18%
Other	3%

It is possible that 8% of the total transportation energy needs (NEE 25.36 x 10^{18} J (24.02 x 10^{15} Btu)) in the year 2000 will be in the military sector which will be completely supplied by hydrogen. This basis was used to project total hydrogen demand which is distributed among the air, water and ground transportation sectors according to the percentages mentioned above.

Some of the fleet vehicles and commercial trucks could be operating on hydrogen after 1985. The NEE projection estimates the following total energy needs:

Auto	8.7 x 10^{18} J (8.2 x 10^{15} Btu)
Truck	5.1 x 10^{18} J (4.8 x 10^{15} Btu)

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Notes for Table VI-17 (cont)

(8) (cont) To military transportation needs we added 1% of auto and 10% of truck transportation energy needs for estimating an upper hydrogen demand.

Hydrogen demand for the transportation sector:

Military	
Air	0.99 (0.94)
Ground	0.42 (0.40)
Water	0.63 (0.60)
Subtotal	2.05×10^{18} J (1.94×10^{15} Btu)
Civilian	
Auto	0.087 (0.082)
Truck	0.507 (0.480)
Subtotal	0.593×10^{18} J (0.562×10^{15} Btu)
Transportation total hydrogen demand:	2.642×10^{18} J (2.502×10^{15} Btu)

The first major use in the transportation sector is expected to be for air transportation because when the spectrum of possible fuels is considered, only one — liquid hydrogen — even promises any really major improvements in aircraft performance.

DOD transportation usage fluctuates according to unpredictable military needs, and there are indications of some decrease recently. However, the documented data above appear to be a reasonable basis for this projection.

(9) No significant hydrogen usage is estimated in the residential and commercial sectors. It is possible that some recreational vehicles could use hydrogen as an appliance fuel to a very limited extent.

(10) Studies by the Public Service Electric and Gas Company of New Jersey [Cassaza et al., 1974] estimate that once the nuclear capacity of an electric power system exceeds 30% of the total system capacity, rapidly increasing amounts of off-peak nuclear energy should become available. Since the NEE model estimates a total of 99×10^{18} J (94×10^{15} Btu) of nuclear energy representing 45.4% of a total supply of 219×10^{18} J (207×10^{15} Btu), the PSE&G study would indicate that close to 10% of the total energy generated could be available in the form of off-peak nuclear energy. Since batteries, pumped storage, and fly wheels are also attractive storage systems, we believe that one-fourth of the total off-peak nuclear electric power could be stored and reused by a hydrogen based system (electrolyzer-fuel cell). This hydrogen demand is captive.

Captive hydrogen demand =

10%	x	99×10^{18} J (94×10^{15} Btu)	x	40%	x	25%	x	90%
Off-Peak Percentage		Nuclear Capacity		Generator Efficiency		Hydrogen Contribution		Electrolyzer Efficiency

= 0.90×10^{18} J (0.85×10^{15} Btu)

(11) Studies [Gregory, 1972] indicate that up to 8% hydrogen could be added to the gas system to supplement our gas supplies without change in the gas distribution system of appliance. We assume that 8% by volume hydrogen is blended with the natural gas supply estimated in NEE 9.5×10^{18} J (9×10^{15} Btu) in order to meet occasional shortfalls.

(12) Miscellaneous uses of hydrogen, such as cooling of large electric generators, industrial welding, etc., and some process heat are estimated to grow at the past nine-year rate of 8.7%.

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Chapter VII

HYDROGEN PRODUCTION*

In this chapter the state of hydrogen production technology is evaluated in order to provide a broad technical basis for the determination of which lines of research and technology advancement might be emphasized to advantage.

The most important issue in meeting future hydrogen needs and in bringing forward new production methods will be cost-effectiveness (together with energy efficiency). Hydrogen production technology will have to be tuned economically in the same way that electricity technology has been optimized. This work can be as important as providing the technology in the first place. In most new fuel uses of hydrogen, it must compete with present energy systems in price and efficiency.

A. HISTORICAL DEVELOPMENT

Hydrogen was produced at the beginning of this century as a byproduct from electrolytic oxygen generated for oxy-acetylene welding applications. The demand for hydrogen grew for industry and airships, and new methods were developed to manufacture it from carbon-based sources, chiefly coal. The most popular method was by the water/gas reaction in which steam was passed over hot carbon to form hydrogen and carbon monoxide. Steam/iron processes using "producers" were used to prepare hydrogen which was free from carbon monoxide. The advent of the Haber process to fix nitrogen for fertilizer created a large demand for pure hydrogen after World War I. This demand was satisfied first by coal and then by natural gas as it became available after World War II. Introduction of hydrocracking and hydrotreating of petroleum concurrent with the very large increase in petroleum production led to the very large uses of hydrogen which is still supplied mainly by steam reforming of natural gas. Most of the needs for hydrogen were supplied by captive production in which the hydrogen manufacture was integrated into the overall process.

In the 1950's, the Centaur rocket program required liquid hydrogen, and industry undertook the problems of production and distribution of the liquid hydrogen. In the 1960's, plants were built with capacities up to 71 x 10^4 m^3/day (25,000,000 SCF/day) of hydrogen for the Apollo program. These plants used natural gas as the primary feedstock. By comparison, the largest plant for the production of hydrogen for ammonia in Donaldson, La., produces about 3.68 x 10^6 m^3/day (130,000,000 SCF/day) of hydrogen to manufacture about 1.8 x 10^6 kg (2000 tons) of ammonia per day.

Hydrogen is produced in smaller amounts by electrolysis of water, but only when special considerations of purity or distribution allow substantially higher costs. Most electrolyzers are used to produce hydrogen for laboratories, food processors, semiconductor manufacturers and similar users for whom the cost of hydrogen has a minor impact on the cost of the product. Electrolyzers of American manufacturers range in size from about 0.2 m^3/day to about 425 m^3/day, the latter being the size of the Teledyne electrolyzer. European module sizes are substantially larger; German (Lurgi) and Italian (de Nora) manufacturers are vending units with capacities up to 28 x 10^3 m^3/day. Much of the research and development of electrolyzers in the United States is being sponsored by military organizations primarily for the generation of oxygen for aircraft and submarines.

The emerging resources of nuclear, geothermal and solar energy will ultimately be needed to produce hydrogen as a chemical and for use as a fuel. The methods of using these sources to produce hydrogen are being widely studied and discussed. The most obvious method of hydrogen production is by electrolysis. Other methods which make direct use of heat or radiation are being studied, but practical processes have not yet been developed. The National Science Foundation is the major sponsor of research in these areas.

B. HYDROGEN PRODUCTION FROM FOSSIL FUELS

The detailed chemistry of the processing of carbon-based fuels is very complex and in fact is largely unknown. The overall thermochemistry is well known, and it is convenient and informative to treat these processes as all-inclusive reactions. The production of hydrogen from natural gas is simple, consisting of only three steps after which a relatively pure gas results. The process is most complex with coal as the feedstock, because of the difficulties in handling solids, ash, and sulfur at the rate of tens of thousands of kilograms per day [Buividas, 1974].

1. Steam Reforming of Methane

Most of the hydrogen produced in North America is made by the catalytic reforming of natural gas with steam by the process shown in Figure VII-1. The hydrogen-producing reactions are

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*By C. England, J. Chirivella, T. Fujita, R. Jeffe, D. Lawson, and R. Manvi.

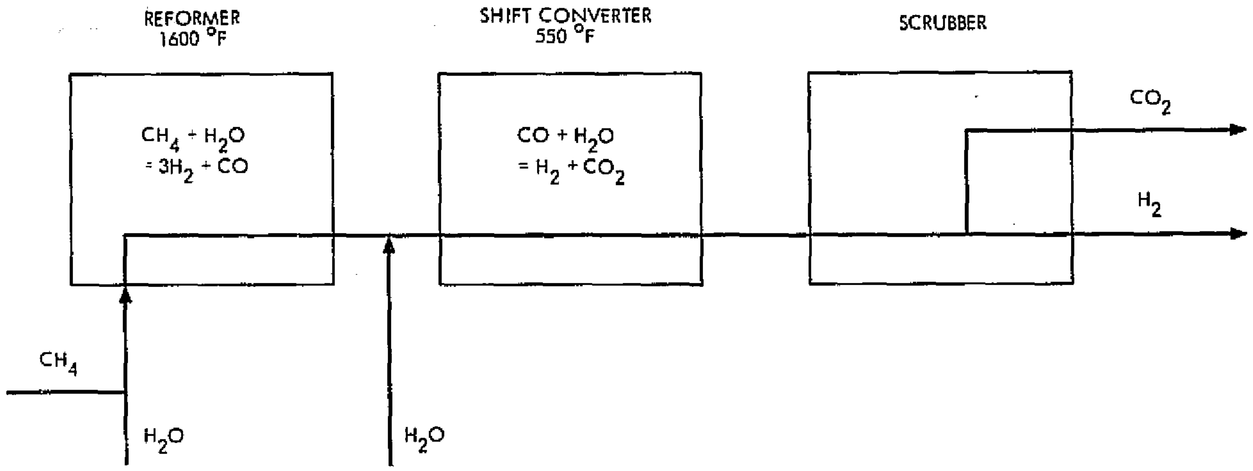

Figure VII-1. Steam reforming process for methane

$$CH_4 + H_2O \xrightarrow[927°C]{cat} CO + 3H_2 \qquad (VII-1)$$

and

$$CO + H_2O \xrightarrow[349°C]{cat} CO_2 + H_2 \qquad (VII-2)$$

for which the overall reaction is

$$CH_4 + 2H_2O \longrightarrow CO_2 + 4H_2. \qquad (VII-3)$$

Half of the hydrogen produced is derived from steam and half from methane. Reaction (VII-1) absorbs 31,316 J/g of hydrogen (fully shifted) and this energy must be supplied by burning additional fuel (not necessarily methane). The steam-reforming step is performed in tubes lining the inside of a combustor which supplies the reaction heat. The tubes are filled with an inexpensive catalyst which allows reaction below the temperature at which cracking of methane can occur.

Reaction (VII-2) is the water/gas shift reaction which produces hydrogen from carbon monoxide. The reaction is exothermic, reflecting the higher heating value of carbon monoxide, and it releases about 20,720 J/g of hydrogen produced. The approximate overall reaction to produce hydrogen from methane is given by the formula

$$CH_4 + 1.05\ H_2O + 0.48\ O_2 \longrightarrow CO_2 + 3.05\ H_2{}^{*} \qquad (VII-4)$$

if the required reforming energy is supplied by the combustion of methane, and the gases are completely shifted to eliminate carbon monoxide.

After the gases have been through the water/gas shift, a scrubbing process reduces or eliminates the primary dilutant, carbon dioxide. This is done by absorption in amine solution or by low temperature processes such as scrubbing with cold methanol or even liquid nitrogen if high-purity hydrogen is required. The gas leaves this step as essentially pure hydrogen.

2. Steam Reforming of Light Hydrocarbons (Naphtha)

Hydrogen can be produced by catalytic reforming of light hydrocarbons provided only that the hydrocarbons can be vaporized completely without carbon formation. Some hydrogen is made in the United States by this method, but only when low-cost natural gas is not available. Naphtha has a hydrogen/carbon ratio of about 2.2, and the reforming reaction is approximated by the formula

$$CH_{2.2} + H_2O \xrightarrow{cat} CO + 2.1\ H_2 \qquad (VII-5)$$

which is followed by the shift reaction

$$CO + H_2O \longrightarrow CO_2 + H_2 \qquad (VII-6)$$

for which the overall reaction is

$$CH_{2.2} + 2H_2O \longrightarrow CO_2 + 3.1H_2 \qquad (VII-7)$$

Water supplies 64.5% of the hydrogen, which is greater than the proportion supplied by water for methane reforming. Consequently the energy requirement for reaction (VII-5) is a little greater, amounting to 32,083 J/g of hydrogen as compared to 31,316 J/g using methane. The approximate overall reaction to produce hydrogen from light hydrocarbons is given by the formula

---

* Overall reactions in this section are for purposes of comparison only. Product composition will vary according to the particular process.

$$CH_{2.2} + 1.22\ H_2O + 0.39\ O_2 \longrightarrow CO_2 + 2.32\ H_2 \qquad (VII\text{-}8)$$

when the reforming energy is supplied by the combustion of naphtha and the gases are completely shifted to eliminate carbon monoxide.

The process for producing hydrogen from naphtha is similar to that for methane feedstocks, except that the fuel must be desulfurized prior to reaction.

3. Partial Oxidation of Heavy Oils (Residual Oils)

The production of hydrogen from heavy oil is undertaken in a different process from the lighter feedstocks. Heavy oil cannot be processed catalytically because it cannot be completely vaporized without carbon formation and because of the relatively high sulfur and ash content. To circumvent these problems, the residual oil is subjected to partial combustion in the presence of steam. The overall reaction is similar to the combined reforming/combustion process of the lighter fuels except that the combustion products are intimately mixed with the products of the reforming reactions, and must be removed from the final product.

The hydrogen/carbon ratio of heavy oils is about 1.8, and the hydrogen-producing reactions are the reforming reaction,

$$CH_{1.8} + H_2O \longrightarrow CO + 1.9\ H_2 \qquad (VII\text{-}9)$$

and the shift reaction

$$CO + H_2O \longrightarrow CO_2 + H_2 \qquad (VII\text{-}2)$$

for which the overall reaction is

$$CH_{1.8} + 2H_2O \longrightarrow CO_2 + 2.9\ H_2. \qquad (VII\text{-}10)$$

Water supplies 69% of the hydrogen. The energy needed to drive reaction (VII-10) is about 52,296 J/g of hydrogen fully shifted* which is about 40% greater than that for the light hydrocarbon feedstock. This energy is supplied by the combustion reaction

$$CH_{1.8} + 1.45\ O_2 \longrightarrow CO_2 + 0.9\ H_2O \qquad (VII\text{-}11)$$

which, when included in the process, gives an overall reaction to produce hydrogen described by the formula

$$CH_{1.8} + 0.98\ H_2O + 0.51\ O_2 \longrightarrow CO_2 + 1.87\ H_2 \qquad (VII\text{-}12)$$

when the gases are completely shifted. Pure oxygen must be used in the process shown in Figure VII-2 because of the difficulty of separating nitrogen from hydrogen to produce a pure product.

The costs of the oxygen plant and the additional cost of the desulfurization steps represent a dramatic increase in the capital costs of producing hydrogen. As a result, there is industry resistance to implementing the partial oxidation process to produce hydrogen.

4. Partial Oxidation of Coal

Hydrogen production from coal is basically a partial oxidation process similar to that for heavy oil. The process is complicated by the necessity to handle a relatively unreactive fuel as a solid and to remove large amounts of ash. The solids-handling problem has a severe impact on costs and prevents much of the technology and equipment developed for petroleum from being used in the conversion of coal. Coal, steam and oxygen react in the basic gasifier processes to produce hydrogen as shown in Figure VII-2

The hydrogen-carbon ratio of coal is about 0.8 and the hydrogen-producing reactions are the reforming reaction

$$CH_{0.8} + H_2O \longrightarrow CO + 1.4\ H_2 \qquad (VII\text{-}13)$$

and the shift reaction

$$CO + H_2O \longrightarrow CO_2 + H_2 \qquad (VII\text{-}2)$$

for which the overall reaction is

$$CH_{0.8} + 2H_2O \longrightarrow CO_2 + 2.4\ H_2 \qquad (VII\text{-}14)$$

Water supplies 83% of the hydrogen produced, and the energy requirement for reaction (VII-14), fully shifted, amounts to 85,267 J/g of hydrogen.

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*Reaction conditions differ from those resulting from steam reforming; the feedstock counterflow process is used in steam reforming and partial oxidation requires oxygen.

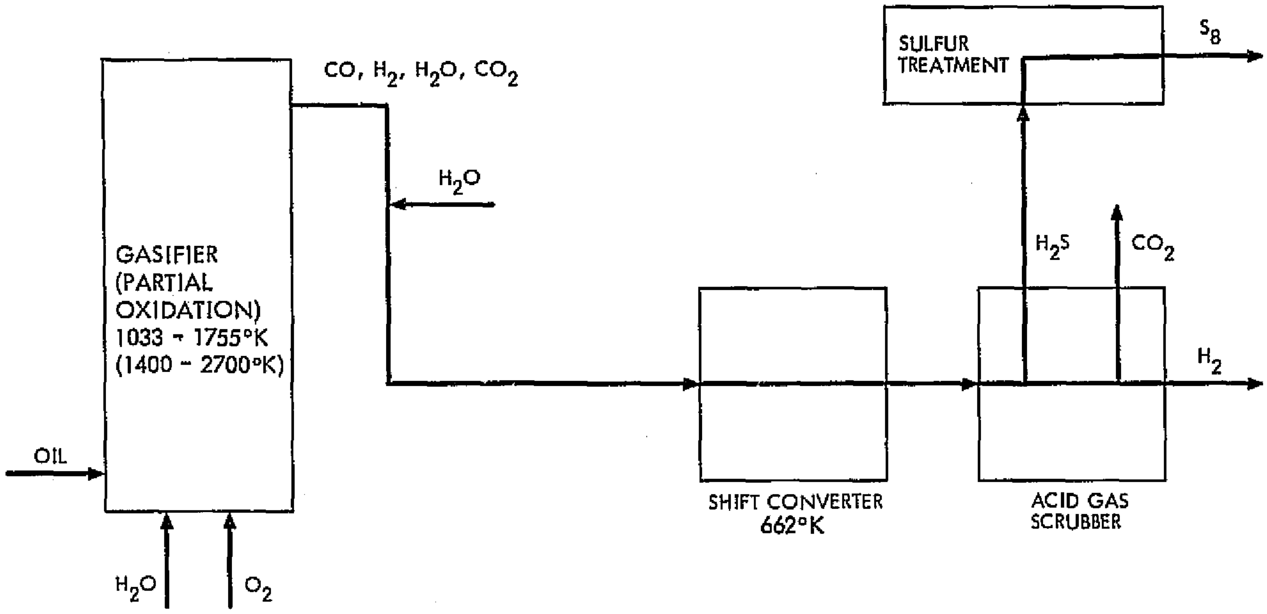

Figure VII-2. Partial oxidation process for production of hydrogen from heavy oil

This is substantially higher than that for partial oxidation of residual oil and reflects, in part, the low heating value of coal relative to petroleum feedstocks. The energy is supplied by the combustion reaction

$$CH_{0.8} + 1.2\ O_2 \longrightarrow CO_2 + 0.4\ H_2O \qquad \text{(VII-15)}$$

which, when included in the process, gives the following overall reaction to produce hydrogen:

$$CH_{0.8} + 0.70\ O_2 + 0.60\ H_2O \longrightarrow CO_2 + 1.0\ H_2 \qquad \text{(VII-16)}$$

As in the case of heavy oil, pure oxygen must be used in the basic gasification process although other schemes have been proposed to avoid the costly air-separation process. The details of coal conversion are discussed in a later section.

5. Partial Oxidation of Solid Wastes

Solid waste, including municipal trash, sewage, and industrial wastes, can be gasified by methods similar to those used for coal, producing synthesis gas consisting primarily of H_2, CO, CO_2 and water vapor [Snyder, et al., 1975]. Typical dried rubbish has a heating value of 18 to 20 x 10^6 J/kg and has a composition near that of cellulose. Hydrogen is produced by the reaction

$$CH_{1.67}O_{0.83} + 0.17\ H_2O \longrightarrow CO + 1.00\ H_2, \qquad \text{(VII-17)}$$

while energy for this reaction is supplied by the reaction

$$CH_{1.67}O_{0.83} + 1.00\ O_2 \longrightarrow CO_2 + 0.84\ H_2O. \qquad \text{(VII-18)}$$

The overall reaction to produce hydrogen is

$$CH_{1.67}O_{0.83} + 0.73\ H_2O + 0.22\ O_2 \longrightarrow CO_2 + 1.57\ H_2 \qquad \text{(VII-19)}$$

when the water/gas shift reaction is performed, yielding 0.12 kg of hydrogen per kg of waste. This is only 40% the yield for coal, but it requires only 50% of the oxygen.

Thus, differences in capital costs would be based largely on costs of solids handling. The total municipal waste generated in the United States was 113 × 10^9 kg per year (1971 figures), or about 1.5 kg/capita/day. In terms of hydrogen production, the municipal wastes of about 10,000 persons could supply a ton of hydrogen per day.

Much of the effort in recovering energy from solid wastes centers on incineration, particularly in Europe. From this technology, methods of removing metals and glass are available. Direct partial oxidation of municipal trash has not been demonstrated commercially, but equipment would be similar to that used for low-pressure coal gasification.

6. Technological Requirements for Fossil Fuels

The preceding discussion describes the declining quality of fuels as one goes from gas to oil to coal, and additional processing steps as well as additional energy are required to produce hydrogen from the lower grade fuels. The additional steps are the major areas of needed technical advances because they present new problems such as sulfur removal, ash handling or catalyst poisoning.

Steam reforming is fully commercial and requires little additional research except perhaps for improved methods of removing carbon dioxide from the hydrogen stream. Current methods of scrubbing with basic solutions or low temperature organic liquids remain large consumers of energy. Packaged processes are available (some using liquid oxygen) for partial oxidation of oils. Although the technology is well in hand, sulfur-resistant shift catalysts and improved methods of oxygen manufacture and acid gas scrubbing would substantially increase overall process efficiency.

For coal, the major additional problem is development of the high-pressure gasifier capable of high throughputs of coal and ash. The problem is intimately related to the technique of introducing coal continuously into a high-pressure environment, and to the reliability of this technique. All advanced coal-gasification processes have this problem in common, and the ultimate design of the gasifier will depend on the performance of the feed - and ash-removal systems. The need for high-temperature desulfurization and improved methods of oxygen manufacture and acid gas scrubbing all relate to the problem of increasing process efficiency. Low-pressure coal-gasification methods are commercially available for the production of hydrogen or synthesis gas, but efficiencies and capital utilization are low. Advanced processes may improve hydrogen yield from coal by 30%.

Most current research centers on meeting natural gas deficits by the gasification of coal to produce methane, and most efforts towards advancing gasification technology concentrate on developing the high-pressure, lower-temperature gasifiers that maximize methane production. The state of technology of hydrogen production is much less advanced, and until recently was an afterthought of substitute natural gas (SNG) technology. However, it should be more cost-effective to produce hydrogen from coal, using processes similar to SNG production, because the higher temperature required by hydrogen greatly increases the throughput of the gasifier.

Synthesis gas is the major product of even advanced hydrogasifiers and it is potentially advantageous to produce both hydrogen and methane from a single plant. Such a plant would have the highest thermal efficiency for coal conversion. It would require a hydrogen-methane separation step, which would be balanced by elimination of the methanation step, common to all SNG plants.

C. COAL-GASIFICATION PROCESSES

Partial oxidation of coal or similar processes to produce hydrogen from coal are of particular interest as an interim source of clean fuels from coal. Current technology is centered largely in Europe and South Africe while newer processes with higher efficiencies are being developed in the United States. Several reviews of coal-gasification processes are available [Perry, 1974; Mudge, 1974], most of which review the technology for production of high Btu gas or SNG from coal. The term "coal gasification" commonly refers to the production of SNG since this has been the major thrust of research in this country. The need for hydrogen in the production of synthetic liquid fuels from coal, however, has increased attention on processes to produce hydrogen from coal. Much of the technology for the production of SNG is directly applicable to the production of hydrogen since the main products of the gasification step in all processes are carbon monoxide and hydrogen. Advanced technology in SNG production centers on increased direct production of methane by increased gasifier pressures. This technology favors increased efficiency in hydrogen production from the reduced compression requirements of the processes. Hydrogen processes, however, must operate at considerably higher temperatures.

1. Conventional Technology

The basic coal-gasification process can be represented by the schematic given in Figure VII-2. After preparation, coal is introduced into a gasifier where it is reacted with steam and oxygen to form hydrogen, carbon monoxide and carbon dioxide. The gasifier operates under reducing conditions, and sulfur appears in the product gases as hydrogen sulfide, H_2S. The gases are cleaned of ash and tar and compressed, if necessary, to lower the volume of the remaining downstream processing steps. Several options are available for the remaining steps to hydrogen, and the most probable is that the gases will be scrubbed to remove H_2S and CO_2 and then sent to a shift converter to form hydrogen from CO. The CO_2 added in the shift reactor is scrubbed, and the resulting gas is hydrogen with traces of carbon monoxide. Depending on the application, the CO can remain in the product or be eliminated by methanation* or by liquid-nitrogen scrubbing. In the latter case, the LN_2 source can be part of the air-separation plant used to produce oxygen for the gasifier.

The major process used to gasify coal is the Lurgi gasifier, which operates a fixed bed gasifier

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*The purity of the hydrogen depends on the effectiveness of the scrubbing as well as the completeness of the water-gas reaction.

at pressures up to 2800 kN/m^2 (400 psi). The Lurgi gasifier is presently being used in Europe and South Africa to produce synthesis gas (CO and H_2) for the production of alcohols and hydrocarbons. Its major drawbacks as a hydrogen producer are the low throughput, and the high levels of tar and hydrocarbon gases that must be removed for further processing to H_2. It is the only commercial process that operates at relatively high pressure. The Koppers-Totzek entrained-bed gasifier is also used to gasify coal, but operates at near ambient pressure, thus avoiding the complexity of feeding coal to higher pressures. The need for subsequent compression of synthesis gas for treatment, purification, and delivery appear to weigh heavily against low-pressure gasifiers.

2. Comparison of Current and Developmental Methods

New technology in coal gasification is based on high-pressure, low-temperature gasification to promote the direct formation of methane. High-pressure operation is also favorable for the production of hydrogen from coal because it allows reduced compression requirements for pipeline use or for subsequent liquefaction. Advanced gasifiers operate at pressures of 7000-10,000 kN/m^2 (1000-1500 psi) and temperatures of 900-1300°K (1200°F - 1900°F). The high pressure and low temperature favor methane formation, but the low temperature also results in a slow reaction rate, i.e., the gasifier throughput is low. Operation for hydrogen would require increased temperature up to 1700°K (2600°F), causing severe corrosion of gasifier materials, but would also result in a substantially increased throughput and, thus, fewer gasifiers than needed for SNG production. A substantial reduction in gasifier costs should result.

Table VII-1 shows the composition of gases exiting several different gasifiers. A wide variation in composition exists, with the lowest methane formation from high-pressure gasifiers resulting from the U-Gas and BIGAS gasifiers. The CO_2 (acceptor) process gives a large hydrogen composition because of the occurrence of the shift reaction within the process, but operates at lower pressures. These three processes appear promising for optimization for hydrogen production. A higher-pressure (entrained-flow) reactor which continues to produce little or no methane would also offer a promising route to hydrogen from coal. The "U-Gas" process of the Institute of Gas Technology (IGT) may offer the same benefits since it operates a 2400 kN/m^2 (350 psia) and up to 1300°K (1900°F). It is not at the demonstration phase as yet, and problems with lock hopper feed and fluidized-bed operation must be resolved before commercialization.

Another attractive system for hydrogen from coal is the modified steam-iron process also being studied at IGT. The process produces raw-gas compositions of up to 96% hydrogen at 2400 kN/m^2 (psia), but is substantially more complex than more conventional processes. The elimination of the air-separation plant and downstream cleanup is a major advantage of this process.

Improvement in coal-gasification technology may eventually have a substantial effect on the capital costs of a hydrogen plant including reduced gasifier costs, reduced compression requirements, and improved efficiencies. Table VII-2 shows the influence of gasifier variables on the ultimate production of SNG or hydrogen. The last value gives the potential efficiency of a hydro-gasifier such as the HYGAS unit in which 14% of the output is methane produced in the gasifier and the remaining gases are shifted to produce hydrogen. The highest theoretical efficiencies occur when methane is formed directly

Table VII-1. Exit composition of gases from coal gasification reactors

Gasifiers	Koppers-Totzek	Lurgi	HYGAS (oxygen gasifier)	BIGAS	SYNTHANE	CO_2 (acceptor)	U-Gas
Pressure, kN/m^2 (psi)	130 (20)	2000-3000 (300-450)	7000 (1000)	7000-1000 (1000-1500)	3500-7000 (500-1000)	1000-2000 (150-300)	2400 (350)
Temperature, K (°F)	1700 (2600)	1050 (1400)	900 (1200)	1200 (1700)	1250 (1800)	1100 (1500)	1300 (1900)
Composition (mole %)							
H_2	33.1	20.1	22.8	12.7	17.5	44.6	27.2
CO	50.4	9.2	18.0	22.9	10.5	14.1	38.5
CH_4	0.0	4.7	14.1	8.1	15.4	17.3	1.6
CO_2	5.6	14.7	18.5	7.3	18.2	5.5	8.8
H_2O	9.6	50.2	24.2	48.0	37.1	17.1	30.0
Dry heating value, 10^6 J/m^3 (Btu/Scf)	11.1 (298)	11.3 (302)	13.9 (374)	14.1 (378)	15.1 (405)	16.4 (440)	11.7 (315)

Table VII-2. Theoretical Performance of Gasifiers and Hydrogasifiers for Coal

Gasifier Type (Current Technology)	Exit Temp.	Oxygen Required kg/kg (ton/ton) Coal	SNG Production kg/kg (ton/ton) Coal	H_2 Production kg/kg (ton/ton) Coal	Thermal Efficiency
Low-temperature gasifier					
Methanation	1050 K (1400°F)	1.68	0.33	—	0.62
H_2 Shift	1050 K (1400°F)	1.68	—	0.17	0.75
High-temperature gasifier					
Methanation	1300 K (1900°F)	1.75	0.31	—	0.59
H_2 Shift	1300 K (1900°K)	1.75	—	0.16	0.71
Hydrogasifier					
Methane only	1050 K (1400°F)	1.26	0.43	—	0.81
Mixed products	1050 K (1400°F)	1.51	0.17	0.10	0.77

from coal, or when hydrogen is produced from synthesis gas instead of methane.

3. Nuclear-Assisted Coal Gasification

In principle, nuclear heat can supply the energy to react coal directly with water according to reaction (VII-16). Nuclear heat must be lower in cost than heat derived from the combustion of coal for this method to be practical, and, since this is the case in some parts of Europe, interest in nuclear-assisted coal gasification centers there [Westinghouse, 1974; General Atomic, 1974; General Electric, 1974]. The decisive technical problem is that of transferring the nuclear heat to the gasifier without risk of contaminating the primary reactor coolant. This probably requires a secondary coolant loop which, along with the heat exchanger in the gasifier, will result in some loss in utilization of the nuclear heat.

Nuclear-assisted coal conversion requires substantial improvements in integrating the nuclear heat source with the gasifier. This may be accomplished most directly by choosing an indirect gasification method which uses a molten bath (e.g. ATGAS [Perry, 1974]) to aid in heat transfer from the reactor.

4. In-Situ Coal Gasification

Gasification of coal while it is still in the ground is potentially a more environmentally acceptable means of producing clean fuels from coal, and interest in in-situ gasification has been renewed after unsuccessful programs concluded in the 1950's. In-situ gasification requires injection of air or oxygen into the ground (with or without steam). The oxidant supports combustion of the coal seam, and the resulting gases are brought to the surface for further processing. Pure oxygen is now believed essential to adequately control the combustion of the coal bed. The major problems with in-situ methods are related to the inhomogeneity of the bed and the associated difficulties of maintaining stable combustion conditions underground. Emphasis centers on improved monitoring of the gasification zone as it moves through the bed.

The technology of in-situ gasification of coal is in the early research stage and requires substantial effort to be a proven source of energy from coal.

D. ELECTROLYSIS OF WATER

The theoretical energy required for the electrolysis of water at 298 K,

$$2H_2O(\ell) = 2H_2 + O_2, \qquad \text{(VII-20)}$$

is the negative of the heat of combustion of hydrogen.

$$\Delta H = -\Delta H = 286.25 \text{ kJ/g-mole} (68{,}317 \text{ cal/g-mole})$$

The energy is related to the electrolysis voltage by the equation

$$\Delta H = -n\mathcal{F}E \qquad \text{(VII-21)}$$

where n is the number of electrons transferred per mole of water, $\mathcal{F}$ is Faraday's number (966315 J/volt equiv), and E is the electrolysis voltage. Thus, the energy required for electrolysis of water can be supplied by application of 1.481 volts (at 298 K).

The minimum electrical energy required for electrolysis, however, is given by the minimum work required which in turn is governed by the Gibbs free energy, ΔG. For water at 298 K and in the liquid state,

$$\Delta G = +237.53 \text{ kJ/g-mole}$$

which is equivalent to 1.299 volts. The remaining energy can, in principle, be supplied by ambient heat.

Additional heat can be supplied by prevaporizing the water, for which the electrolysis energies are

$$\Delta H = +242.18 \text{ kJ/g-mole}$$

which is the lower heating value of hydrogen, and

$$\Delta G = +228.94 \text{ kJ/g-mole}$$

corresponding to voltages of 1.253 and 1.185 volts, respectively. Since electrical energy is increasingly a premium energy source from the viewpoint of both availability and cost, it is advantageous to substitute heat for electrical work when possible.

The electrolysis voltage decreases with increasing temperature according to the Gibbs-Helmholtz equation [Pitzer and Brewer, 1961]

$$\frac{dE}{dT} = \frac{1}{T} E + \left(\frac{\Delta H}{n\mathscr{F}T}\right)$$

which for water vapor at 298 K equals 0.08 volts per 100 K.

Increasing pressure increases the electrolysis voltage, as implied by LeChatelier's principle, with 2 volumes of gaseous water generating 3 volumes of product. Quantitatively, this can be described by the Nernst equation

$$\Delta E^0 = -\frac{RT}{n\mathscr{F}} \ell n \frac{P_{H_2}^2 \, P_{O_2}}{P_{H_2O}^2}$$

or

$$\Delta E^0 = 0.0295 \log P.$$

where P is in atmospheres and ΔE^0 is in volts.

Thus, the voltage changes only logarithmically with pressure, and the electrolysis voltage at 7000 kN/m^2 (1000 psi) is about 0.54 volts higher than the voltage at atmospheric pressure.

The thermochemistry of electrolysis sets the lower voltage limit on electrolysis, but this voltage is attainable only at infinitesimally small currents. In practical electrolyzers, the electrolysis voltage is somewhat higher than theoretical, and this voltage ranges up to 2.3 volts from the calculated minimum of 1.23 volts .

The difference between the actual and theoretical electrolysis voltage is known as the overvoltage (also called polarization or overpotential). The reasons for the higher voltages are many, but they basically are due to the limited rate of processes that occur at the surface of the electrodes, including

Limited rates of half-cell reactions at the electrodes,

Limited rates of diffusion of desired species to the electrode,

Blockage of the electrodes by gases,

Localized increase in electrical resistance due to concentration of the electrolyte at the electrodes.

Other considerations include the ohmic resistance of the electrolyte/separator which keeps the product gases from mixing, and miscellaneous ohmic losses due to cell and electrode construction. In present electrolyzers, much interest and research has been centered on increasing the rates of the electrode reactions, usually by increasing the catalytic activity of the electrodes. As a result, a sound theoretical basis has been laid in this area, although further research must be performed. As electrolyzers increase in current density, the other factors will become increasingly important in determining the efficiency of an electrolyzer.

1. Reactions at the Electrodes

The overall reaction of electrolysis is

$$2H_2O \longrightarrow 2H_2 + O_2$$

but this reaction occurs only partially at each electrode. In alkaline solution, the overall reaction to produce hydrogen is

$$2H_2O + 2e^- \longrightarrow H_2 + 2OH^- \qquad \text{(VII-22)}$$

and the overall reaction to produce oxygen is

$$4OH^- \longrightarrow 2H_2O + O_2 + 4e^- \qquad \text{(VII-23)}$$

The actual mechanism of each of the reactions is unknown, but reaction (VII-23) is the most difficult to perform. From a more general view, it can be argued simply that it is difficult to perform a four-molecule reaction quickly. In any case, electrolyzers are usually operated with an alkaline electrolyte to promote reaction (VII-23) by increasing the concentration of OH^- ions.

The actual rates of reaction are governed by the rate of reaction of water or OH^- ion with the electrode. At constant voltage, this can be represented by an equation of the Arrhenius type involving the active sites on the electrode and the active species in the electrolyte, i.e., for the hydrogen evolution reaction,

$$r_{H_2} = kC_n^aC_{H_2O}^b \exp(-E_{act}/RT) \qquad \text{(VII-24)}$$

where r_{H_2} is the rate of evolution of hydrogen, C_n is the concentration of active sites on the electrode, C_{H_2O} is the concentration of water at the electrode, k is the specific rate constant, and E_{act} is the activation energy for the reaction. The constants a and b depend on the particular mechanism of reaction, but it is seen that the reaction rate varies exponentially with temperature. For many reactions, the reaction rate approximately doubles for each 10°K increase in temperature, a fact that has led electrolyzer manufacturers to attempt high-temperature operation.

2. Types of Electrolyzers

A good review of electrolyzer technology has been given by Gregory [Gregory and Konopka, 1974] and the major types and advantages of each are given below. The alkaline electrolyte systems usually operate with a maximum-conducting solution of potassium hydroxide (20 - 30% KOH) as the electrolyte to reduce ohmic losses. Other systems are the solid-polymer electrolyte (SPE) (General Electric Company) and possibly a high-temperature oxide-conducting electrolyte (also General Electric Company). No work is being conducted on aqueous-type acid electrolyzers although the acid fuel-cell technology of Pratt and Whitney [Leukel and Farus, 1974] may be applicable to new types of devices.

Figure VII-3 shows the performance characteristics of typical electrolyzers which may be available commercially. The trend is to attain higher current densities at low overvoltages, although operation below 1.48 volts (equivalent to the heat of formation of hydrogen) has not been demonstrated at commercial current densities. Real goals are for operation at about 1.6 volts (92% efficiency) at very high current densities. This can be achieved in alkaline cells by continually increasing the temperature and pressure; in SPE cells, increased catalyst loading is the most important factor.

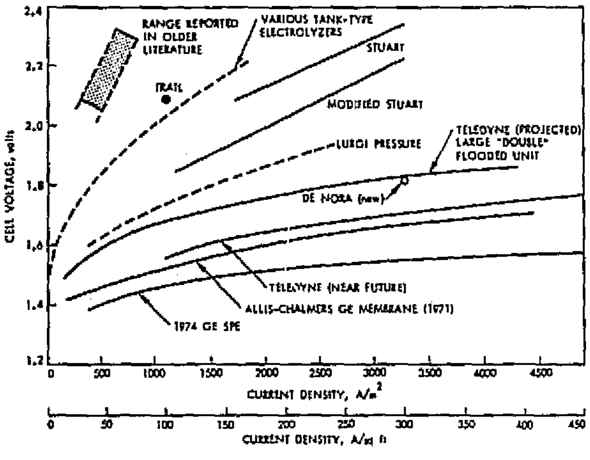

Figure VII-3. Comparative performance of electrolytic systems [IGT, 1973]

a. Alkaline Electrolyte Systems. The two major electrolyzer types are the tank type and the filter-press type, with the latter gaining predominance in current electrolyzer designs. The tank-type electrolyzer is a low-voltage device in which positive and negative electrodes are alternated in a tank, with electrodes of each polarity wired in parallel. For a multiplate configuration, the applied voltage is that of a single large cell. The low voltage necessitates high currents which in turn necessitates extreme care in dealing with ohmic losses. Gregory points out that difficulties in AC to DC power conditioning may also be substantial when low voltages and high currents are required.

The filter-press type electrolyzer utilizes a bipolar construction in which one side of an electrode evolves hydrogen and the other side evolves oxygen. The major advantages of this system are that (1) the packing density of cells in the electrolyzer system is high, giving a smaller electrolyzer and (2) the electrodes are connected in series but with no separate busbar or interconnection other than the electrode itself.

Alkaline electrolyte cells suffer significant problems, such as the relatively high voltage required to produce hydrogen as compared with the theoretical voltage. At typical operating voltages, the thermal efficiency of hydrogen generation at 2.0 volts is only 62%, based on the lower heating value of hydrogen (corresponding to 1.253 volts). Since electrical energy is presently a premium energy source, it is desirable to lower electric-power requirements towards the theoretical limits. The influence of electrolysis voltage on cost is given in Appendix F.

The overvoltage problem is a multifacet problem as shown previously. For alkaline electrolyte systems, the main approach to reducing overvoltage is simply to raise the temperature and pressure of the electrolysis. The electrode reaction rates are increased substantially by temperature as can be seen in equation (VII-24). Increasing the temperature, however, increases the corrosion rate of the alkaline electrolyte on the cell and also greatly degrades the asbestos separators that are normally used in the electrolyzers. Research is presently underway to discover temperature-resistant separators for the conventional electrolyte systems. Increasing the electrode surface area or activity also increases the reaction rate at the electrodes. It adds substantial costs to the electrolyzer, and there is some concern as to lifetime and high-rate blockage problems.

b. Solid-Polymer-Electrolyte Systems. As an outgrowth of their fuel-cell work, General Electric has developed an electrolyzer in which the only electrolyte is a fluorocarbon-based material capable of conducting hydrogen ions when wet. The electrolyte is attached mechanically to current collectors on either side, and a voltage is applied across these collectors. The electrode reactions are basically reactions (VII-22) and (VII-23) occurring in acid solution. At the negative electrode, hydrogen ions receive electrons to form hydrogen:

$$2H^+ + 2e^- = H_2 \qquad \text{(VII-25)}$$

while at the positive electrode, water is decomposed to form oxygen:

$$H_2O = 2H^+ + \frac{1}{2} O_2 + 2e^- . \qquad \text{(VII-26)}$$

Considerable development has gone into the construction of the solid-polymer electrolyte (SPE) electrolyzers, the most important of which is the development of the polymer itself. The electrolyte was developed by duPont for the chloralkali industry and as such has not yet been optimized for electrolyzer operation. There is a general belief that SPE systems will be substantially more expensive than more conventional alkaline systems because of the high cost of the membrane electrolyte (about \$161/m^2, \$15/ft^2) and because of the large noble metal quantities needed for the electrode catalysis and current collectors. They may be able to operate at higher hydrogen production rates and higher efficiencies, however, and compete in overall economics with the more conventional systems.

c. Other Solid-Electrolyte Systems. General Electric has proposed an electrolyzer utilizing a solid-oxide membrane operating at temperatures up to 1350°K (2000°F). Electrolysis proceeds via oxide ion exchange with water absorbing electrons at the negative electrode and releasing hydrogen:

$$H_2O + 2e^- \longrightarrow H_2 + O^{-2} \qquad \text{(VII-27)}$$

and oxide ions releasing electrons at the positive electrode:

$$O^{-2} \longrightarrow \frac{1}{2} O_2 + 2e^- . \qquad \text{(VII-28)}$$

The electrolyte is a metal oxide such as zirconia that is capable of ionic conductivity, but has a low electronic conductivity. A major developmental problem is that electron conduction short-circuits the cell.

3. Technological Requirements of Electrolysis

Large-scale production of hydrogen by electrolysis is only accomplished in areas where hydroelectric power is in surplus and can be supplied at low cost. The reason is, of course, that the costs of hydrogen by electrolysis are dominated by electric-power costs, and that electrical power has been a premium energy form compared to methane, naphtha or other fossil fuel feedstocks. The market for large electrolyzers has been small and comparatively little research and development on improved electrolyzers has been made. Especially lacking are studies on integrated electrolysis/electrical generating stations producing both pure hydrogen and oxygen for sale. Such plants may eventually replace fossil-based plants as fossil fuels become more expensive.

Alkaline electrolyzers are the most advanced commercial systems but are limited in production rate, primarily because they cannot operate at temperatures above about 370 K (200°F). Higher temperatures are a major factor in reducing overvoltage in the electrolyzer, and therefore decreasing electrical usage.

Electrolyzers utilizing solid-polymer electrolytes have not been built on a commercial scale and firm cost data are not available. The environment for SPE systems is less corrosive than for alkaline, and temperature is limited primarily by electrolyte stability which appears to be good. Costs of SPE electrolyzers, however, are high, and production rates at low overvoltage must be very good.

Aqueous acid cells or oxide conducting electrolyte cells are not currently being studied, and probably deserve some attention as alternatives to the two better-known electrolyzers. In particular, the former type may be easier to adapt to high temperature electrolyzers because materials that are resistant to acid at elevated temperatures are more common than those resistant to alkali.

The level of research in electrolysis is low, and considerable improvements can be projected in the areas of higher-temperature operation, improved electrode design, improved electrocatalysts and improved separators. Improved operation allows smaller modules which are amenable to high pressure operation, a factor in decreasing compression costs required for delivery.

E. THERMOCHEMICAL PRODUCTION OF HYDROGEN

The desire to free the production of hydrogen from Carnot efficiency limitations has led to interest in chemical methods to extract hydrogen from water by heat alone. These methods have come to be called "closed thermochemical cycles" by which is meant to imply a system of linked regenerative chemical reactions which accept only water and heat as feedstocks and produce hydrogen and oxygen. (An open thermochemical cycle is meant to be one in which feedstocks such as fossil fuels could be accepted and products such as carbon dioxide could be rejected.)

A trivial example of a closed thermochemical cycle is illustrated by the two-reaction scheme involving a divalent metal:

$$M + H_2O \xrightarrow{\text{low temp}} MO + H_2$$

$$MO \xrightarrow[\text{low temp}]{} M + \frac{1}{2} O_2$$

Such simple cycles have low efficiencies, and many other cycles have been proposed which promise to produce hydrogen at efficiencies comparable with electrolytic manufacture. Methodologies have been developed for analyzing these cycles, and Appendix E presents a comparison of several cycles.

Thermochemical cycles are well known to the chemical industry, and illustrative examples occur in the older literature for the production of oxygen by thermal cycling of compounds, e.g.,

$$2BaO + O_2 \xrightarrow{air} 2BaO_2$$

$$2BaO_2 \xrightarrow{600°F} 2BaO + O_2$$

A major difference of the production of hydrogen from water, however, is the very large amount of energy (143 kJ/kg) which must be applied to produce hydrogen and oxygen. The transfer of this energy tends to give a low process efficiency to thermochemical cycles and reduces their theoretical advantage over Carnot-limited production. In fact, very large energy-consuming processes are largely unknown to the chemical process industry upon whose technology thermochemical cycles must draw.

Major work in thermochemical hydrogen production is being conducted at several institutions among which are the Euratom laboratories at Ispra, the Nuclear Research Center in Juelich, and Mitsubishi Heavy Industries in Tokyo. In the USA, work is being conducted at Los Alamos, Brookhaven and Argonne National Laboratories under ERDA sponsorship; at the University of Kentucky and at Westinghouse under NASA sponsorship; and at the Institute of Gas Technology under AGA sponsorship. General Atomic and General Electric also have company-supported projects.

The large amounts of energy required for the decomposition of water to its elements has inspired analyses of the thermodynamics of multistage processes, and from these analyses it is possible to make some conclusions about the nature of thermochemical processes. An illustrative example involves the analysis of the simple two-stage, two-temperature process. For an ideal process involving no useful work ($\Delta G = 0$), the positive entropy change for the high temperature reaction can be shown to be too large for real substances [Abraham and Schreiner, 1974]. An outline of such an analysis is given in Appendix E.

A review of many thermochemical cycles that have been reported in the literature up to 1973 was given by Chao [Chao, 1974] who grouped all the processes into four basic families: halide processes, processes based on the reverse Deacon reaction, iron and carbon oxide processes, and metal and metal alkali processes. Other processes, of course, may be proposed, and "hybrid" cycles utilizing low-voltage electrolytic steps have been proposed [Westinghouse, 1974].

Closed thermochemical cycles have at least three distinct reaction steps, including 1) a hydrogen-producing reaction, 2) an oxygen producing reaction, 3) a reaction which regenerates materials. Halide processes refer to cycles which bind water by direct reaction with a halide salt, e.g., the iron-chloride reaction (see Table VII-3).

$$3\,FeCl_2 + 4\,H_2O = Fe_3O_4 + 6\,HCl + H_2$$

Cycles based on the reverse Deacon reaction oxidize water with chlorine to release oxygen by the reaction.

$$H_2O + Cl_2 \longrightarrow 2HCl + 1/2\,O_2$$

Iron oxide/carbon oxide processes react water directly with elemental iron or carbon to produce hydrogen, and the oxidized elements are regenerated by methods familiar to open-cycle steam-iron chemistry. Metal or alkali processes which react elemental metals with water or alkaline materials with metal oxides and water operate by reactions such as

$$2H_2O + 2Cs \longrightarrow 2CsOH + H_2$$

or

$$H_2O + Mn_2O_3 + 2Na_2O \longrightarrow$$
$$2Na_2OMnO_2 + H_2$$

Chemically, these are considered similar because metals such as cesium are strong Lewis bases.

Many of these cycles have been examined based on the thermodynamic analysis, and two of the more promising systems are examined in Appendix E.

In addition to pure thermochemical cycles, systems have also been proposed which combine heat-driven reactions with electrochemically-driven reactions, and these are referred to as "hybrid" cycles. The most prominent is that proposed by Westinghouse, originally as a topping cycle for commercial power plants. The major reactions are 1) the thermal decomposition of sulfuric acid

$$H_2SO_4 \longrightarrow H_2O + SO_2 + \tfrac{1}{2}\,O_2$$

and 2) the regeneration of sulfuric acid by electrochemical oxidation of SO_2,

$$H_2O + SO_2(aq) \longrightarrow H_2 + H_2SO_4$$

The above reaction requires about 0.2 volts. An analysis of this system is also presented in Appendix E.

It has been suggested [Bowman, 1974] that the maximum efficiency of a thermochemical cycle can be achieved only if the cycle can be optimized for the temperature available from the heat source. Thus, a different cycle may be desirable for each of the various types of nuclear reactors or solar concentrators. The Institute of

Table VII-3. Thermochemical processes

Process	Temperature (°K)
a. Halide processes	
Calcium Bromide Process, De Beni, Euratom, 1970	
$CaBr_2 + 2H_2O \longrightarrow Ca(OH)_2 + 2HBr$	1000
$Hg + 2HBr \longrightarrow HgBr_2 + H_2$	520
$HgBr_2 + Ca(OH)_2 \longrightarrow CaBr_2 + HgO + H_2O$	470
$HgO \longrightarrow Hg + 1/2\ O_2$	870
Strontium Bromide Process, De Beni, Euratom, 1970	
$SrBr_2 + H_2O \longrightarrow SrO + 2HBr$	1070
$2HBr + Hg \longrightarrow HgBr_2 + H_2$	470
$SrO + HgBr_2 \longrightarrow SrBr_2 + Hg + 1/2\ O_2$	770
Manganese Chloride Process, De Beni, Euratom, 1972	
$6MnCl_2 + 8H_2O \longrightarrow 2Mn_2O_4 + 12HCl + 2H_2$	970
$3Mn_3O_4 + 12HCl \longrightarrow 6MnCl_2 + 3MnO_2 + 6H_2O$	370
$3MnO_2 \longrightarrow Mn_3O_4 + O_2$	1170
Iron Chloride Process, Hardy, Euratom, 1972	
$6FeCl_2 + 8H_2O \longrightarrow 2Fe_3O_4 + 12HCl + 2H_2$	920
$2Fe_3O_4 + 3Cl_2 + 12HCl \longrightarrow 6FeCl_3 + 6H_2O + O_2$	450
$6FeCl_3 \longrightarrow 6FeCl_2 + 3Cl_2$	690
b. Processes based on the reverse Deacon Reactions	
Vanadium Chloride Process, Funk and Reinstrom, Allison Div., G. M., 1964	
$H_2O + Cl_2 \longrightarrow 2HCl + 1/2\ O_2$	970
$2VCl_2 + 2HCl \longrightarrow 2VCl_3 + H_2$	300
$4VCl_3 \longrightarrow 2VCl_4 + 2VCl_2$	970
$2VCl_4 \longrightarrow 2VCl_3 + Cl_2$	300
Iron Chloride Process, De Beni, Euratom, 1972	
$H_2O + Cl_2 \longrightarrow 2HCl + 1/2\ O_2$	970
$2HCl + 2FeCl_2 \longrightarrow 2FeCl_3 + H_2$	870
$2FeCl_3 \longrightarrow FeCl_2 + Cl_2$	620
Iron Chloride-Iron Oxide Process, Hardy, Euratom, 1972	
$3H_2O + 3Cl_2 \longrightarrow 6HCl + 3/2\ O_2$	970
$3Fe_2O_2 + 18HCl \longrightarrow 6FeCl_3 + 9H_2O$	390
$6FeCl_3 \longrightarrow 6FeCl_2 + 3Cl_2$	690
$6FeCl_2 + 8H_2O \longrightarrow 2Fe_3O_4 + 12HCl + 2H_2$	920
$2Fe_3O_4 + 1/2\ O_2 \longrightarrow 3Fe_2O_3$	620

Table VII-3. Thermochemical processes (contd)

Process	Temperature (°K)
b. Processes based on the reverse Deacon Reactions (contd)	
Copper Chloride Process	
$H_2O + Cl_2 \longrightarrow 2HCl + 1/2\ O_2$	970
$2HCl + 2CuCl \longrightarrow 2CuCl_2 + H_2$	470
$2CuCl_2 \longrightarrow 2CuCl + Cl_2$	870
Chromium Chloride Process, Knoche, Julich, 1972	
$H_2O + Cl_2 \longrightarrow 2HCl + 1/2\ O_2$	970
$2HCl + 2CrCl_2 \longrightarrow 2CrCl_3 + H_2$	470
$2CrCl_3 \longrightarrow 2CrCl_2 + Cl_2$	1070
HCl Thermal Decomposition Process	
$H_2O + Cl_2 \longrightarrow 2HCl + 1/2\ O_2$	970
$2HCl \longrightarrow H_2 + Cl_2$	1070
c. Iron oxide and carbon oxide processes	
Steam-Iron-CO_2 Process, Von Fredersdorff, IGT, 1959	
$Fe + H_2O \longrightarrow FeO + H_2$	
$3FeO + H_2O \longrightarrow Fe_3O_4 + H_2$	820 to
$Fe_3O_4 + CO \longrightarrow 3FeO + CO_2$	1220
$FeO + CO \longrightarrow Fe + CO_2$	
$2CO_2 \longrightarrow 2CO + O_2$	590
Carbon-Steam-Iron Process, Marchetti-De Beni, Euratom, 1970	
$C + H_2O \longrightarrow CO + H_2$	920
$CO + 2Fe_3O_4 \longrightarrow C + 3Fe_2O_3$	520
$3Fe_2O_3 \longrightarrow 2Fe_3O_4 + 1/2\ O_2$	1670
d. Metal and alkali metal processes	
Tin Oxide Process, Souriau, Gaz De France, 1972	
$Sn + 2H_2O \longrightarrow 2H_2 + SnO_2$	670
$2SnO_2 \longrightarrow 2SnO + O_2$	1970
$2SnO \longrightarrow SnO_2 + Sn$	970
Manganese-Sodium Oxide Process, De Beni, Euratom, 1972	
$Mn_2O_3 + 4NaOH \longrightarrow 2NaO \cdot MnO_2 + H_2O + H_2$	1070
$2NaO \cdot MnO_2 + H_2O \longrightarrow 2NaOH(aq) + 2MnO_2$	370
$2MnO_2 \longrightarrow Mn_2O_3 + 1/2\ O_2$	870

Gas Technology [Gregory, et al, 1975] has indicated that other factors are also involved, namely: 1) generally the fewest number of required chemical reactions produce the higher cycle efficiencies, 2) cycles using higher input temperatures produce higher efficiencies and 3) the lower corrosivity product compounds create less operational difficulties.

F. PRODUCTION OF HYDROGEN BY SOLAR ENERGY

Solar energy is a clean, non-depletable energy source and has attracted much attention as an alternative to fossil and nuclear energy for future use in the high-grade energy market. The major problem with solar energy is the cost of collecting it. The surface of the earth receives about 550-1400 watts/m^2 (50 to 100 watts/ft^2) of radiation which can be collected without concentrators at less than 520°K (250°F). By contrast, a coal-fired power plant receives about 2200 kw/m^2 (200,000 watts/ft^2) in the firebox at temperatures of 1500°K (2400°F) resulting in a low cost, compact energy conversion system. Concentration of solar radiation to similar values requires substantially higher costs of collectors, but it is generally conceded that concentration is necessary to produce synthetic fuels or electricity.

Another feature of solar energy is its diurnal nature which, from an economics standpoint, means that capital tied up in solar collectors is utilized only 50% of the time or less. This effectively doubles the cost of solar energy over continuous energy sources of comparable capital outlay. Thus, the successful utilization of solar energy to produce hydrogen must center on low-cost or highly efficient collection of energy. Several methods have been proposed to do this including methods to directly use both solar heat and solar radiation, and methods using biological activity by modified photosynthesis, or by digestion of biological materials.

The diurnal nature of solar energy requires also that energy be stored to provide a continuous energy supply, and it has been proposed that hydrogen be used as the energy storage medium [Eisenstadt and Cox, 1975]. For indirect methods such as digestion of biological materials, storage is accomplished merely by providing a sufficient inventory of digestible material.

Several methods for the production of hydrogen from solar energy have been proposed, and these can be roughly separated into those that use solar heat, and those that use solar radiation, usually from the more energetic portion of the ground-level spectrum. Combinations of the two have not been studied because of the preliminary nature of the latter techniques, but the application towards increasing efficiencies is apparent.

1. Solar Heat

Solar heat can be concentrated to form high grade energy which can be used to produce hydrogen through processes similar to nuclear or combustion heat, i.e., steam-cycle/electrolysis or thermochemical cycles. These technologies have been discussed in earlier sections and depend primarily on collection of heat at sufficient temperature to drive the processes efficiently. In addition, collection to very high temperatures may allow direct thermal splitting of water at low pressure [Sebacher and Sabol, 1975], a process that might be considered as a topping cycle when such temperatures are available. Figures VII-4 and VII-5 show the approximate effects of temperature and pressure on the equilibrium radical concentrations of water at high temperature and low pressure. In principal, hydrogen is diffused through a palladium membrane or similar device so that the system is maintained in a non-equilibrium state. Materials problems are severe and volumetric efficiencies are low because of the low pressure.

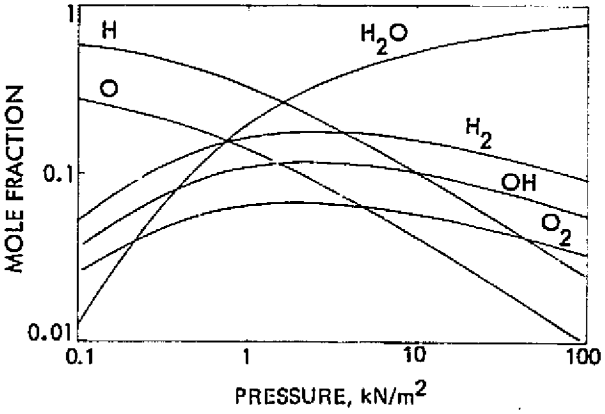

Figure VII-4. Species concentration for equilibrium H_2O
T = 2800 K

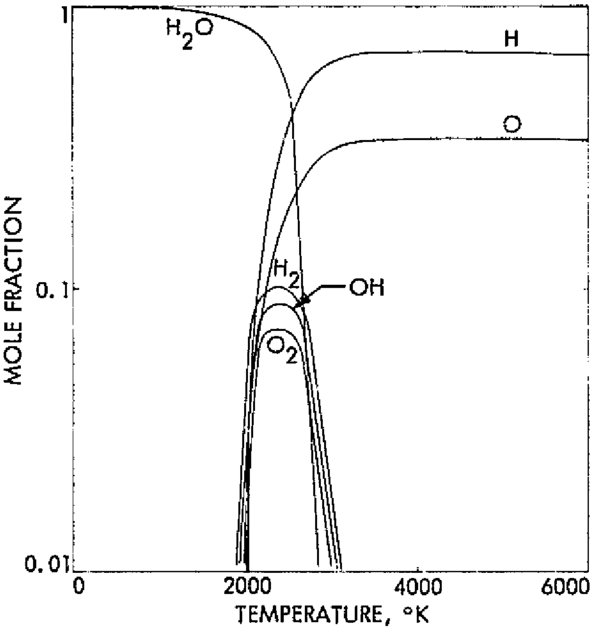

Figure VII-5. Species concentration for equilibrium H_2O
P = 132 N/m^2

2. Direct Use of Solar Radiation

Solar radiation at wavelengths below 525 nm contains sufficient energy to decompose water directly. Water, however, does not absorb light appreciably at wavelengths above 185 nm, and, as a result, direct photolysis does not occur appreciably at ground level. An energy transfer mechanism is required to allow the photon energy to decompose water directly.

Several methods of energy transfer have been proposed which allow the direct use of radiative energy to produce hydrogen without resorting to a Carnot-limited procedure. These include:

Photovoltaic-electrolysis methods.

Heterogeneous photo-assisted oxidation-reduction reactions.

Homogeneous photo-assisted oxidation-reduction reactions.

As in thermal water splitting, single or multistep processes can be utilized, with multistep processes having the advantage of potential use of the full ground-level solar spectrum from which to draw their energy. Single-step water splitting requires efficient utilization of radiation which, in a practical sense, means that recombination reactions must be slow. This is difficult in the very energetic reactions that single-step photolysis must employ.

a. Photovoltaic Methods. Photovoltaic cells, when placed in series, can generate the voltage needed to split water electrolytically. The electrical intermediate can be considered as the energy transfer medium, and since single cells can generate less than about a volt, the method can be considered as a multistep process.

The well-known factor in photovoltaic systems is the high cost of the solar cells, with current costs at about \$1600/m^2 (\$150/ft^2). Estimates are that costs must be reduced to about \$90/m^2 (\$8/ft^2) for feasible commercial systems. Considerable promise for new, low-cost manufacturing techniques has recently been demonstrated for both silicon-crystal and gallium-arsenide technology.

b. Heterogeneous Photo-Redox Methods. Heterogeneous photo-assisted redox reactions generally refer to reactions at semiconductor surfaces, and the production of H_2O_2 from ZnO, CdS and CdSe surfaces upon irradiation is well known [Calvert, 1963].

A recent study [Fujishima and Honda, 1972] has shown that irradiation of n-type TiO_2 semiconductors liberated oxygen and, at a platinum electrode through an electrical connection, liberated hydrogen. Figure VII-6 shows a schematic of their system in which the major reactions were

$$n - TiO_2 \xrightarrow{h\nu} 2e^- + 2p^+ \qquad (VII\text{-}50)$$

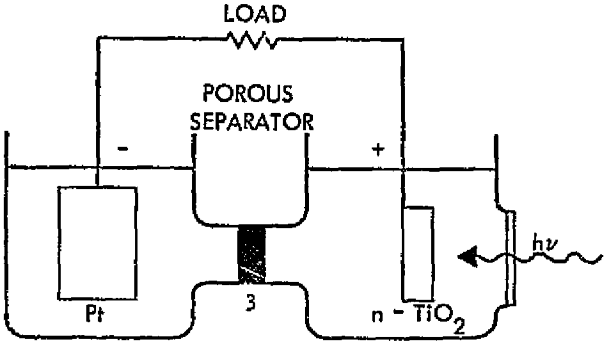

Figure VII-6. Photo-electrochemical cell

$$2p^+ + H_2O \xrightarrow{TiO_2} \frac{1}{2} O_2 + 2H^+ \qquad (VII\text{-}51$$

$$2e^- + 2H^+ \xrightarrow{Pt} H_2 \qquad (VII\text{-}52)$$

The radiation produces electron/hole pairs of sufficient energy to evolve oxygen on the semiconductor and hydrogen externally. TiO_2 can be considered the energy transfer medium for the photolysis of water. The process occurs only at wavelengths shorter than 415 nm with quantum efficiencies of about 0.1. The overall efficiency is only about 0.8% since only 8% of the sea level radiation lies below 415 nm.

c. Homogeneous Photo-Redox Methods. Homogeneous photo-assisted redox reactions refer to direct irradiation of solutions which contain chemicals capable of absorbing solar radiation and transferring it to water for photolysis. Organic systems including dye systems are generally considered too susceptible to bleaching for this purpose, and efforts center on inorganic systems. An example of such a system frequently cited [Heidt, 1951] is based on cerium ions

$$2Ce^{+++} + 2H_2O \xrightarrow{h\nu} 2Ce^{++++} + H_2 + 2OH^- \qquad (VII\text{-}53)$$

$$2Ce^{++++} + H_2O \xrightarrow{h\nu} 2Ce^{+++} + 2H^+ + \frac{1}{2} O_2 \qquad (VII\text{-}54)$$

Reaction (VII-53) is a photo-oxidation reaction, and (VII-54) is a photo-reduction reaction. The net result is the decomposition of one water molecule. This particular reaction sequence occurs at wavelengths less than 254 nm while the shortest wavelength in the ground-level spectrum is about 290 nm. Efforts are presently underway to develop systems that absorb in the ground level spectrum [Ryason, 1974]. This may require multistep reactions which absorb lower energy radiation, much like the process that occurs in photosynthesis.

G. BIOLOGICAL PRODUCTION OF HYDROGEN

The potential of using biochemical reactions for the production of hydrogen is such that if the numerous problem areas can be surmounted it would fill a moderate percentage of the forseeable future energy requirements of the United States. Only very small proportions of hydrogen are evolved from living matter in nature. Most biological reactions are complex and sensitive. The ultimate external feedstocks for a great number of these processes are water and carbon dioxide, which are used with solar energy to form carbohydrates by green plants in the photosynthesis process.

The myriad chemical reactions on which all living processes depend are brought about by enzymes. These are large-molecule proteins which function as catalysts upon various substrates in aqueous systems. The individual reactions are quite sensitive to a variety of local conditions, such as temperature, reactant concentration, and the presence of other chemical species, and may be reversible on changes in conditions. Many reactions, each controlled by its particular enzyme, may form a long chain to constitute a particular synthesis or other process.

Processes which produce hydrogen in biological systems are governed by series of enzymes called hydrogenase systems. The final enzyme in such a system is called hydrogenase; it produces molecular hydrogen from a predecessor substrate or, if the reaction is reversed, converts the hydrogen into the substrate for ultimate metabolic application. Hydrogenase does not itself split water; even a hydrogenase system does not usually begin operating on water, but usually on an organic intermediate such as adenosine triphosphate.

1. Photosynthesis of Hydrogen

A few unicellular algae and photosynthetic bacteria are able to use light as an energy source in the production of small amounts of gaseous hydrogen. All these organisms use some form of a chlorophyll and/or carotenoid molecules as the light-trapping agents. Oxygen tends to reduce the production of hydrogen and, under anaerobic metabolism, a simultaneous reabsorption of hydrogen gas occurs with an equilibrium between evolution and consumption. It appears feasible that a mutant may be found where the reabsorptions of hydrogen would be suppressed. Considerable efforts would be required to bring the technology to a useful level.

2. Anaerobic Fermentations

In anaerobic fermentations a large number of unicellular organisms produce small proportions of hydrogen in mixed gaseous evolution (less than 1% hydrogen, 65-70% methane, 25-30% carbon dioxide). In municipal sewage sludge digesters which use this biological method, large volumes of the mixed gas are produced and used as fuel. It would be possible, though unlikely to be competitive, to remove the methane evolved in such plants and steam reform it to hydrogen.

3. Summary

Biological production of hydrogen is in the research stage at present. A thorough understanding of the relevant reactions and their governing conditions and enzymes might lead to the development of practical hydrogen production processes. At this point two plausible approaches appear:

1. Production via hydrogenase in living systems at yields greatly improved by some means, following improved understanding of biochemical processes.
2. Conversion of fermentation-produced methane to hydrogen, under circumstances in which it is cost-effective and energy-efficient to do so.

H. SUPPLY OPTIONS

The spectrum of hydrogen production methods, their relative costs and technology status, as delineated in previous sections of this chapter, constitute a basic framework within which supply options can be selected to meet the projected usage levels of Chapter II. Two use scenarios and associated projections, a "Reference" based on the FTFB and an "Expanded" based on the NEE, were developed. These projections can be supplied by "captive" hydrogen produced as an integral part of the end use system or by "merchant" hydrogen which is produced in separate facilities and sold to operators of end use systems.

Two supply options, a "low-merchant" and a "high-merchant" case, were identified in Chapter III as bounds on the division between merchant and captive modes of supply. The present-day mode of supply is "low-merchant" based on natural gas and petroleum-based processes. Due to factors such as economies of scale and plant siting constraints, a shift to "high-merchant" supply options is indicated for processes employing coal, nuclear, solar, and geothermal feedstocks and/or energy sources.

1. Projections of Merchant Hydrogen Usage

Hydrogen usages for the Reference and Expanded projections are presented in Tables II-2 and II-3, respectively. The quantity of merchant hydrogen used to meet this usage is presented in Table VII-4 in terms of both the low and high merchant options. Notes accompanying this table describe the rationale employed to estimate merchant quantities. Basically, the fraction of hydrogen that could be supplied by merchant hydrogen for each end use category was first estimated in terms of representative processes (see Table III-1). The high merchant quantities are based on the highest fraction deemed possible whereas the low merchant quantities are estimated largely on the basis that (1) present merchant markets will continue to be viable and (2) no new merchant markets will be created.

Table VII-4. Merchant hydrogen projections, 10^{18} J (10^{15} Btu) of hydrogen

Use Category	Year 1985				Year 2000			
	Reference		Expanded		Reference		Expanded	
	LOW	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
Unique Chemical								
Ammonia[1]	NIL	0.767 (0.726)	NIL	1.101 (1.044)	NIL	1.828 (1.731)	NIL	4.181 (3.960)
Petroleum Refining[2]	NIL	0.367 (0.348)	NIL	0.282 (0.267)	NIL	0.584 (0.553)	NIL	0.277 (0.262)
Methanol and Others[3]	NIL	0.143 (0.135)	NIL	0.197 (0.187)	NIL	0.400 (0.379)	NIL	2.865 (2.713)
Hydrogenation of Oils and Fats	0.006 (0.006)	0.012 (0.011)	0.006 (0.006)	0.011 (0.010)	0.027 (0.026)	0.033 (0.031)	0.023 (0.022)	0.029 (0.027)
Synthetic Fuels[4]								
Shale	NIL	0.0273 (0.0259)	–	NIL	NIL	0.106 (0.100)	–	NIL
Coal to SNG	–	–	NIL	0.478 (0.453)	NIL	0.342 (0.324)	NIL	3.363 (3.185)
Coal to SNC	–	–	–	–	NIL	0.893 (0.846)	NIL	2.680 (2.538)
Direct Reduction	NIL	0.064 (0.061)	NIL	0.222 (0.210)	NIL	0.229 (0.217)	NIL	0.686 (0.650)
Transportation								
Space Shuttle[5]	NIL	0.0014 (0.0013)	NIL	0.0014 (0.0013)	NIL	0.0014 (0.0013)	NIL	0.0014 (0.0013)
Air	NIL	NIL	NIL	NIL	NIL	NIL	0.993 (0.940)	0.993 (0.940)
Ground	NIL	NIL	NIL	NIL	NIL	NIL	1.016 (0.962)	1.016 (0.962)
Water	NIL	NIL	NIL	NIL	NIL	NIL	0.634 (0.600)	0.634 (0.600)
Residential and Commercial								
Utilities								
Electric	–	–	NIL	NIL	NIL	NIL	NIL	NIL
Gas							0.248 (0.235)	0.248 (0.235)
Miscellaneous[6], including welding and process heat	0.086 (0.081)	0.154 (0.146)	0.121 (0.115)	0.190 (0.180)	0.358 (0.339)	0.427 (0.404)	0.586 (0.555)	0.655 (0.620)
Total Merchant	0.09 (0.09)	1.5 (1.4)	0.13 (0.12)	2.5 (2.4)	0.39 (0.37)	5.1 (4.8)	3.5 (3.3)	24 (22)
Total Demand	2 (1.9)	2 (1.9)	4 (3.8)	4 (3.8)	5.8 (5.5)	5.8 (5.5)	18 (17)	24 (22)
Percentage of Total %	5	79	3	63	7	88	15	75

Note to Table VII-4

[1] Ammonia: At the present time, in this country, the feedstock natural gas which provides the hydrogen in ammonia cannot be easily or economically replaced by other sources. The hydrogen required for ammonia synthesis may come from a number of other sources. Some of these in order of increasing cost are: steam reforming of naphtha, partial oxidation of heavier hydrocarbons, coal gasification, steam iron process, electrolysis, and other advanced H_2 production processes. The existing ammonia production plants would require considerable equipment modification if they are required to use feedstocks other than natural gas for H_2 production. Also, if pipeline H_2 is used, then air separation plants are required for nitrogen supply. Hence, in the low case it is unlikely that merchant hydrogen would be used by ammonia industry in 1975-1985 time frame. We have assumed that present plants would continue to operate with traditional supplies, and if forced to seek alternate feedstocks would switch to available hydrocarbons. In the high case, we assume that all hydrogen requirements for ammonia production above the 1973 level could be potentially met by merchant hydrogen. For the 1985-2000 time frame, with traditional fossil fuels hard to obtain at reasonable cost, market for merchant hydrogen could potentially be the total H_2 demand for ammonia production.

[2] Petroleum Refineries: In 1970, a total of 111×10^3 m^3/day (1.63×10^{18} J/year) (700,000 (1.54×10^{15} Btu/year) barrels/day) of hydrocracking capacity was installed. Whereas, in 1972, 133,396 m^3/day (839,080 barrels/day) or 1.877×10^{18} J/year (1.778×10^{15} Btu/year)) of hydrocracking was reported [Oil and Gas Journal, Mar. 1972]. The prime reason for the accelerated interest in hydrocracking is because it accomplishes two needed functions in the petroleum economy: large, unwieldy molecules are cracked, and the needed hydrogen is added to produce useful, high quality fuels. Hydrocracking requires large quantities of hydrogen consumption 267-534 m^3/m^3 (1500 scf—3000 scf/barrel) of feed. To take full advantage of hydrocracking, the process must be integrated in the refinery with other processes. For example, the hydrocracker product must be further processed in a catalytic reformer in gasoline production. Catalytic reforming produces about 142 m^3/m^3 (800 scf/barrel). Hence, it is evident that plants which have hydrocracking facilities could use the "deficit" of about 125-392 m^3/m^3 (700 scf—2200 scf/barrel) as externally supplied, i.e., merchant hydrogen. Indeed, the Standard Oil of California (Richmond Isomax) has a large integrated plant processing 10254 m^3 (64500/barrel) per day supplied by a 3.82×10^6 m^3/day (135×10^6 scf/day) hydrogen production plant operating on natural gas (average external H_2 ~374 m^3/m^3 (~2100 scf/barrel)). [Biederman, 1975].

In 1971, hydrocracking consisted 7.3 percent of the total crude charged [Oil and Gas Journal, 1972]. Hydrocracking growth has been about 5.8 percent for the past several years [Mason, H.F., and Tolberg, R.S., 1973]. Hence, the hydrocracking processing (crude equivalent) could be anywhere between 7.3% and 10% of the total crude processed in the energy demand supply scenarios. Maximum merchant hydrogen potential estimated at 392 m^3/m^3 (2200 scf/barrel) of feed to hydrocracking units 0.119 J H_2/J (0.119 Btu H_2/Btu) of crude feed to hydrocrackers.

[3] Methanol and Other Chemicals: When we estimated the total hydrogen demand, we used a figure of ~2.34 m^3/Kg (~75000 scf/ton) of methanol. Recent studies by the Institute of Gas Technology indicate that if hydrogen is externally available, shift reaction in methanol production could be avoided and thus the total coal consumption decreased. Externally obtained H_2 requirements are 1.436 m^3/Kg (~46000 scf/ton). Therefore we assume that this then is the merchant hydrogen requirement for methanol production. For the low case in 1975-1985 time frame, it is assumed that past ways of production techniques continue. For the high case, it is assumed that all excess capacity over 1973 levels is merchant H_2 supplied. For the 1985-2000 time frame, all new methanol production facilities are assumed to be planned and built with externally supplied hydrogen to reduce the carbon consumption.

[4] Synthetic Fuels: When we estimated the total hydrogen demand for synthetic fuels, we used the following figures for hydrogen consumption:

$$\left.\begin{array}{l} \text{Coal} \longrightarrow \text{SNG } 44\ m^3/28\ m^3 \text{ (1560 scf/1000 scf)} \\ \text{Coal} \longrightarrow \text{SNC } 1158\ m^3/m^3 \text{ (6500 scf/barrel)} \\ \text{Shale} \quad \rightarrow \text{SNC } 232\ m^3/m^3 \text{ (1300 scf/barrel)} \end{array}\right\} \quad \text{Hydrogen per unit of the product}$$

The above mentioned quantities are the total H_2 requirements for obtaining the correct carbon/hydrogen ratios. All the processes designed for coal to synthetic fuel could be modified for external hydrogen use. This involves in some, getting rid of the shift reactor and directly adjust the C/H ratio by adding the outside hydrogen at the appropriate process step. Coal consumption could be significantly reduced by providing merchant hydrogen. Modified coal to synthetics would require the following quantities of merchant hydrogen.

Coal ⟶ SNG ~8 $m^3/28\ m^3$ (~1000 scf/1000 scf)
Coal ⟶ Gasoline ~1318 m^3/m^3 (~7400 scf/barrel) (Includes hydrogen required for refining)
Coal ⟶ SNC ~891 m^3/m^3 (~5000 scf/barrel) (Allowing 427 m^3/m^3 (2400 scf/barrel) for hydrogen processing)
Shale ⟶ SNC ⟶ Gasoline ~427 m^3/m^3 (~2400 scf/barrel)
Shale ⟶ SNC ~196 m^3/m^3 (~1100 scf/barrel) (Allowing 232 m^3/m^3 (1300 scf/barrel) for refining)

Note that for Shale ⟶ Gasoline, by providing increased quantities of hydrogen, a significant amount of medium Btu fuel gas could become a byproduct or feed for SNG production.

[5] Space Shuttle: Inability of merchant hydrogen suppliers to meet NASA's liquid hydrogen requirements appears to be forcing NASA to build its own hydrogen plant. This plant will use coal gasification and will involve ERDA participation in research and technology development.

[6] Miscellaneous: For the low case, it is assumed that during the 1975-1985 time frame ~50-75% of required hydrogen for this category is produced and consumed on site by small production devices. For the 1985-2000 time frame this reduces to less than 20% because of the increase availability of externally produced hydrogen. For the high case, the total requirement is met by externally produced hydrogen.

2. Low Merchant Supply Option

The percentage of hydrogen supplied by primary feedstock/energy sources for the low merchant option is presented in Table VII-5. The percentage breakdown is given in terms of major end use categories. These estimates are based on current established practice and trends that are consistent with the Reference scenario and use projection. The end use breakdowns are summed to show the total percentage of hydrogen that is to be supplied by each source.

This percentage source breakdown is then used in Table VII-6 along with the appropriate hydrogen production efficiency (see Fig. III-4) to determine the quantity of primary sources required. The source breakdown is presented within the framework of the FTFB energy scenario and the Reference hydrogen use projection derived in the context of this energy scenario. A breakdown is also presented for actual 1973 usage to provide a basis for comparison.

An overall value for hydrogen production efficiency based on a weighted average of the processes employed is also presented in Table VII-6. This weighted average efficiency decreases for the 1985 and year 2000 projections because there is a shift away in terms of percentage usage from the more efficient production process of steam reforming involving use of natural gas. In terms of actual quantities, use of natural gas for hydrogen production increases from the present through the year 2000. A rise in the usage of coal for hydrogen production to the point where it is the dominant source by the year 2000 is indicated. Table VII-6 also shows that the percentage of primary sources required for hydrogen production will increase from about 3% in 1973 to approximately 10% in the year 2000.

3. High Merchant Supply Option

The high merchant supply option is treated in a manner parallel to the low merchant option. Since the Reference Use projection was used for the low merchant option, it is also used for the high merchant option to provide a basis for direct comparison. The high merchant option is predicated on shifts to merchant supply modes and associated processes. But in terms of the time required to implement new processes, there will essentially be no major change evident by 1985. Thus, the high merchant percentage breakdown of Table VII-7 for 1985 is essentially the same as the low merchant estimate of Table VII-5.

By the year 2000, however, a comparison of Tables VII-5 and VII-7 indicates that the high merchant option involves a major shift to sources other than natural gas, oil, and coal. For the low merchant option, the category of "other" sources comprised only 1% in the year 2000 whereas in the high option it accounted for approximately 22%.

Using hydrogen production efficiencies for fossil fuel process (see Fig. III-4), nuclear processes (see Fig. III-6), and other non-fossil energy systems (see Fig. III-7), together with the percentage source breakdown of Table VII-7, permits the estimation of primary source usage shown in Table VII-8. For the FTFB and associated Reference projection, results from Table VII-8 can be directly compared with corresponding estimates for the low merchant option given in Table VII-6. In the year 2000, the greater use of merchant options having lower efficiency has resulted in an average efficiency of about 36% for the high option as compared to about 45% for the low option.

Table VII-5. Low-merchant percentage matrix of sources and uses (Reference Use Projection)

End Use	1985					2000				
	Totals by Use	Supplied By				Totals by Use	Supplied By			
		Gas	Oil	Coal	Others*		Gas	Oil	Coal	Others*
Ammonia	39.3	30.0	9.3	—		31.5	12.0	10.5	9.0	
Refineries	35.8	5.8	30.0	—		14.3	5.0	9.3	—	
Methanol and Others	12.0	8.0	4.0			11.0	—	2.0	9.0	
Synthesis for Coal, Shale, Solid Wastes	1.0			1.0		31.2			31.2	
Direct Reduction	3.3	1.0	2.3	—		4.0		2.2	1.8	
Miscellaneous including Shale	8.6	5.2**	2.8	—	0.6	8.0	4.2**	2.8**	—	1.0
Totals by Source	100%	50.0	48.4	1.0	0.6	100%	21.2	26.8	57.0	1.0

Note: The numbers in the table represent percentage of the total hydrogen demand estimated in the Reference use projection (see Table II-2).

*Includes shale, tar sands, dispersed small electrolytic units, solid wastes, etc.

**Merchant hydrogen needs (see Table II-2 for Reference Projections) of 47% in 1985 and 67% in 2000 met by these sources.

Table VII-6. Primary energy sources required for low merchant options

	Actual 1973	Reference 1985	Expanded 1985	Reference 2000	Expanded 2000
Total Energy Demand, 10^{18} J (10^{15} Btu)	79 (75)	98 (93)	116 (110)	131 (124)	219 (207)
Total H_2 Demand, 10^{18} (10^{15} Btu)	1.1 (1.0)	2.0 (1.9)	4.0 (3.8)	5.8 (5.5)	23.6 (22.3)
Sources Required, 10^{18} J (10^{15} Btu), with % of hydrogen supply	(10^{15} Btu)				
Coal	0.03 (0.03) 1%	0.04 (0.04) 1%	1.0 (1.0) 13.7%	6.5 (6.2) 51%	22.9 (21.7) 45%
Oil	0.6 (0.6) 23%	2.3 (2.2) 49%	3.8 (3.6) 40.5%	3.8 (3.6) 27%	2.4 (2.2) 5%
Natural Gas	1.3 (1.2) 76%	1.9 (1.8) 50%	2.6 (2.5) 40.3%	2.5 (2.3) 22%	2.0 (1.9) 5%
Solid Wastes	—	Negligible	Negligible	Small	Small
Nuclear	—	—	1.5 (1.4) 7%	—	41.0 (38.8) 40%
Solar-Thermal	—	—	—	—	5.9 (5.6) 5%
Total Sources Required	1.9 (1.8) 100%	4.2 (4.0) 100%	9.0 (8.5) 100%	12.8 (12.1) 100%	74.2 (70.2)
Overall Hydrogen Production Efficiency*	52%	45.8%	44.9%	45.1%	31.78%
Percentage of Primary Source* Required for Hydrogen Production	2.8%	4.4%	7.7%	9.8%	33.9%

Source: Table VII-4 and Figure III-2.

*For the estimated mix of primary sources

Table VII-7. High-merchant percentage matrix of sources and use

End Uses	1985					2000				
	Total By Use	Supplied By				Total By Use	Supplied By			
		Gas	Oil	Coal	Others*		Gas	Oil	Coal	Others*
Ammonia	39.3	30.0	9.3			31.5	12.0	10.0	—	9.5
Refineries	35.8	5.8	30.0			14.3	5.0	9.0	—	0.3
Methanol and Others	12.0	8.0	4.0			11.0	—	2.0	9.0	—
Synthesis for Coal, Shale, Solid Wastes	1.0	—	—	1.0		31.2	—	—	24.0	7.2
Direct Reduction	3.3	1.0	2.3			4.0	—	1.0	2.0	1.0
Miscellaneous including Shale	8.6	5.2**	2.8		0.6	8.0	42	—	—	3.8
Totals By Source	100.0%	50.0	48.4	1.0	0.6	100.0%	21.2	22	35**	21.8**

Note: The numbers in the table represent percentage of the total hydrogen demand estimated in the Reference use projection (see Table VI-2).

*Includes large integrated production facilities coupled with solid waste processing, nuclear, solar, wind, geothermal, etc., plants.

**These sources partially supply the total High Merchant estimates of 78.5% in 1985 and 87.8% in the year 2000 for the Reference projection. See Table VII-4.

Table VII-8. Primary energy sources required for high merchant supply option

	Actual 1973	Reference, 1985	Expanded 1985	Reference, 2000	Expanded 2000
Total Energy 10^{18} J (10^{15} Btu)	79 (75)	98 (93)	116 (110)	130 (124.5)	219 (207)
Total Hydrogen Demand, 10^{18} J (10^{15} Btu)	1.1 (1.0)	2.0 (1.9)	4.0 (3.8)	5.8 (5.5)	23.6 (22.3)
Sources Required, 10^{18} J (10^{15} Btu), with % of hydrogen supply					
Coal**	0.03 (0.03) 1%	0.04 (0.04) 15%	1.0 (1.0) 13.7%	4.4 (4.2) 35%	22.9 (21.7) 45%
Oil	0.6 (0.6) 23%	2.3 (2.2) 49%	3.8 (3.6) 40.5%	3.1 (3.0) 22%	—
Natural Gas	1.3 (1.2) 76%	1.9 (1.8) 50%	2.6 (2.5) 40.3%	2.5 (2.4) 21%	—
Nuclear**	—	—	1.5 (1.4) 7%	—	40.9 (38.8) 40%
Solar, Wind, Hydro**	—	—	—	5.8 (5.5) 22%	17.7 (16.7) 15%
Total Sources Required	1.9 (1.8) 100%	4.2 (4.0) 100%	9.0 (8.5) 100%	15.8 (15.1) 100%	81.5 (77.2) 100%
Overall Hydrogen Production Efficiency*	50%	45.8%	44.9%	36.4%	29%
Percentage of Primary Source* Required for Hydrogen Production	2.8%	4.4%	7.7%	12.2%	37.2%

Source: Table III-6 and Figures III-6 and III-7.

*For the estimated mix of primary sources.

**Sources potentially suitable for high merchant supply at 62.3% in 1985 and 74.7% in the year 2000 for the Expanded Use projections.

The basic procedures described above for estimating merchant hydrogen quantities for the Reference use projection are of course applicable to the Expanded use projection. The final column in Table VII-8 pertains to the NEE and associated Expanded projection for the year 2000. It has been included to show that implementation of the Expanded projection has major ramifications, particularly since it infers that about 3% of primary sources will be required for hydrogen production.

4. Implications of Supply Options

The investigation of supply options shows that significant fractions of primary energy sources will be required to meet projected hydrogen usage. In addition to natural gas, the present day dominant source, new sources having inherently lower efficiencies and higher costs must be used. In this context, technological advances to improve cost effectiveness of new production processes is essential for both economic viability and resource conservation.

The supply options and their ramifications with regard to primary resource and production technology requirements constitute a basic input to the foundation for program planning established in the present report.

I. HYDROGEN PRODUCTION COST EVALUATION

A method of evaluating costs for various hydrogen production methods was needed by the HEST Study because cost is and will be the dominant parameter by which major means of production compete and are selected notwithstanding other economic factors such as scale and distribution, technical parameters such as purity and environmental and other impacts, which will undoubtedly influence decisions regarding hydrogen production.

The purposes of the cost evaluation were to compare the costs of hydrogen produced by the various methods, and to direct recommendations on new technology toward the most cost-effective options. The approach was to construct a flexible cost-evaluation scheme which permitted the variation of the assumptions relative to defined input parameters, the isolation of the effect of any single parameter, and the determination of the most cost-effective alternative as a function of the assumptions.

The estimation of capital costs for hydrogen production by different processes is rendered uncertain (according to available studies of new production technologies, such estimates are accurate only within an order of magnitude) by the lack of commercial experience with most such technologies — in some cases, the technology is only conceptual. Estimates of most feedstock costs are made uncertain by their dependence on factors (such as government regulatory policy, energy-independence policy, and foreign or domestic prices) whose future directions are themself uncertain.

Therefore the hydrogen production cost evaluation scheme developed for this Study stressed evaluation of the effect of changes in the cost factor parameters on the cost of hydrogen rather than any attempt to generate precise cost estimates. The scheme, which is described and worked out in detail in Appendix F, permits alternate assumptions and cost factor estimates to be "plugged in" as the reader prefers or as various factors become better understood.

Costs were calculated for six alternative methods of producing hydrogen, which represent great variation in the degree to which cost factors may be estimated accurately, as well as in the influence of various kinds of factors. The methods are:

1. Steam reforming of natural gas, the predominant current method, which is dominated by the cost of the natural gas.
2. Partial oxidation of heavy oils, an increasingly popular method, also dominated by feedstock costs.
3. Coal gasification, a near-future method considered to be rather more dependent upon capital costs and operating expenses than the two preceding.
4. Nuclear electrolysis, a future method with well-defined but not well-developed technology calling for the integration of two major systems (nuclear-electric power and electrolysis) and assumed to be rather capital-dominated overall.
5. Thermochemical, a future method using nuclear heat and a thermochemical technology which is still in the research stage, assumed to be dominated heavily by capital and operating costs.
6. Solar electrolysis, also a future method, included primarily to show an extreme case of capital dominance.

Cost of water as a feedstock was not estimated separately for any process, because this cost is low and will vary more with locality than by the different use rates of different processes.

Cost-computing formulas were constructed for each of the six methods. These are believed to represent the way in which the cost of hydrogen is accumulated for each method, with due allowance for the early, untried, or mature state of technology in the various cases. Data used to compute costs were obtained partly from the open literature [Project Independence, 1974; Gregory, 1974; Gregory, 1973] and partly from HEST Study estimates of future costs. The most reliable data are considered to be those for steam reforming, followed by partial oxidation. Coal gasification costs are reasonably accurate since design specifications exist, but the literature offers large differences on the basis of different processes assumptions and questions of how costs may be reduced on wide application. Future feedstock costs, as noted previously, are uncertain and unpredictable, affecting the three fossil-based methods above. Nuclear electrolysis and especially thermochemical have no firm basis for costing, because there are no existing or designed integrated commercial-scale plants. Solar-electrolysis costs were based largely on the photovoltaic cost figure of $1000/kw, assumed a resonable early goal for this equipment.

The initial estimates were computed by using base cost-factor values in the technology-peculiar formulas. Base values represent the case of well-defined but not necessarily advanced technology; no production growth over the life period is assumed, and no allowance for different construction dates, or for abnormal inflation. Adjustment for these variations can be made to the assumptions and the costs recomputed as described in Appendix F. In addition to the base estimates, high and low cost estimates were also computed from corresponding assumptions.

Capitalization factors for this evaluation are taken from the Description of Gas-Cost Calculation Methods Used by the Synthetic Gas-Coal Task Force of the Federal Power Commission National Gas Survey. These factors, though intended for illustrative purposes, are consistent with current capital-market conditions. Base, high, and low factors were generated and used for all production methods, as follows:

Factor:	Base	High	Low
Debt fraction, %	75	65	85
Debt interest, %/year	9	12	9
Equity return, %/year	15	20	15
Income tax, %/year	48	55	45
Depreciation, %/year	5	6.7	4

Resulting cost estimates for the six processes are calculated in Appendix F, and summarized in Table VII-9.

J. SUMMARY OF HYDROGEN PRODUCTION METHODS

The major differences between hydrogen production processes are dictated by the energy source. Fossil fuels produce hydrogen by open thermochemical cycles in which carbon removes oxygen from the system, thus eliminating the need for liberating oxygen. Fossil fuels also contribute their own hydrogen to the process and, as

Table VII-9. Production cost estimates

Production Method	Base Value $\$/10^9$ J ($\$/10^6$ Btu)	High Value $\$/10^9$ J ($\$/10^6$ Btu)	Low Value $\$/10^9$ J ($\$/10^6$ Btu)
Steam reforming	1.42 (1.50)	6.59 (6.96)	0.82 (0.87)
Partial oxidation	2.59 (2.73)	7.76 (7.37)	1.55 (1.64)
Coal gasification	2.62 (2.77)	4.90 (5.17)	1.26 (1.33)
Nuclear electrolysis	6.03 (6.37)	32.13 (33.92)	2.69 (2.84)
Thermochemical	6.52 (6.88)	30.45 (32.13)	2.09 (2.20)
Solar electrolysis	15.34 (16.18)	208.53 (220.00)	4.76 (5.02)

a result, the energy required to manufacture hydrogen is relatively small.

Other energy sources must supply the full energy needed to decompose water into its elements (equivalent to the heat of combustion), and the efficiency of supplying this energy is reduced because of the increasing complexity of incorporating this energy into the water. From the engineering standpoint, it can be argued simply that since more heat transfer steps are needed, the efficiencies are reduced. Table VII-10 compares the energy and efficiency of various hydrogen-producing methods. The cost of hydrogen (Table VII-8) is reflected from the total energy required to produce it, because the processing of energy requires large capital outlays. In the special case of solar energy, low utilization of capital due to the diurnal nature of the source exaggerates the cost.

The capital costs are determined by the cost of collecting and processing energy. At the present time drilling or mining for fossil fuels is a relatively inexpensive means of collecting this energy, partly because the resulting product is in a concentrated form. The costs of collecting solar energy are large because of its dispersed form and its periodic nature. For nuclear sources, the costs of processing energy (in terms of the capital costs of building plants that utilize nuclear fuel) are high. This is largely because the efficiencies are low. If the efficiency of a practical light-water reactor were doubled to 50%, the cost of electricity or hydrogen would be almost halved. Thus, open-cycle hydrogen production techniques will compete favorably with the new energy sources until the cost of collecting fossil fuels is comparable with the collection and processing of advanced energy sources.

1. Hydrogen from Natural Gas and Oil

Hydrogen is produced at high thermal efficiency from natural gas and light oils by direct catalytic reaction with steam. The cost of hydrogen is primarily related to the feedstock costs because of the relatively low requirements for capital equipment. For example, no oxygen plant is needed and scrubbing for CO_2 and H_2S is reduced up to 3-fold as compared to coal processing. As a result, these feedstocks will be used to produce hydrogen until they are in short and unreliable supply, until they are very expensive, or until the prevailing capital charges (mainly interest rates) are greatly reduced.

Hydrogen is produced from heavy oil by processes similar in principle to those using coal, but the technology for processing oil is well developed. Addition of an oxygen plant raises capital costs substantially, and CO_2 removal becomes a larger problem than with the lighter feedstocks. In comparison to coal, however, heavy oil lacks the solids handling and ash removal problems that drive up operating and capital costs, and is a preferred feedstock when natural gas and light oils are not available.

2. Coal

Coal is the near-term answer to the problem of adequate energy supplies to produce hydrogen. The state of technology of coal processing, other than simple combustion, is relatively poor and, as a result, efficiencies to gasify coal to hydrogen or synthesis gas are low. Even so, it is superior to energy feedstocks that must produce hydrogen by decomposition of water because of the large amounts of total energy that are needed to accomplish this decomposition.

There is considerable room for advancement of coal processing, both in more efficient processes and in reduced capital outlay. Increased efficiency generally means a smaller plant with lessened requirements for coal, water and oxygen. Current efforts in this area center on development of the high-pressure gasifier which could potentially raise overall process efficiencies from about 55% to 65%. This would reduce coal consumption per unit of hydrogen by 18%. Table VII-11 indicates the dollar value of such an improvement for the cumulative period up to the year 2000. The quantity estimate for hydrogen is the low merchant projection for coal (see Table VII-6), which projects hydrogen production from coal at 2.9×10^{18} J/yr (2.8×10^{15} Btu/yr) in the year 2000.

Table VII-10. Comparison of hydrogen production methods

Method	Heat of reaction, kJ/kg H_2 (Btu/lb H_2)	Approximate base-case process efficiency	Approximate total energy kJ/kg H_2 (Btu/lb H_2)
Steam reforming of natural gas	31,309 (13,450)	0.75	191,000 (82,000)
Partial oxidation of oil	38,525 (16,550)	0.65	220,000 (95,000)
Coal gasification	71,231 (30,600)	0.55	260,000 (112,000)
Nuclear/electrolysis	143,110 (61,479)	0.33	434,000 (186,000)
Nuclear/thermochemical	143,110 (61,479)	0.33*	434,000 (186,000)
Solar/thermal/electrolysis	143,110 (61,479)	0.33*	714,000 (307,000)

*Estimated.

Table VII-11. Cumulative costs of hydrogen from coal (Reference Projection, Low Merchant Option)

Factor	Cumulative Costs to 2000 A.D.	
	Present Technology (Process Efficiency = 0.55)	Advanced Technology (Process Efficiency = 0.65)
Capital Costs+	\$10 Billion	\$8.4 Billion
Feedstock Costs*		
\$0.017/kg (\$15/ton)	\$23 Billion	\$19 Billion
\$0.044/kg (\$40/ton)	\$61 Billion	\$52 Billion

+Based on hydrogen production from coal of 2.9×10^{18} J/yr (2.8×10^{15} Btu/yr).

*Based on hydrogen usage from 1985 to 2000 of 22×10^{18} J (21×10^{15} Btu).

The major impact on cost is in reduced feedstock consumption, amounting to 2.4×10^{11} kg (270×10^6 tons) over the 15 year period from 1985 to 2000. Depending on fuel cost, the potential for savings range from 5 to 10 billion dollars. Capital cost advantages are smaller but can amount to \$1.5 billion based on conservative energy projections.

3. Electrolysis

The economics of electrolysis center on the tradeoff between the cost of the electrolyzer and the current density within the electrolyzer, the latter determining the operating voltage and, consequently, the electrical usage. Present technology is limited to operation at 2200 A/m^2 (200 amps per square foot) (ASF) at about 2 volts. A reasonable goal is for operation at 1.6 volts and 22000 A/m^2 (2000 ASF). This would drop the number of electrolyzers tenfold, and would allow for substantial increases in the capital costs per electrolyzer.

Table VII-12 shows the projected costs of hydrogen produced by electrolysis, with the assumption that the capital costs per unit of hydrogen are relatively constant. The cost is assumed to be proportional to the electric power usage which, in turn, is directly proportional to the cell voltage. Dollar estimates are given for the high merchant projection (see Table VII-8) which predicts non-fossil energy consumption for the production of hydrogen at a level of 1.3×10^{18} J/yr (1.2×10^{15} Btu/yr) in the year 2000. It is assumed that non-fossil energy sources would all use electrolysis as the route to hydrogen.

The costs are largely dependent on electricity costs which are dependent on the period of usage and other factors unique to the electric utility industry. Based on the relatively conservative FTFB energy projections, however, reduction in costs by \$34 billion could be achieved over a 15 year period from 1985 to 2000 with a reduction in cell voltage from 2.0 to 1.6 (or increasing efficiency from 0.75 to 0.93). The actual energy saved would be about 6×10^{18} J (5.8×10^{15} Btu) or the equivalent of 2.1×10^{11} kg (230×10^6 tons) of coal.

4. Thermochemical

Thermochemical hydrogen production introduces new technology for conventional chemical processing methods because it requires the processing of very large amounts of energy. The

Table VII-12. Cumulative costs of hydrogen by electrolysis (Reference Projection, High Merchant Option)

Factor	Cumulative Costs to 2000 A.D.	
	Present Technology (Electrol. Efficiency = 0.75)	Advanced Technology (Electrol. Efficiency = 0.93)
Capital Costs+	$2.16 Billion	$2.16 Billion
Costs of Electricity*		
$5.50/GJ (2¢/kwh)	$70 Billion	$57 Billion
$13.90/GJ (5¢/kwh)	$176 Billion	$142 Billion

+Based on hydrogen production by electrolysis of 1.3 x 10^{18} J/yr (1.20 x 10^{15} Btu/yr).

*Based on electrolytic hydrogen usage from 1985 to 2000 of 9.5 x 10^{18} J (9.0 x 10^{15} Btu).

only comparable technology in terms of energy is the electric power industry which, of course, represents the major potential competition to thermochemical production via electrolytic production. The major questions concerning thermochemical production, then, are 1) can the efficiency of thermochemical production exceed that of electrolytic production?, and 2) given an increase in efficiency, can the capital costs of thermochemical production compete with the costs of electrolytic production?

Predictions for overall process efficiencies indicate that thermochemical methods might be capable of overall thermal efficiencies between 20 and 60%, while electrolytic production efficiency now ranges from about 20 to 30% with present technology. A rough comparison of capital costs can be made by comparing the capital cost of a typical large-scale chemical plant to that of a nuclear generating station. If comparisons are made on the basis of energy consumed, the capital cost of an oil refinery, for example, is about $\$825/\text{kW}_t$ which represents the consumption of about 8% of the feedstock energy. The capital cost of an electrical generating station operating at 33% efficiency is about $\$200/\text{kW}_t$. The comparison indicates that chemical processing tends to be more expensive than electrical generation and that thermochemical methods of hydrogen production will tend to be capital-intensive.

Thus, thermochemical cycles with fewer steps, particularly hybrid cycles, may be favored over the more complex pure thermochemical cycles from the point of view of first cost.

5. Solar Energy

Solar energy is presently not competitive with the more conventional energy sources to produce hydrogen or other high-grade energy carriers because of the high collection cost. Construction and maintenance costs of concentrating collectors are very high, and the inability to utilize these collectors without direct sunlight severely lowers the capital utilization. Biological and photolytic methods of hydrogen production are more attractive in the sense that they do not require concentrators and can utilize diffuse light. They are, however, in their infant stages of research and cannot be projected as signficant energy conversion methods without substantial advances.

As conventional fuel costs rise, or possibly, as the cost of capital decreases, solar energy could become competitive, and production of hydrogen would serve as a convenient energy storage method for the diurnal source. In this case, hydrogen would be a premium energy carrier relative to electricity and extra costs could be borne for its direct production.

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Chapter VIII

FACTORS AFFECTING THE BROADENED USE OF HYDROGEN

The quantities of hydrogen used in traditional ways are primarily dependent on the well known laws of supply and demand. However, the acceptance of new and innovative uses of hydrogen depend upon the additional factors of technology and society. To determine the probability of success or to encourage the acceptance of a new process, the potential impact of these factors must be evaluated and understood. Further, because these new uses of hydrogen have the capability of creating significant changes in the energy use structure of our society, it is imperative that these factors be addressed, and appropriate responses be developed.

There are undoubtedly a large number of factors which will influence the future role of hydrogen. The more significant ones will be discussed. These are 1) storage, transmission, and distribution problems; 2) problems of materials compatibility and safety; 3) the environmental and social implications of increased hydrogen usage; and 4) the economics related to expanding hydrogen use. The following discussions address the technological questions, identify the areas of uncertainty, describe the influence and impact of actions, and describe what needs to be done. An in depth assessment of the cause and effect relationships between these factors and the future use of hydrogen must be left for a later time.

A. STORAGE, TRANSMISSION, AND DISTRIBUTION OF HYDROGEN*

Factors discussed elsewhere in this report relate to the needs, advantages and disadvantages, attractiveness and economics of the hydrogen fuel system. One positive point is evident here; the operational experience with storage, transmission, and distribution of hydrogen in different forms that has been accumulated is significant. The technology and techniques, while not ideal in some areas, permit the safe use of gaseous and liquid hydrogen for numerous chemical or metallurgical processes and for other important energy uses. Hydride storage systems, likewise, have an increasing technology base. Gaps in the applied technology can be filled to improve costs and further increase desirability, but the experience base is ample to assure viable systems.

Hydrogen can be transmitted as a gas at relatively low pressures for short distances and at higher pressures for long distances at transmission unit costs lower than electric power. It can be stored in large stationary containers as a liquid or in a hydride form, and can be transported in reasonable bulk quantities as a liquid. It can be used for automotive power through storage as a liquid, a hydride, or a gas, within certain constraints. Liquid hydrogen can be used as an aircraft fuel.

Most natural gas is piped directly from the well to the user, with only a small amount of gas entering the pipe used as the pumping or motive force. Transport of hydrogen as a liquid will be a significant segment in a total transmission system; but the bulk of the transmission will likely be through a large scale nationwide network of pipelines similar to that used for natural gas today.

The most economical means of transporting hydrogen in bulk quantities overland will probably be by pipeline transmission, even if new lines must be built. It may be economically more attractive to adapt parts of the existing system to hydrogen, depending on use patterns, conversion schedules and technical factors.

1. The Existing Hydrogen Pipeline Technology

A hydrogen delivery network has been in operation in Germany for about thirty years [Gregory, 1972 and 1975]. Chemishe Werke Huls AG (CWH) owns and operates a network totaling about 209 km (130 miles) in the Ruhr area of West Germany. Gregory described the system operation and significance as follows: "The original system was constructed in 1938 and was expanded after 1954. The purpose of the pipeline network is to distribute by-product hydrogen, mainly produced from electric-arc pyrolysis of methane to produce acetylene, and also from a chlorine-caustic soda electrolytic plant. This relatively pure, 95%, hydrogen is transmitted at a pressure of (15 atm) (225 psia) 1551 kN/m^2, which is the operating pressure of the pyrolysis producers. Electrolytic hydrogen is compressed to this level in reciprocating units. There are no pipeline compressors or storage vessels, and the system is operated essentially at constant pressure. There are four separate injection points and nine separate users.

"It is interesting to note that the annual throughput of the system has been between 250 and 330×10^6 (standard) m^3 per year (roughly 8.7 to 11.6×10^9 SCF per year) since 1969; peak delivery rates were as high as 13.92 m^3/s (50,000 (standard) m^3 per hour) (about 1.77×10^6 SCF per hour); and the measured losses were within the limits of accurate measurement, less than 1%. The system is designed for an operating pressure of 2586 kN/m^2 (25 atm (375 psia)), and the pipe diameters range from 0.15 to 0.30 m (6 to 12 inches). The pipes are buried 1 meter deep in a 10-meter wide protected right-of-way. The lines pass through seven large towns, each having a population of more than 100,000. The entire area is subject to severe mining subsidence, and this is compensated for by the use of expansion joints. The pipe steel is St. 35.29 grade, which is equivalent to SAE 1015 or 1016."

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*By W.H. Boggs, NASA, J.F. Kennedy Space Center

Several industrial gas manufacturers in the United States operate small diameter hydrogen delivery pipes. One line is 0.2 m (8 inches) in diameter and about 15 miles total length. It was constructed of Schedule-40 pipe in 1969 and used only for hydrogen at 1329 kN/m^2 (200 psig). Another line uses older 4-in. pipes at 5516 kN/m^2 (800 psig) were originally used for natural gas. Purity ranges from 0.995 to 0.999 have been transmitted without incident or apparent detriment to the line.

2. The Existing Natural Gas System and Comparison

A brief description of the existing natural gas system contained in the NASA-ASEE summer study report [Johnson Space Center, 1973] states that: "The existing natural gas pipeline system consists of three basic components: transmission, storage and distribution systems. At first, natural gas was utilized near the source of supply only; but, through the development of high pressure, large diameter lines, natural gas is presently transmitted as far as 3218 km (2000 miles). Transmission pressures of 4140 to 6895 kN/m^2 (600 to 1000 psig) are used. Storage near the consumption centers has become a necessity as a safeguard in case of pipeline failures and to handle the peak demand, while maintaining near maximum gas transmission throughout the year. As an example of the non-uniform demand, because of heating requirements, residential customers use five times as much gas in winter as in summer.

"The distribution system begins with the transmission main operating at pressures of 414 to 1724 kN/m^2 (60 to 250 psig). The gas distribution continues from the transmission main through the trunk main to the feeder mains and finally to distribution mains. The pressure in the distribution mains range from 0.1 m (6 inches) water column to 689 kN/m^2 (100 psig). Residential and commercial appliances generally utilize natural gas at pressures below 3 kN/m^2 (0.5 psia), while some industrial use at pressures of approximately 345 kN/m^2 (50 psi).

"Natural gas is stored in various types and sizes of containers and at various pressures. Local storage in large low-pressure cylindrical tanks up to 10 cu. ft. with pressures under 3 kN/m^2 (0.5 psi) are sometimes used. In rural area, high pressure bottle-type or pipe-type holders have been used for underground storage. Pressures over 1379 kN/m^2 (2,000 psig) and capacities of 42 x 10^3 to 3398 x 10^3 m^3 (1.5 x 10^6 to 120 x 10^6 cu. ft.) have been used in installations of this type. Daily peak-shaving requirements may also be provided by transmission line or line-pack storage. During periods of low demand, the operating pressure may be increased in a line. An increase of 689 kN/m^2 (100 psig) will store approximately 7 times the pipeline volume. The main disadvantage of line-pack storage is that a break in the line would cause a loss of transmission capacity as well as a large portion of the gas stored in the line."

Large systems utilize underground gas storage by injection of natural gas into the natural rock or sand reservoirs, such as depleted oil and gas fields. Aquifers are also used by displacing water with the natural gas. There are some essential reservoir characteristics which will allow only certain formations to be used for underground storage. Storage fields should be near their markets and main transmission lines should be large enough to supply the seasonal peak-shaving requirements of the pipeline system. Excess gas produced in the summer may be injected into the underground storage field and withdrawn for winter use. In 1970, there were 325 underground pools in 26 states with a majority of the underground storage in the northeastern part of the country. The amount of natural gas withdrawn from underground storage in 1970 was equal to approximately a 23-day supply, and the total storage capacity was equal to an 80-day supply, based on the average daily consumption. For systems where underground large-scale storage reservoirs are not available, liquefied natural gas storage is used to provide daily and seasonal peak-shaving. Additional data on natural gas pipelines may be obtained from the Gas Engineers Handbook. Table VIII-1 clarifies and emphasizes the importance of the existing natural gas system to the nation's economy.

[Gregory 1975] makes these observations: "It is of interest to compare the design of a pipeline for hydrogen with that of a pipeline for natural gas, for which much experience and data are available. It is useful to consider the energy-carrying capacity of a given pipeline. At first sight, one might expect the capacity of the pipeline to be far lower for hydrogen than it is for natural gas, because the heating value of hydrogen is only 12.1 mJ/m^3 (325 btu/cu. ft.) compared with about 37.3 mJ/m^2 (1000 btu/cu. ft.) for natural gas. This implies that to deliver the same quality of energy, 3 times the volume of hydrogen must be transmitted. On closer inspection, however, one finds that the capacity of a given pipe depends upon the square root of the density of the gas, and because the density of hydrogen is about one-ninth of that of natural gas, there is a compensating factor of one-third that results in the given pipe having essentially the same energy-carrying capacity for natural gas as for hydrogen. In other words, a given length of a given diameter operating with the same pressure drop across its length will carry the same number of J (Btus) per hour when working with hydrogen as it will with natural gas.

"This rather fortuitous compensation applies only at atmospheric pressure. As the pressure increases to typical pipeline operating pressures of 5171 kN/m^2 (750 psig) or so, the compressibility factor for hydrogen is somewhat different than for natural gas, and this results in a slightly unfavorable carrying capacity for hydrogen. At 5171 kN/m^2 (750 psi), the ratio of heating values for a given compressed volume of hydrogen and natural gas has changed from 3:1 to 3:83:1.

"Long-distance gas transmission lines of lengths greater than about 97 km (60 miles) must be supplied with pipeline compressors at fairly regular intervals. When we examine the compressor requirements for hydrogen, we begin to find some very significant differences for the case of natural gas. First of all, for hydrogen the compressors must handle a considerably greater volume of gas — somewhere between 3 and 4 times the number of m^3 (cubic feet) for the same energy capacity. The horsepower required to drive a

Table VIII-1. Natural gas system data
(United States 1970)

Consumption	
1.81×10^9 m^3/day (63.8×10^9 cu. ft./day)	24.64×10^{18} J/yr (23.34×10^{15} Btu/yr.)
Storage Capacity	
Underground gas reservoir	146.6×10^9 m^3 ($5,178 \times 10^9$ cu. ft.)
Liquefied Natural Gas (scf)	0.424×10^9 m^3 (15×10^9 cu. ft.)
Total	147.0×10^9 m^3 ($5,193 \times 10^9$ cu. ft.)
Length of Pipeline	
Field and gathering main	107,089 km (66,556 mi.)
Transmission main	406,467 km (252,621 mi.)
Distribution main	958,406 km (595,653 mi.)
Total	1,471,961 km (914,830 mi.)
Number of customers (meters)	
Residential	38,097,000
Commercial	3,131,000
Industrial	199,000
Total	41,427,000

given compressor for a given energy throughput is considerably greater than the horsepower required to drive a quantity of natural gas of the same energy capacity. (The design of rotary compressors commonly used for natural gas lines appears to be inadequate for hydrogen operation. Few, if any, compressors could be expected to be able to increase their throughput capacity 2 to 4 times.)

"Table VIII-2 indicates the requirements for the conversion of an existing natural gas line to operate on hydrogen.

"The first line of the table indicates the reference case of a natural gas line with unit energy-carrying capacity that is fitted with a given size of compressors driven by engines of a given horsepower. The second line indicates what happens when hydrogen is introduced into the line without mechanical modification. The energy-carrying capacity of the line is limited by the volume capacity of the compressors, and the total energy-carrying capacity is reduced to 26% of the value for natural gas. However, to drive these compressors, only about one-tenth of the horsepower of the installed engines is required, and so the engines are grossly under-utilized. The third line of the table shows what would happen if the compressor capacity were increased to the level at which the entire installed horsepower of the driving engines were to be absorbed. In order to do this, the volume capacity of the compressors has to be increased by a factor of 2.1. When this has been done the resulting energy-carrying capacity of the line is 56% of the original capacity for natural gas. The fourth line in the table indicates the modifications necessary to reinstate the pipeline to its original energy-carrying capacity. In order to do this, both the volume capacity of the compressors and the horsepower of the engines have to be increased by factors of 3.8 and 5.5 respectively, over their original values."

3. Costs of Transmission

Cost assertions are sensitive to assumption of source energy unit costs; pitfalls can be avoided by a broad parametric range of system studies. The results of such a systems study reported [Gregory, 1975]: "It is impossible to estimate the cost of transmitting hydrogen by pipeline from a knowledge of the required pipeline diameter, compressor capacity and horsepower, and energy throughput required. For natural gas lines, these cost data optimize at operating pressure levels of about 5171 kN/m^2 (750 psia), with pressure ratios across the compressors of about 1.3:1. However, if we begin a complete redesign of a pipeline specifically for hydrogen, we must take into account not only the different physical properties of hydrogen but also the cost of fuel in powering the engines used to drive the compressors. Several published studies on hydrogen pipeline costs differ in their conclusions quite markedly, because they have assumed rather different fuel costs for their compressors. Because the compression energy is so much higher than that for natural gas, the costs for hydrogen-transmission are more sensitive to this factor.

"At IGT we have carried out a detailed hydrogen-pipeline optimization calculation in which hydrogen fuel costs are varied from \$0.941 GJ to \$3.791 GJ (\$1/million Btu to \$4/million Btu). We find that for a hydrogen fuel cost of \$2.841 GJ (\$3/million Btu) and a compressor station spacing of 161 km (100 miles) optimum pipeline costs are obtained at operating pressures in the region of 12.41 mN/m^2 (1800 psig), with pressure ratios across the compressors of only 1.1:1 or less. Hydrogen transmission at typical pipeline pressures of 5171 kN/m^2 (750 psig) will cost about 2-1/2 times more than natural gas, but operating pipelines at 1241 mN/m^2 (1800 psig) will cost about 50% more than natural gas.

Table VIII-2. Relative capacity of transmission line on hydrogen and natural gas at 5171 kN/m^2 (750 psia)*

Gas	Compressor capacity	Compressor horsepower	Energy delivery rate
Natural Gas	1.0	1.0	1.0
Hydrogen	1.0	0.1	0.26
	2.1	1.0	0.56
	3.8	5.5	1.0

*Note that these figures relate to the assumption that compressor efficiency is unchanged, an assumption valid only for reciprocating compressors - not for radial turbocompressors. The table also indicates that modifications in both the compressor and the engine must be made in order to recover the original capacity of the line. In this case, turbocompressors would be replaced with custom-designed equipment intended for hydrogen service. Considerable benefit would result from operating the line at a higher pressure, but this is considered impracticable for existing pipelines.

"The cost of moving energy by hydrogen pipeline is significantly less than that of moving the same amount of energy by overhead electric transmission line. Electric transmission costs vary widely with voltage, load factor, and terrain, but a 230 kV overhead line operates at a cost in the range of \$0.58/GJ/100 km (\$1.00 per million Btu/100 miles), between 18 and 30 times more than hydrogen transmission."

A similar, more detailed report has been given of the IGT system study [Konopka and Wurm, 1974]. References are given therein to support the electrical cost comparisons.

4. A Hydrogen Gas Pipeline System

Many general statements can be made about the development steps and full configuration of a hydrogen gas pipeline system. Portions of the existing natural gas system can be used if diverted to hydrogen and if off-optimum efficiency is acceptable. The low pressure distribution system would need little or no modifications, leaving the compressors as the major item to be changed.

The present location of the pipelines should be considered. The existing lines originate in the Southwest and deliver gas to the East coast, Midwest and West coast. Hydrogen generation may be at dispersed locations, such as near the coasts where nuclear power plant heat and/or electricity will be used as the generation energy source. Generation from coal by a partial oxidation process would probably confine the location to the mining vicinity. There may be many regional solutions, with piecemeal conversion of the distribution systems by locality and construction of new networks with limited range and conversion of greater portions of the existing networks.

5. Distribution and Use of Gaseous Hydrogen

Hydrogen must be delivered to customers who have various total demands and demand rates. Chemical feedstock and metallurgical reduction uses require large amounts and may dictate location of a generating plant nearby. Intermediate users will use the hydrogen as a fuel gas primarily and residential users will use it as a fuel for heating, cooking, and cooling. Distribution systems must be designed to serve the customer with special high purity requirements as well as the user whose only requirements are safe, compatible burning properties. Odorants and possibly illuminants will be added for the latter users.

Looking at the present distribution systems, and excluding further discussion of the case where the user has a captive hydrogen generation plant, there are two other potential cases. One case should just be mentioned, that is liquefaction and shipment in liquid form for subsequent vaporization and distribution. The economics of liquefaction would preclude widespread use of such a system. The use of the existing low pressure gas distribution system today serving residential and commercial users is the important case to consider.

There is little reason to doubt the compatibility of existing systems to distribute hydrogen. The flow characteristics of hydrogen will compensate for the density difference to within six percent of the same energy flow as natural gas. If none of the trace impurities will sustain the swelling effect of the current hydrocarbons on rubber and other organic seals and diaphragms, some replacements and adjustments may be necessary at transition time.

Odorants, especially sulfur compounds, may prove to be a significant problem for catalytic users; e.g., fuel cells. Sulfur must be removed or catalyst poisoning will occur for most processes. Other suitable odorants may possibly be found. The applicable codes, USASB 31.8-1968, the minimum code of the Department of Transportation and the National Fire Code are compatible with the use of hydrogen.

6. Hydrogen Liquefaction and Storage

The production of liquid hydrogen is well established in industry. The processes require high capital investment, and high operation and maintenance costs. Efficiencies are limited by the inherent thermodynamic losses that will prove mostly insensitive to technological improvements. The cost of production can be significantly improved by system designs that take advantage of recovery of the liquefaction energy.

A detailed treatment of investment costs and parametric efficiency versus cost computations are given in a National Bureau of Standards survey of existing equipment [Storbridge, 1974]. Overall system cost for cryogenic refrigerators and liquifiers was estimated by the relation $C = 6000\ p^{0.7}$ where C is the cost in dollars and p is the installed input power, in horsepower.

Current hydrogen liquefaction processes operate at approximately 36% of Carnot efficiency thus requiring 38.8 x 10^6 J of work per kilogram (4.89 kwh per pound) of liquid produced. Table VIII-3, summary of major areas of thermodynamic losses in hydrogen liquefaction systems, was obtained from [Linde 1975]:

Table VIII-3. Thermodynamic losses in hydrogen liquefaction

By Process	10^6J/kg	(kWh/lb)	%
H_2 Liquifier	16.4	(2.07)	42.33
H_2 Liquifier	6.19	(0.78)	15.95
Feed Compressor	2.14	(0.27)	5.52
Total Losses	24.7	(3.12)	63.80
Theoretical Work	14.0	(1.77)	36.20
Actual Work	38.8	(4.89)	100.00
By Equipment Type			
Compressors	13.1	(1.65)	52.81
Turbines	4.36	(0.55)	17.63
Heat Exchangers	3.81	(0.48)	15.36
Converters	1.11	(0.14)	4.49
Precooler	0.63	(0.08)	2.68
Mixing, Throttling, etc.	1.75	(0.22)	7.03
	24.8	(3.12)	100.00

When the electrical requirements of production auxiliaries such as cooling towers and thawing heaters, and the lighting, heating, and air conditioning of the plant are considered the practical energy requirements for liquefaction is 45.0 x 10^6 J/kg (5.67 kWhr/lb).

To improve overall system efficiencies and economics research and development studies on the hydrogen and nitrogen liquifiers and especially on the compressors, turbines, and heat exchangers are needed.

As an alternative to current liquefaction systems, new systems based on magnetic cooling may be technically feasible and potentially more economic than present systems. Physicists for several decades have used adiabatic demagnetization to produce very low temperatures in both one shot and cyclic processes. The development, in recent years, of high-field superconducting magnets has removed constraints that previously limited magnetic cooling to temperatures below 4.5°K. These magnetic refrigerators have several advantages over the state-of-the-art gas refrigerators. One advantage is that the working material (paramagnetic salt) density does not change during the cycle, permitting more efficient heat transfer design. Few moving parts are needed, resulting in higher efficiencies (near Carnot cycle efficiencies are theoretically possible) and lower weight processes.

Cryogenic storage systems for the liquid have a substantial design and operational experience base. Beginning in 1958 and expanding with Centaur support in 1961, NASA has accrued experience; storing quantities up to 3217 m^3 (850,000 gallons) of liquid hydrogen for Apollo/Saturn launches. Designs for handling high flow rates were perfected at the Mississippi Test Facility and at the Kennedy Space Center. Evacuated Perlite insulated dual wall stainless steel tanks are used along with vacuum jacketed pipelines 0.25 m (ten-inch maximum). Although the tank requires only periodic painting the vacuum jacketed lines present both initial expense and maintenance costs that hopefully can be reduced by better passive insulation schemes. A 0.25 m (ten-inch) pipe costs typically $1000 per foot installed and $5.25/m ($1.60 per foot) per year maintenance. The high cost of installed line represents the active vacuum producing equipment, and includes connections and joints. The cost of the tank is estimated at $10.09/$m^3$ ($3.82 per gallon) (1975 dollars) for the 3217 m^3 (850,000 gallon) design. A more detailed treatment of the subject of cryogenic storage is contained in Appendix G.

7. Transportation of Liquid Hydrogen

Presently hydrogen is transported either by rail or truck. Both rail and truck transportation use double walled vacuum insulated systems. Barge transportation of liquid hydrogen has been used in connection with the Saturn rocket program. Future transportation of hydrogen would be by the same land modes as with liquid natural gas type tankers used for marine transport. Table VIII-4 gives some characteristics of hydrogen transportation modes used presently and expected to be used in the future. The characteristics of each hydrogen transportation method will be discussed.

Because of the low quantity of hydrogen which can be moved in the individual vehicle, gaseous hydrogen transport either by rail or by truck does not appear to have significant potential for energy transportation. Descriptions of transport systems are included for completeness and comparison, in Table VIII-4. Because truck size is constrained by the nation's roadways, the truck of the future should be approximately the same as the trucks presently used to transport liquid hydrogen [Bain and Boggs, 1975].

Presently NASA has six railcars used to transport liquid hydrogen. If large-scale transportation of hydrogen energy occurred, rail transport would play a significant role. However,

Table VIII-4. Comparison of hydrogen tanker transport modes

Time/Parameter	Mode			
	GH2 Rail/Truck	LH2 Rail	LH2 Truck	LH2 Marine
Present/description	Individual high pressure cylinders	Vacuum insulated tank cars	Vacuum insulated double-walled trailers	Special purpose barge
Capacity (lb) kg	436/227 (1000/500)(1)	7711-9072 (17,000-20,000)	(7000-5443)(3,4)	72,600 (160,000)
Maximum size (height, width - ft) m	~5,2 (~16,8)	~5,3.3 (~16, 10.7)	~5,2 (~16, 8)	
Efficiency (quantity delivered/ quantity used)	1.00	~1.00	~1.00	
Construction cost ($/lb) $/kg	220 (100)(1)	29 (13)(4)	44 (20)(4)	
Operating cost ($/ton-mile) $/x$10^3$ kg-km	1.57 (2.30)(4)	0.10-0.09 (0.15-0.13)(4)	0.15-0.09 (0.22-0.13)(4)	
Utilization rate (miles/yr) km/yr	On demand	On demand	On demand	
Future/description	Same as present(4)	Unit train of interconnected cars(5)	Same as present (4)	LNG type tankers(6)
Capacity (lb) kg		9 x 10^5 (2 x 10^6)		9 x 10^6 (2 x 10^7)
Maximum size (height, width - ft) m		~5, 3.3 (~16, 10.7)		
Efficiency (quantity delivered/ quantity used)		~1.00		10,600 km 0.75 @(6600 mi)
Construction cost ($/lb) $/kg		29 (13)		9-18 (4-8)
Operating cost ($/ton-mile) $/x$10^3$ kg-km		0.10 (0.15)		0.0007 (0.001)
Utilization rate (miles/yr) km/yr		97,000 (60,000)		1,300,000 (800,000)

(1) Private communications with W. Pierl, Western Sales and Testing, Amarillo, Texas.

(2) [Bartlett, et al., 1972.]

(3) [Bain and Boggs, 1975.]

(4) [Hallett, 1968.]

(5) Private communications with S. Mayers, Great American Transportation Corp., Chicago, Ill.

(6) [Uhl and Giese, 1973.]

because of the difficulty in handling liquid hydrogen, unit trains of tank cars might be used.

Unit trains of interconnected tank cars existing today are used to transport petroleum products in "strings" of up to twenty cars. Each string of cars forms a unit although more than one string could be placed in a train. The tank cars were modified with an end housing which contained isolation valves and a bellows connects adjacent cars. In transit the isolation valves are closed so that neither liquid or vapor flows between cars. At the terminal the valves are opened, and loading or unloading occurs through connections at the end of the string. Figure VIII-1 shows the loading and unloading. The pressurizing blimp or railcar is needed because the present system is not designed for self pressurizing fluids. Even though hydrogen is self-pressurizing, the pressurant source would remain in the system in order to provide helium purging gas.

8. Marine Transportation

Large scale marine transportation of liquid hydrogen would resemble present day marine transportation of LNG. The costs shown in Table VIII-4 for the future marine transportation of hydrogen are based on a volumetric ratio for the costs of LNG transportation. The operating cost in \$/kg-km (\$/ton-mile) does not include the cost of fuel necessary to transport hydrogen. This occurs because the hydrogen is assumed to power the ship. For the other modes of transportation, the fuel cost is included in the operating cost. The lower construction cost estimate for marine transportation is based on a direct volumetric ratio of the cost of LNG transportation. The higher estimate reflects the greater costs of liquid hydrogen storage tanks relative to the costs of LNG storage tanks. On a volumetric basis there is a two to one ratio in these costs.

The relatively low efficiency for the marine transportation of hydrogen results from hydrogen being used to power the ship. Approximately 10% of the LNG loaded [Uhl and Giese, 1973] is consumed as fuel for a 9654 km (6000 mile) delivery distance. Since hydrogen has 1/6 the density of LNG and about 2.5 times the heating value, about 2.5 times as much hydrogen volume would be consumed for the same delivery distance. If liquid hydrogen cost \$3.79/GJ (\$4.00/10^6 Btu), the fuel component of the operating cost would be \$0.02/x 10^3 kg-km (\$0.02/ton-mile). This is 20 times the other operating costs, making large scale marine transport of hydrogen energy at intercontinental distances much less attractive.

9. Comparison of Bulk Energy Transport with Rate Energy Transport

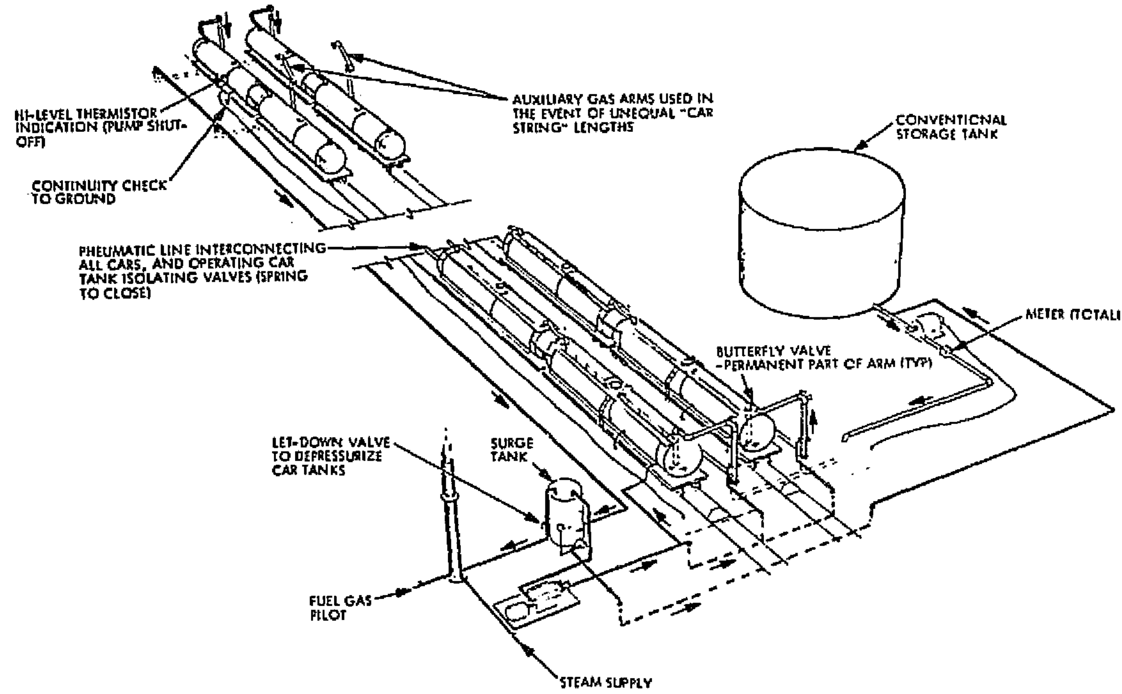
Surface transport of hydrogen involves the bulk transport of energy. Other energy transportation systems are rate dependent. When energy is consumed at a high rate but a low duty cycle, bulk transport of hydrogen may be attractive. Consider the following example. A nuclear power plant is designed to satisfy both base load and peaking power requirements. Peak load is satisfied by continuously generating and liquifying hydrogen. When peak demand occurs, hydrogen is the fuel for a hydrogen-oxygen or hydrogen-air electric generator. The nuclear plant is some distance from the load source. Since hydrogen fueled systems are relatively nonpolluting, they could be located close to an urban load center. Peaking requirements could be satisfied by sizing the electrical transmission line to accommodate the maximum peaking rate. Alternately, the transmission system could be sized only to accommodate the base load and the peaking energy could be rail shipped to the urban center.

The [Federal Power Commission, 1971a] gives a weekly load profile where the integrated power requirement above 82% of capacity is 149%-hrs/week. For a 10,000 MW system this corresponds to 53.6 x 10^{12} J/wk (14,900 MWh/week), which if generated continuously would be 90 MW. Assuming a 70% electricity to hydrogen efficiency, a 1/3 energy requirement for liquefaction, and a 50% combustion efficiency results in a 350 MW nuclear requirement. Assume a 1350 MW plant delivers 1000 MW base load and 350 MW to generate liquid hydrogen which is liquified and stored to meet peaking requirements for a load 161 km (100 miles) away. To satisfy peaking requirements, the transmission system capacity would be 1000 MW base plus 1800 MW peaking. With bulk transport only 1000 MW transmission capacity is needed. Table VIII-5 compares the cost of the two systems. The line costs in Table VIII-5 [Pastuhor and Ruccia, 1969] were based on a fixed right of way cost per km (mile) and a construction cost proportional to the transmission rate. An operating cost of \$0.10/x 10^3 kg-km (\$0.15/ton-mile) may be high for user-owned tank cars. However, operating costs are only about 10% of the total yearly cost and about half the cost of car ownership. The storage capacity given is only that at the terminal end. Its minimum capacity is caused by the high cost of storage construction. The storage capacity at the generating end is common to both systems and therefore is not included in the cost comparisons. The electric plus rail system shows a slightly less yearly cost than the all electric system. If the transmission distance were to double, the all electric costs would also double while the electric plus rail costs would increase less. In this comparison both electrical line and hydrogen transfer losses were neglected.

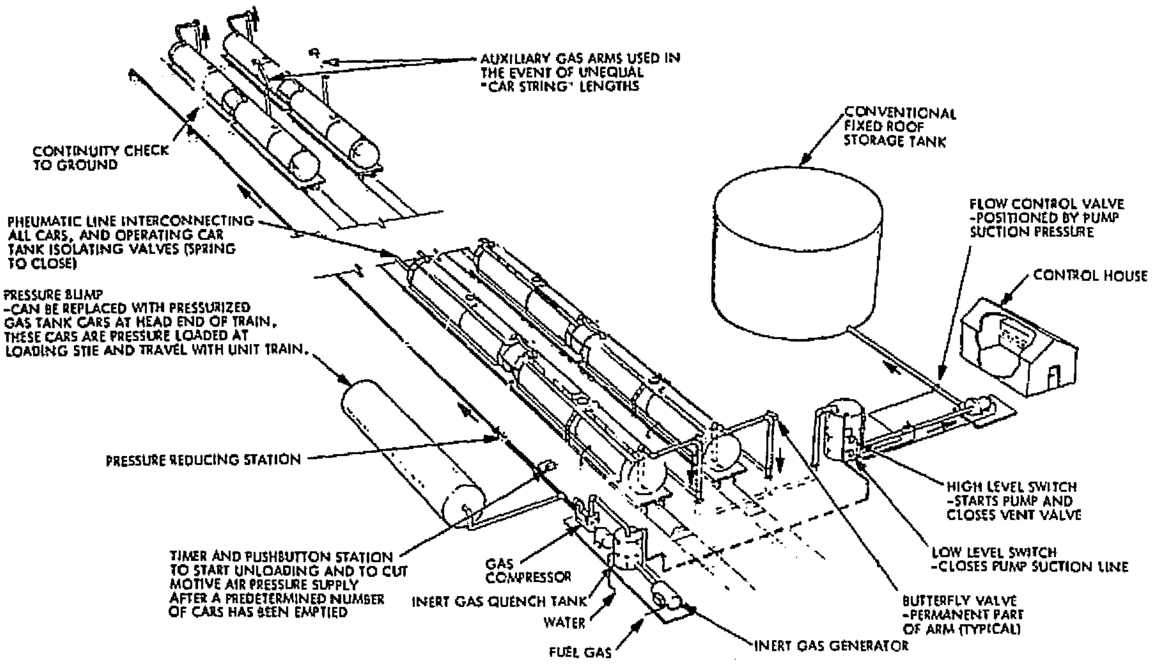
10. The Importance of Liquified Natural Gas Plans

Liquefaction and transportation of natural gas by ocean going tanker is a steadily increasing practice. Electric power utilities are using LNG for peak shaving energy storage. Some of the natural gas that was formerly flared and wasted in the Middle East is being liquified and used to power transoceanic shipment to depot tanks along the U.S. waterways. In June 1973 thirty five utility sites had one or more LNG tanks for peak shaving storage. The dependence on natural gas in this form is being widely established, as is the experience base for cryogenic storage in coastal metropolitan areas.

Risk management for the storage depots having tanks up to 22710 m^3 (6 million gallon) capacity is being established by efforts of the New York City Fire Department with Kennedy Space Center, Boeing and the IBM Corporation through the NASA Technology Utilization Program.



a. Loading



b. Unloading

Figure VIII-1. Terminal operations of liquid hydrogen unit train

Table VIII-5. Comparison of all electric and electric plus rail energy transport for peaking requirements

Electric	All Electric	Electric + Rail
Transmission rate, MW	2800	1000
Transmission distance, km (miles)	161 (100)	161 (100)
Line cost, \$	22.9×10^6	9.7×10^6
Year line cost @ 15%, \$/yr	3.44×10^6	1.46×10^6
Peaking energy J/week (MW-hr/week)		54×10^{12} 1.5×10^4
Conversion efficiency, %		50
Thermal energy, J/week (MW-hr/week)		108×10^{12} (3.0×10^4)
Fuel weight, kg/week (lbs/week)		907×10^3 (2.0×10^6)
Trips per week		7
Utilization, %		80
Rail capacity, kg (lbs)		1.6×10^5 (3.6×10^5)
Rail construction cost rate, \$/kg (\$/lb)		29 (13)
Rail construction cost, \$		4.7×10^6
Yearly construction cost @ 15%, \$/yr		7.1×10^5
Operation, kg-km/yr (ton-miles/yr)		3.8×10^9 (2.6×10^6)
Operating rate, $\$/10^3$ kg-km (\$/ton-mile)		0.10 (0.15)
Yearly operating cost, \$/yr		3.9×10^5
Storage capacity, kg (lbs)		0.2×10^6 (0.5×10^6)
Storage cost rate, \$/kg (\$/lb)		14.3 (6.5)
Storage cost, \$		3.3×10^6
Yearly storage cost @ 15%, \$/yr		4.9×10^5
Total yearly cost, \$/yr	3.44×10^6	2.85×10^6

The routine manner in which LNG shall soon be handled will provide confidence and acceptance of liquid hydrogen in the near future.

11. The Energy Pipe

The concept of the distribution of cryogenic fluids and electrical power simultaneously utilizing the same cross country apparatus is known as the "Energy Pipe." When the energy transfer occurs at a higher temperature than the critical (superconductive transition) temperature of the conductor, the transfer is called "cryogenic resistance cable transmission." At lower than the critical temperature of the conductor the transfer is called "cryogenic superconductive cable transmission."

The concepts, thus far, consist of multi-element coaxial coated tubes separated by various layers of insulation and cryogenic fluids. [Whitelaw, 1974] states "Four new technologies make the concept realistic:

> The discovery of superconductive alloys of reasonable cost with transition temperatures up to 20°K and corresponding resistivities below 10^{-12} ohm-cm.
>
> Superinsulation, such as opacified evacuated perlite, having thermal conductivity $k = 7 \times 10^{-4}$ J/s-m-°K ($k = 4 \times 10^{-4}$ B/ft-h-°F) at feasible vacuum pressure.
>
> Metals such as 'Cryonic' and 9% Ni steel with adequate strength and toughness at the temperatures of liquid hydrogen and helium.
>
> Efficient and economical pipeline installation techniques and large quantity cryogenic gas liquefaction.

Hydrogen is not the only cryogenic liquid that can be used [Savage, et. al., 1973]. However at LNG temperatures the electrical resistance of copper is reduced by only a factor of four. The reduction factor is ten at liquid nitrogen temperatures and two hundred to five hundred for liquid hydrogen temperatures, depending on the purity of the copper conductor.

In order to present an authoritative discussion, the report of the FPC [Federal Power Commission, 1971b] is quoted as follows:

"Another method of high voltage, high power, underground transmission that is receiving increased attention utilizes resistive cryogenic cables. Resistive cryogenic cables operate at extremely low temperatures but above the superconducting transition of the conductor to increase line rating while avoiding the higher capital expenditure required for superconductivity. There are several competing designs that are under development and it is still too early to predict which may be reduced to practice first or which will prove to be the most economical in the long run. Present indications are that prototypes of two designs will have been tested by the end of 1975. Assuming successful completion of these test programs, with no prohibitive problems being uncovered, resistive cryogenic cable systems might be available commercially about 1980.

"Conceptual designs for resistive cryogenic cables include one in which the cryogenic fluid (liquid hydrogen or liquid nitrogen) is used as an impregnant for a cable of conventional design using paper or synthetic tapes, another design in which the cryogenic fluid is the only insulation, and a design in which a vacuum is used as the insulating medium. In the first instance the cable is similar to conventional pipe-type cable and would be pulled into the pipe in long lengths and then both cable and pipe are filled with liquid hydrogen or nitrogen. These are classified as flexible cryogenic cables. When the cryogenic fluid or a vacuum is used as the insulating medium, spacers are required to support the conductors within the containment pipe. These are classified as rigid cryogenic cables.

"Preliminary research carried out for the Electric Research Council Underground Transmission Committee indicates that the most probable candidate for successful deployment is the liquid nitrogen cooled, flexible cable.

"Another separate research effort has pursued a rigid cryogenic cable with a high voltage vacuum insulation. Even if these tests should prove fully successful, it is doubtful if any significant commercial installations would be in service before the end of this decade."

An examination was made [Belanger and Jefferies, 1972] of the potential of an underground electrical cable cooled by a cryogenic fluid. Liquid nitrogen rather than liquid hydrogen as the coolant was chosen for this study. There are many advantages for liquid nitrogen, including lower energy requirement for liquefaction, higher heat of vaporization, better electrical insulator, less stringent thermal insulation requirements and fewer safety problems in handling. On the other hand, hydrogen further reduces the resistivity of the conductors. If the resistance is lowered by a factor of ten using nitrogen, however, 90% of the electrical losses are saved, and saving a portion of the remaining 10% cannot be justified economically by using liquid hydrogen.

The Edison Electric Institute is presently funding a major study of cryogenic underground cables [Cryogenics and Industrial Gases, 1973] which should identify the technological developments necessary to prove the system. While these studies use nitrogen, many of the construction problems will be similar for other cryogenic systems.

The FPC report [Federal Power Commission, 1971b] continues, "Superconductivity refers to the phenomenon where the electrical resistivity suddenly disappears at low temperatures. In its application to power cables, it refers to operation at the temperature of liquid helium, in the range of 4° K. The appeal of superconducting cables is that losses in the cable can be reduced to practically zero (in the case of direct currents), or to a very low level (in the AC case), and thus virtually eliminate the heat dissipation problem. Also, superconductors can operate at unusually high current densities and consequently have very large power transfer capability of, say, up to 10,000 MVA at 345 kV."

Whitelaw [1974] describes three superconductive energy pipe concepts — a helium cooled dc system, a hydrogen cooled dc system and a hydrogen/helium cooled ac system. Heat loss calculations for optimization were performed and a cost comparison of the three systems are presented.

Figure VIII-2 shows an estimate for the projected cost of a superconducting line. The ac and dc line costs are drawn so that their intercept on the zero-distance axis corresponds to the cost of two transformer stations, one at each end. In the case of superconducting line, the estimate made by Linde [Meyerhoff, 1971] has been used, and the cost of two typical 345-kV transformers has been added as an intercept.

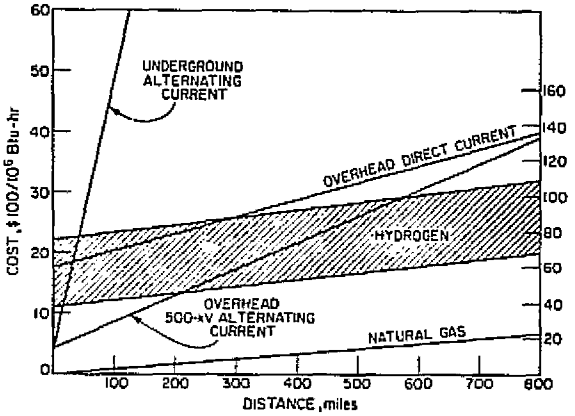


Fig. VIII-2. Cost of entry transmission facilities

One recent development which improves the thermodynamics of liquid hydrogen transmission involves the use of "slush hydrogen" which is a mixture of up to 60% solid hydrogen with liquid hydrogen. The heat capacity of the solid hydrogen significantly increases the apparent heat capacity of the mixture. Use of the slush hydrogen has been investigated by [Minnich and Fox, 1969] and the properties of the mixture have been established. These properties are given in an article by [Sindt 1970]. Efforts to develop this system for future use are recommended.

The superconducting cable can be realized at the present time using liquid helium as the coolant. However, there are indications that superconducting alloys can be used at slush hydrogen temperatures with sufficient conduction capacity to be worthwhile. Where there is an end point need for both liquid hydrogen and electric power, the concept is promising.

12. Hydride Storage

Hydride Storage is a chemical means of storing hydrogen as a bed of solids at ambient temperature and pressure. A reversible reaction is accomplished between the metal and hydrogen to form metallic hydrides. Thus, metal hydrides offer a chemical means for storing hydrogen at high densities and low pressures. For example, the storage of hydrogen as titanium hydride achieves a storage density of 1.2 times that possible for liquid storage. Table VIII-6 illustrates the properties of a variety of metal hydrides.

The last column shows the total hydride (metal plus hydrogen) weight which would have the equivalent energy of a 7.6 x 10^{-2} m^3 (20 gallon) gasoline tank (about 59 kg (130 pounds) including the tank). The weights shown in this column do not include the weight of the hydride container or the heat exchangers required for refueling and/or liberation of the hydrogen when needed, nor has any consideration been given to the reported 44 to 58 percent increase in efficiency of hydrogen over gasoline.

Reports on the dynamic behavior of hydride storage beds during charging and discharging [Cummings and Powers, 1974] have been made. Brookhaven National Laboratory (BNL) and other industrial laboratories have researched powdered metal beds. The chief restriction, weight, tends to limit the technique to stationary applications.

A stationary application was reported by BNL [Strickland, 1974] on tests of a hydrogen reservoir containing 14 lb of hydrogen in the form of 893 lb of granular iron titanium hydride. After several hydriding and dehydriding cycles, the system was able to deliver 1.15 kg H_2/hr (2.54 lb H_2/hr) for five (5) hours. Charging was accomplished at 3.55 mN/m^2 (515 psia) in approximately six (6) hours.

A mobile application was reported by Billings Energy Research Corporation [Billings, 1974] on tests of an iron-titanium hydride bed installed in a 1973 Chevrolet Monte Carlo. Operating on hydrogen from the hydride or alternately from a liquid hydrogen tank developed by Beech Aircraft, the car has accumulated over 321,800 km (200,000 miles) (some simulated).

For mobile applications only metal hydrides with a high weight percent hydrogen would be most suitable. Referring to Table VIII-6 it appears that alkaline hydrides are the most likely candidates. Sodium, magnesium, potassium, and calcium are inexpensive and their hydrides contain 3-8% hydrogen. Figure VIII-3 shows that of the alkaline hydrides, magnesium hydride is preferred because of its relatively high dissociation pressure. A magnesium hydride bed that could contain 21 kg (46 lb) of hydrogen would weigh 318 kg (700 lb) and occupy 0.31 m^3 (11 ft^3).

A theoretical model of an automobile equipped with a magnesium hydride bed has been reported [Cummings and Powers, 1974]. Results show it to be technically feasible but problems with start up, recharging rate, and system safety need further investigation.

The maximum yield without the aid of catalysts or grinding is reported to be 80%. The presence of 5-10% nickel or copper greatly improved the kinetics of reaction and gave yields of 90-95% hydride [Powers and Cummings, 1974]. Further work is needed to optimize the use of catalysts.

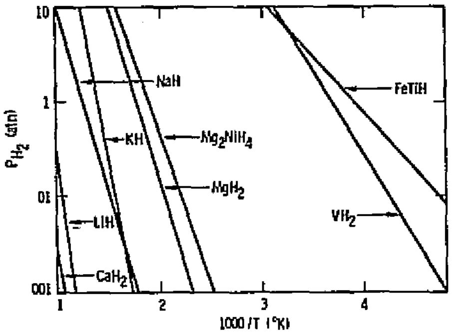


Fig. VIII-3. Equilibrium dissociation pressure
[Cummings and Powers, 1974]

13. Conclusions

The methods and materials for storage, transmission and distribution of hydrogen in both gas and liquid form have been successfully established and demonstrated. Costs of materials is an obvious area for reduction. Liquefaction processes need equipment design, improvements in efficiency; and need examination for integrated facility alternatives that might offer symbiotic incentives. Programs of research into hydrogen embrittlement, materials evaluation and selection, and safety practice for "everyday" users are indispensable and need continued support.

B. MATERIALS COMPATIBILITY AND SAFETY*

Being the lightest element and having some unique physical properties causes certain problems to arise in the handling of hydrogen. Properties which tend to cause problems are 1) low mass density, 2) high permeance characteristics, 3) low volumetric energy density as a gas, 4) extremely low liquefaction temperature, 5) low flame luminosity, 6) high flame speed and 7) low ignition energy. Each of these characteristics tends to require the use of special materials or special attention to safe handling procedures, but these potential problem areas can be accommodated.

1. Materials Compatibility with Hydrogen

The subject of materials compatibility with hydrogen is discussed in detail in Appendix H together with recommendations for research. Compatibility questions are summarized here. Many of the current and future hydrogen production processes involve chemical or thermochemical reactions that occur at elevated temperatures and pressures in a variety of aggressive environments. Such conditions may severely degrade the mechanical properties of structural alloys, influence system reliability, and increase

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Table VIII-6. Properties of certain metal hydrides [DAVITIAN, 1974]

Initial and Final Composition		Dissociation Heat ΔH^f MJ/kg of H_2 (kW-h/kg of H_2)	Available wt % H_2	Equilibrium Temperature 1.0×10^5 n/m^2 (at 1 atm) of H_2 °K (°C)	Cost of Metal per kg	Ratio of Dissociation Heat to Low Heat of Combustion	(a) Total Hydride Wt., H_2 - Metal (kg)
Li	LiH	-90.0 (-25.0)	12.7	(800) 1073	$18.03	0.75	155
Mg	MgH_2	-37.1 (-10.3)	7.7	(290) 563	0.84	0.31	256
Ca	CaH_2	-86.8 (-24.1)	4.8	(920) 1193	4.85	0.72	410
Na	NaH	-50.0 (-13.9)	4.2	(525) 798	0.66	0.42	469
$Mg_2NiH_{0.3}$	$Mg_2NiH_{4.2}$	-32.0 (-8.9)	3.5	(250) 523	2.20	0.27	562
K	KH	-56.5 (-15.7)	2.5	(715) 988	0.77	0.47	787
$UH_{0.95}$	$UH_{2.0}$	-20.0 (-5.6)	2.0	(12) 285	8.82	0.17	984
$FeTiH_{0.1}$	$FeTiH_{1.0}$	-12.0 (-3.2)	0.9	(0) 273	4.23	0.10	2187

(a) Does not include weight of container or heat exchangers for refueling and liberation of H_2

maintenance costs. Since the specific operating conditions of many proposed hydrogen production processes have not yet been defined, this discussion will focus on general material compatibility problems that will be encountered during hydrogen production, such as: hydrogen embrittlement, corrosion, oxidation, and erosion (Table VIII-6).

Table VIII-7. Potential materials problems in hydrogen energy system

Hydrogen Embrittlement

Corrosion

- Acids
- Halides
- Liquid Metals
- Heat Transfer Fluids and Salts

Oxidation

- Carburization
- Decarburization
- Sulfidation
- Nitridation

Erosion

- Coal Slurries
- Heat Transfer Slurries

Regardless of which hydrogen production processes eventually prove economically feasible, transmission and storage of hydrogen will always be required in a hydrogen energy system to link hydrogen production with utilization. Potential problems of hydrogen embrittlement will be considered in some detail. The types of hydrogen embrittlement and their occurrence throughout a hydrogen energy system will be identified. A more detailed discussion is given in Appendix H together with more specific concluding remarks and research recommendations.

Hydrogen embrittlement of metals is an old, frequently encountered, and often misunderstood phenomenon. Metals processing, chemical, and petrochemical industries have experienced various types of hydrogen problems for many years. More recently, however, the aerospace industry has experienced new and unexpected hydrogen embrittlement problems. There are many sources of hydrogen, several types of embrittlement, and various theories for explaining the observed effects. Hydrogen embrittlement is classified into three types:

> Hydrogen Reaction Embrittlement — Although the source of hydrogen may be either atomic or molecular, this type of embrittlement is quite distinct from the other two types. Once hydrogen is absorbed, it may react to form a new phase near the surface of the metal or diffuse substantial distances within the metal before it reacts. Hydrogen can react with itself, with the metal, or with a foreign element in the metal. The chemical reactions that comprise this type of embrittlement or attack are well known and are encountered frequently in the petrochemical industry. The new phases formed by these reactions are usually quite stable and embrittlement is not reversible during low temperature aging treatments.
>
> Internal Reversible Hydrogen Embrittlement — Internal reversible hydrogen embrittlement has also been termed slow strain rate embrittlement and delayed failure. This is the classical type of hydrogen embrittlement that has been studied quite extensively. Widespread attention has been focused on the problem resulting from electroplating — particularly of cadmium on high-strength steel components. Other sources of hydrogen are processing treatments such as melting and pickling. More recently, the embrittling effects of many stress-corrosion processes have been attributed to corrosion-produced hydrogen. Hydrogen that is absorbed from any source is diffusable within the metal lattice. To be fully reversible, embrittlement must occur without the hydrogen undergoing any type of chemical reaction after it has been absorbed within the lattice.
>
> Hydrogen Environment Embrittlement — Hydrogen environment embrittlement was recognized as a serious problem in the mid 1960s when NASA and its contractors experienced failures of ground-based hydrogen storage tanks. These tanks were rated for hydrogen at pressures of 35 to 70 mN/m^2 (5000 to 10,000 psi). Because of these failures and the anticipated use of hydrogen in advanced rocket and gas-turbine engines and auxiliary power units, NASA has initiated both in-house and contractual research. The thrust of the contractual effort generally has been to define the relative susceptibility of structural alloys to hydrogen environment embrittlement. A substantial amount of research has been concerned with the mechanism of the embrittlement process. There is marked disagreement as to whether hydrogen environment embrittlement is a form of internal reversible hydrogen embrittlement or is truly a distinct type of embrittlement.

The characteristics of the types of hydrogen embrittlement are summarized in Table VIII-8. Hydrogen environment embrittlement has been observed over a wide range of gas pressures, temperatures, and in a variety of mechanical tests. Embrittlement appears to be most severe near room temperature. Gas purity and test

Table VIII-8. Characteristics of the types of hydrogen embrittlement
[Gray, H. R., 1974]

Characteristics	Types of embrittlement		
	Hydrogen environment embrittlement	Internal reversible hydrogen embrittlement	Hydrogen reaction embrittlement
Usual source of hydrogen	Gaseous (H_2)	Processing Electrolysis Corrosion } (H)	Gaseous or atomic hydrogen from any source
Typical conditions	10^{-6} to 10^{8} N/m^2 gas pressure Most severe near room temperature Observed -173° to 973°K (-100° to 700°C) Gas purity is important Strain rate is important	0.1 to 10 ppm average H content Most severe near room temperature Observed -173° to 373°K (-100° to 100°C) Strain rate is important	Heat treatment or service in hydrogen, usually at elevated temperatures
Test methods	Notched tensile Unnotched tensile Creep rupture Fatigue (low, high cycle) Fracture toughness Disc pressure test	Notched delayed failure Slow strain rate tensile Bend tests C-rings Torqued bolts	Can be observed visually or metallographically
Crack initiation	(Surface or internal initiation)[a]	Internal crack initiation - Incubation (reversible) - Slow, discontinuous growth - Fast fracture	Usually internal initiation from bubbles or flakes
Rate controlling	Adsorption = transfer step (Absorption or lattice diffusion)[a] = embrittling step	Lattice diffusion to internal stress raisers	Chemical reaction to form hydrides or gas bubbles

[a] Unresolved

strain rate can play significant roles in determining the degree of embrittlement. The overall rate controlling step during hydrogen environment embrittlement is the transfer step of surface adsorption. However, if adsorption is bypassed, the rate controlling step for hydrogen environment embrittlement is either absorption or subsequent lattice diffusion. Analyses of substantial increases in the hydrogen content of embrittled alloys tend to support the necessity for lattice diffusion since it is unlikely that such large quantities of hydrogen can be absorbed within the first atomic layer below the surface. Another important characteristic of hydrogen environment embrittlement that has not been conclusively resolved is the location of crack initiation — at the surface or internally. These characteristics can be compared with those observed for internal reversible hydrogen embrittlement and for hydrogen reaction embrittlement which are also listed in Table VIII-8.

2. Hydrogen Safety

The significant hazards associated with hydrogen include fires and explosions, physiological problems such as freezing (burns) and/or damaging frost bites caused by liquid hydrogen and asphyxiation by diluting air to exclude oxygen. Liquid and gaseous hydrogen are particularly subject to leakage because of their low viscosity and low molecular weight. The leakage rate of hydrogen is about 100 times that of JP-4 fuel. Hydrogen gas, at normal temperature is lighter than air and will rise, however, at temperatures which occur just after evaporation (20-24°K), the saturated hydrogen vapor is heavier than air. Hydrogen vapor from liquid spills show a rapid upward diffusion due to buoyancy when compared to heavy fuel vapors such as LNG. Wind and/or forced ventilation will affect the direction of the released hydrogen. The extent of flammable clouds from liquid hydrogen spills and leaks depend upon factors which include evaporation rates, cloud buoyancy, heating effects, ground surface conditions, spill quantities, and terrain configurations.

Hydrogen gas forms a highly combustible mixture with air over a wide range of mixture ratios. The velocity of the combustion wave of the hydrogen-air mixture may propagate at a subsonic rate, with a weak pressure wave (deflagration), or supersonic with a strong pressure wave (detonation). To prevent hydrogen fires, the general procedure is to eliminate all likely ignition sources. Ignition sources such as open flames, exposed hot surfaces, and electric arcs must be excluded. Precautions must be taken against ignition by static electricity, lightning, and communication equipment. Experience, however, has shown that even when major efforts are made to eliminate or suppress ignition sources, hydrogen, when leaked or spilled, has been ignited.

European pipeline safety experience is described [Isting, 1974] as follows: "Experience has shown that compressed hydrogen frequently ignites on expansion. The cause of this ignition is very complex and reasons cannot exactly be given for the ignition. Ignition of hydrogen takes place during escape as a result of electrostatic charges developed on dust particles. In the presence of Fe_2O_3, hydrogen will ignite very readily, while $Fe(OH)_3$ does not cause ignition of hydrogen.

"The practical experience gained with the flammability of hydrogen on expansion is roughly as follows: If a vessel or a pipeline under pressure is suddenly vented through a rarely used line, the hydrogen will ignite in nearly all cases. If, however, only a small amount is vented initially and venting is then gradually increased until high flow velocities are reached, ignition will seldom occur. Once the vent line is blown clear, the hydrogen can hardly be ignited by increasing the velocity. Major amounts of hydrogen can be vented to the atmosphere for a very long period of time without igniting. The issuing hydrogen will however ignite very easily during thunderstorms, even if these are a great distance away, and also by corona discharge.

"Consequently the following three cases may occur in the event of leakage from hydrogen pipelines:

> Hydrogen issues and ignites immediately.
>
> Hydrogen issues and will ignite later (explosion possible).
>
> Hydrogen issues and does not ignite.

"During the many years of operation of the integrated pipeline network of CWH, explosions have not occurred. Either the hydrogen will ignite immediately on escape or, if no ignition takes place, an explosive mixture cannot form near the ground because of its low density (14.4 times lighter than air). Explosions or even detonations in the pipeline need not be feared, as explosive gas-air mixtures cannot build up because of the pressure prevailing in the line."

Another hazard associated with liquid hydrogen is that exposure to air can form a slurry of solid oxygen and nitrogen. Such slurries can form explosive mixtures sensitive enough to detonate. It is necessary, therefore, to adopt measures providing for the control of leakage, leak detection means and appropriate disposal methods. Disposal systems must consider possible hazards of diffusion flame flashback into the lines and of flow reversal during flaring of hydrogen gas. Purge systems are a necessary part of any hydrogen system to prevent the formation of hydrogen-air mixtures in piping, disposal systems, vessels, and related equipment.

Hydrogen gas is colorless and odorless and not detected by human senses. Detection devices that are developed must be reliable and provide rapid response to permit the successful use of automatic system controls and emergency systems. The number and distribution of sampling points must be based on the possible leakage rate, and on the ventilation and area of facility.

Experience with hydrogen in NASA and AEC operations has been extremely gratifying in that relatively few accidents have occurred. With the use of comprehensive cryogenic and hydrogen safety programs similar to those used in NASA programs, safety problems should not limit the use of hydrogen as a fuel in industry.

The Aerospace Safety Research and Data Institute (ASRDI) was established to support NASA, its contractors, and the aerospace community with technical information and consultation on safety problems. In the process of gathering, evaluating, and applying safety-related information, gaps in the existing safety technology are often noted. Where it appears that progress in filling such gaps can be made through research, ASRDI may undertake or sponsor it. ASRDI also operates a Safety Data Bank of technical information which includes a file of specialized information sources (organizations) and safety specialists. Current activities are concentrated in the safety implications associated with fire and explosion, propellants and other hazardous materials, structural failure, and aircraft systems and operations.

C. HYDROGEN IMPACT IN THE ENVIRONMENTAL AND SOCIAL SPHERES*

The HEST Study was charged with identifying social and environmental factors which will affect the introduction and utilization of hydrogen on a major scale. Because fortelling future consequences of any system depends greatly upon the method of data collection, the type of data, and the analytical approach, a subcontract was let to develop a suitable methodology. The Study's intent is the presentation of the methodology for review, and subsequently to apply it appropriately. Firm conclusions regarding social and environmental consequences cannot be made now or and will not be made until the application of this or a similar approach is carried out.

Before these changes begin to have their effects on the biosphere, the social matrix and the institutional construction created by the introduction of large-scale manufacture and utilization of hydrogen into spheres hitherto unexplored is a concern which must be addressed. This exploration process or technology assessment is being conducted because of the possibility that the societal and environmental impacts of widespread usage of hydrogen might be profound. It is crucial that these impacts be evaluated in advance and coordinated within an overall policy, including energy and quality of life components. Presently, the stimulus for developing alternative energy systems stems from the societal needs. The barriers to these systems result not only from societal and environmental concerns but also from the lack of the necessary technological innovations which would make the economics of hydrogen more attractive. Other factors also affect the economic attractiveness of hydrogen; e.g., the price of foreign petroleum.

In general, technology assessment of hydrogen research and development should relate hydrogen technology development to national goals and problems, offer guidance for research and development programming, suggest institutional arrangements for developing the needed capabilities to best use the new technology, and identify pacing factors that will affect development and use of hydrogen technology.

Technology assessment is a relatively new art; with respect to hydrogen, it is handicapped by a broad but irregular data base. Before a major assessment of hydrogen is undertaken, the methodology must be carefully planned. Such a methodology has been developed but it has yet to be exercised.

The introduction and utilization of hydrogen in each of its potential areas will depend upon five major factors: societal needs; societal and environmental concerns; governmental findings, policies, and regulatory factors; economic considerations; and the capability for purely technological innovation. These are the stimuli and barriers to the introduction and use of hydrogen in greater quantities.

Each major area of innovation — new fuel, substitute fuel, storage and transmission medium, processing input — although closely related, requires a separate assessment. Different functions are involved, different market and institutional relationships are affected. There would be overlap, but consequences, pacing factors, and policy responses might be quite different.

1. A Hydrogen Technology Assessment Methodology

The technology assessment methodology recommended here has been taken from several sources; it draws on work done in the study of the innovation process and depends heavily on the logic flow of the recent Futures Group technology assessment report on geothermal energy. The Denver Research Institute policy analysis methodology is used to orient the assessment and include anticipated changes in society and in national policy as summaries of impacts. A successful synthesis of all these approaches is the desired output. This procedure covers two phases and a continuing review process will be needed after that, as with any forecast. An in depth discussion of this methodology is contained in Appendix I.

The first phase defines the context of the study and its boundaries; e.g., ten-year and 25-year forecast periods. After data gathering, a preliminary assessment should be carried out across the breadth of hydrogen uses. The most significant prospective uses of hydrogen technology should be identified and ranked for in-depth assessment. To the extent to which it is available, reconcilable data will be utilized from previous research.

Phase I consists of the following tasks:

Determine the societal and policy context for development of hydrogen technology;

Assemble and relate estimates of present and future energy supply, demand, and cost data;

Examine trends in energy use;

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*O.R. Citron, Appendix I, J.S. Gilmore, W. Mathews and M.K. Duff, Denver Research Institute, and B. Trout, NASA, JSC.

Examine trends in hydrogen consuming industries (actual and potential);

Describe the general context for development and use of hydrogen technology;

Forecast the development of hydrogen technology;

Describe and forecast the states of society;

Develop scenarios of hydrogen technology development;

Estimate preliminary impacts of hydrogen technology development, societal and policy responses, and other pacing factors for development;

Design in detail the second phase work plan.

a. The Energy Policy Context. Information is gathered on formal and inferred public policy and institutional requirements. Parties interested in hydrogen's prospective roles in energy development are identified. Conflicting policies and objectives are noted concerning energy use in the United States and other societal factors which may affect the use of energy.

An analysis of this information has produced a hierarchy of goals, threats, opportunities, and objectives, which specifically describes the objectives hydrogen technology may help to meet or which might require modification if hydrogen technology is to be developed.

b. Energy Supply, Demand, and Cost Data. The existing studies and forecasts of energy supply demand are collected and reconciled related to different uses of energy, and expressed in comparable units. Energy supply figures involve both fuel reserves and resources, and generation or conversion capacity.

c. Trends in Energy Use. Quantities of fuels and energy from different systems being used are plotted and the trends calculated. Price elasticities are studied and the sensitivity of energy use to cost changes are analyzed. These economic relationships are forecast tentatively through both periods, and compared with available forecasts.

d. Trends in Hydrogen Consuming Industry. Existing, nonenergy uses of hydrogen are inventoried and trends in such consumption are examined and projected through the forecast periods. The potential of substitution of hydrogen for existing hydrocarbon feedstocks to chemical processing are evaluated.

Forecasts of the development of the use of different fuels and development of various energy systems (e.g., from government agencies, the Electric Power Research Institute, and the National Petroleum Council) are collected and related to each other. Various technology assessments completed or in process concerning fuels and energy systems are reviewed. From these, technological obstacles to the development and use of these fuels and energy systems are identified. Additional information on these obstacles is generated by interviews with knowledgeable persons in industrial firms, research organizations and universities, and energy-related governmental agencies.

Similar inquiries are made into technological obstacles to additional uses of hydrogen as a chemical processing feedstock.

e. The General Context for Hydrogen Development. This task embodies information generated in previous tasks to describe, textually and graphically, prospective developments in the energy and energy-consuming industries and the relevant portions of the chemical processing industries which might utilize hydrogen. The description is based in the present and should involve prospective development throughout the forecast period.

The description of this context is based on hierarchial display of technologies for the production of electric power and heat using various energy forms and systems, and also for the potentially hydrogen-related chemical processing activity.

f. Forecasts of Hydrogen Technology Development. These forecasts are undertaken for both forecast periods. The principal questions to be asked in preparing these forecasts are:

What are the sources and uses of hydrogen under consideration?

What are the outputs of these sources and uses?

What major technologies are associated with the development of the capabilities for these sources and uses ?

What applied technological areas are involved in these major technologies?

What systems, processes, or methods are involved in these applied technological areas?

What major components comprise these systems and processes, or what specific techniques are used in these methods?

Interviews with knowledgeable people concerning the appropriate technologies are then carried on to help identify the future course of the hydrogen-related technologies found significant. Opinions are sought on the seriousness of particular impediments and judgments as to when the impediments might be removed and the inputs of capital, manpower, policy changes, or material resources which would be required to affect the removal of the impediments. It is from this inquiry that forecasts of the evolution of hydrogen technology through the forecast periods are prepared.

g. The State of Society Estimates and Forecasts. This statement relates the policy aspects and constraints in the hierarchy of goals, threats, opportunities and objectives to existing social and economic relationships which may be forecast into the future and which might thus indicate how the components of such a hierarchy would change. For instance, changes in per capita annual consumption of energy might substantially change anticipated requirements for energy by 1985; so might a shift in existing fertility rates or other population variables. Federal intervention in state activities is forecast along such variables as planning, preemption of state powers in planning and energy siting, the growth trend of federal to state transfer payments (including revenue sharing), the actions of precursor states whose legislation is commonly followed by other states in the same region, urbanization trends, investor confidence trends as manifested by price earnings ratios of equities, and so forth.

h. Scenario Development. The state-of-society forecasts, and the related forecasted hierarchies are integrated with the technological forecasts to lay out two or more scenarios, possible time-phased patterns of the development of hydrogen technology.

Major state-of-society variables, policy and other identified innovations are then altered if necessary for testing (at least subjectively) of the sensitivity of the forecasts to variation in the different factors. A cross-impact analysis after one or two iterations of sensitivity testing and examination of the interdependency of these variables may be attempted.

Scenarios are prepared specifying assumptions on change and the sequence of change leading into statements of alternative futures embodying the partial or complete development of hydrogen technology. The scenarios are useful for preliminary identification of possible impacts on the development of the technology for various interest groups and institutions, and for first-order speculation about the responses to those impacts. Besides the strictly analytical purpose, the scenarios are useful for gaining information from knowledgeable people for iterative reforecasting of the changes in technology and in the state of society.

i. First Phase Subjective Impact Estimates and Identification of Responses and Pacing Factors. Based on the scenarios and perceptions of the concerns and values of the different parties-at-interest and interest groups, impacts of the development of hydrogen technology and their polarity (are they good or are they bad?) for the major interest groups are estimated.

From the estimated impacts, societal and policy responses are identified and examined for their effect on policy — as expressed in the hierarchy — and for their possible modification of the scenarios on the development of hydrogen technology.

j. Detailed Design of the Second Phase. The work thus far has suggested widely diffused areas of usage for hydrogen technology; the areas having differing degrees of need and significance The technological development in the areas have varying rates of advance. Priorities for in-depth technology assessment of the various areas of use are to be analyzed.

Based on priorities, the degree of overlap among areas, and available resources, in-depth or comprehensive assessments are designed for completion in the second phase. The design reflects the recommended logic flow (see Fig. VIII-4).

The final task of the first phase is to design the second phase work. The following activities are carried out in the second effort:

Redefinition of the Forecasts of Technological Development Including Identification of Research and Development Needs — The relationship of hydrogen technology to existing and prospective energy systems and to chemical processing are reexamined. A re-review of technical judgments and additional inquiry on the likelihood of policy and other innovation factors affecting the sequence of technological development is involved. Based on this, further inquiry is made of knowledgeable people in the various technological fields to revise the technological considerations and to better attach timing estimates (and probability estimates of achievement) for the removal of impediments to the development and use of the technology. A side benefit of this task is expected to be a set of informed comments and possibly concensus on R&D priorities on advancing hydrogen technology.

Development of an Interactive or Dynamic Model for Scenario Construction — The model is designed and based on the revised forecast of technological development and the forecasts or response by the social structure, the policy, and the culture. Ideally, the model is refined to respond to both the announcement effects of response (e.g., changes in policy) and to the actual implementation of policy changes. In any case, the model is amenable to manipulation by introducing alternative policy responses into it, each alternative set of policies being represented by a revised hierarchy.

Policy Analysis and Decision-Making Simulation — A model is developed which is adequate for decision-making simulation by a panel of representatives of the major parties-at-interest or interest groups, specifically including government and industry officials. The simulation is designed to identify responses to events and policies, to note the pacing of events as response and counter-response occur, and to clarify the varying perceptions of impacts (e.g., good or bad?, how good?, how bad?) developed in the assessment.

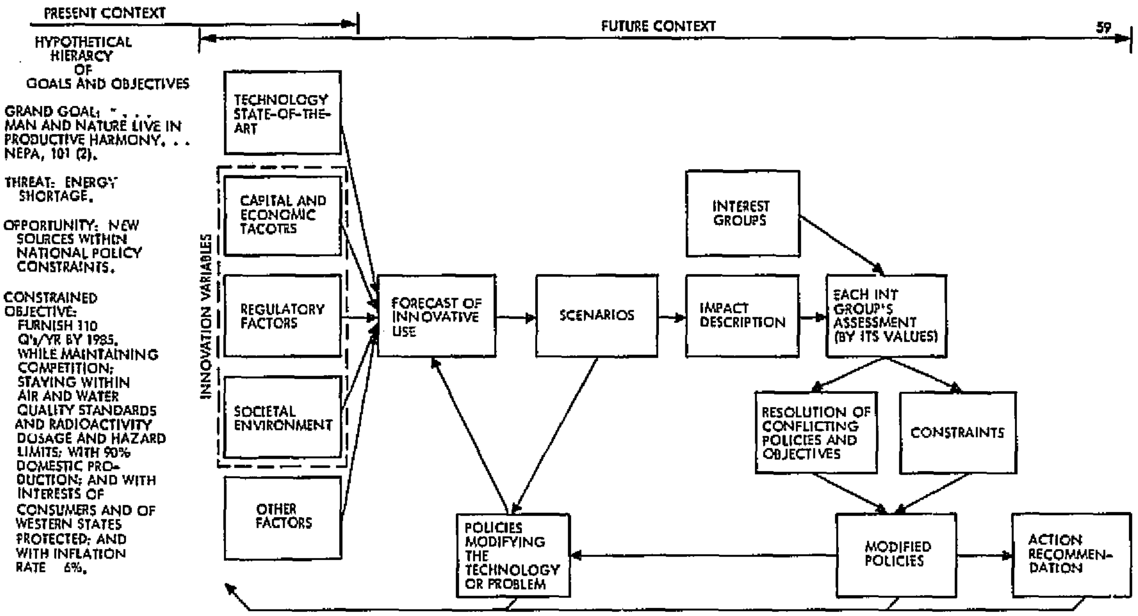

Fig. VIII-4. Synthesized methodology for technology assessment

The simulation is a means of increasing understanding of the pertinent issues and providing a better statement of the potential consequences (positive, neutral, and negative) and responses to hydrogen technology development. It is a means of resolving conflict as an interactive tool general consensus among all potential and actual parties at interest.

The simulation relates alternative futures to differing states of society and to the outcomes of various uses of hydrogen technology and it would supplement the assessment team's cost effectiveness-oriented evaluation of policies and actions relative to the hierarchy's objectives. Both techniques support the logic flow functions of generating proposed policy modifications for government and action recommendations for firms, institutions, and other parties-at-interest or interest groups.

2. The Outputs of the Assessment

There are four major outputs of the entire two phase project:

The Project Report — The substance and the methodology of a hydrogen technology assessment are presented and guidance for the programming of hydrogen research and development is offered.

The Decision-Making Simulation — This permits effective identification and assessment of impacts, and evaluation of policies and actions to deal with those impacts in a variety of situations. It facilitates continuing review of the assessment, and furnishes substantial base for extending the assessment to cover other uses of hydrogen.

Participative Dissemination of the Assessment — Involvement of government and industry officials in the decision-making simulation will arouse their interest in hydrogen technology and in policies and actions affecting it. Their involvement should also improve the quality of the assessment.

Other Options — The need for other assessment action concerning hydrogen technology is uncertain now. The assessment report should recommend: appropriate extension of the assessment to other hydrogen uses or areas; review and revision of the assessment when changes in anticipations on the technology, the state of society and the innovation variables, national policies, other factors, or assessment methodology; revision or interpretation of the report for specific audiences.

These continuing outputs, if obtained, offer prospects for timely introduction of hydrogen technology. This approach integrates developing technological capability with societal needs. Such an effort at well-managed innovation might also contribute to the national policy making process for energy.

3. Industry Receptivity Interviews

A selected group of responsible representatives of industrial energy suppliers and utilities in Texas and California were interviewed in an unstructured informal manner. The objective of the interviews was to ascertain what perspective the represented firms had relative to the introduction of hydrogen as a fuel. These interviews were conducted during October and early November, 1974.

While distinct differences in firm management, economics and planning exist between utilities and producers some general conclusions can be made about these firms in the areas represented by the sample.

> The chief constraints to the use of hydrogen in 1974 are high cost and lack of general availability.
>
> Utilities are not entirely unfamiliar with the potential use of hydrogen in their industry, but immediate problems about conventional fuel availability have produced a deferred interest for most.
>
> No technology problems or safety unknowns are considered to exist in the use of hydrogen as a fuel.
>
> There are engineering and design problems which, given the necessary resources, are solvable.

The overall response to hydrogen fuel by the surveyed companies may be characterized as one of "mild receptivity" to hydrogen, accompanied by virtual indifference to any of the attributes of hydrogen other than cost and availability.

D. ECONOMIC CONSIDERATIONS OF HYDROGEN*

Forecasting the role of hydrogen in a future characterized by substantial changes in the availability of fossil resources is, unavoidably, a speculative exercise. Considerable uncertainties attach to any of the general scenarios of energy use employed above, and to the hydrogen scenarios derived therefrom. If we wish to improve our present policies by intelligent anticipation of future circumstances, however, the choice is not "whether" to deal with uncertainty, but "how" to deal with it. Turning the problem around, the function of a good forecast is to maximize the contribution of what we know to the making of decisions under conditions of uncertainty. The purpose of the present section is to employ economic theory, in qualitative terms to reduce (or at least better understand) the uncertainties inherent in forecasting hydrogen application.

The introduction of "process optimization," and its relationship to scenario-based forecasting is important. A process is "a series of actions, changes, or functions that bring about an end or result." A process requires inputs, and since we will be dealing only with processes which produce "good" results, we will call those inputs "resources." Optimization means, literally, "to make the most of," and process optimization thus refers to the management of a process to maximize some objective. To make the maximization job more challenging (and our description more realistic), we will assume that process optimization must be performed subject to one or more constraints. The concepts above concern us here with respect to understanding the probable responses of the U.S. economy to important changes in the terms of availabilities (prices and/or quantities). To those who manage processes employing the affected resources, changes in the constraints on optimization will, in general, imply changes in the configuration of processes to optimize under the altered circumstances. Less abstractly, the above concepts imply that the extrapolation of present process requirements for hydrogen into a regime of significantly different resource availability is almost certain to misstate future requirements. We can also predict the nature of the misstatement: the dislocations to the economy resulting from increased scarcity of resources are (almost) always much less severe than that implied by extrapolating current process ratio.

The (almost) is inserted to cover the case of a resource which allows absolutely no substitution. The probability of this event is so small as to be almost mythical, for several reasons:

> Most outputs in our economy are "intermediate goods," to be used in turn as input resources to other processes. This means that total inflexibility in a given process "freezes" one link in a chain, and that responses to changed constraints will still occur on both sides of the immobilized "link."
>
> Economies very rarely "run-out" of things. Resource availabilities just do not change in that discrete manner. What happens instead is that particular resource prices rise to the point that several using processes lose their cost competitiveness, and are curtailed. Resources are far more commonly abandoned than exhausted. Those responsible for process optimization resort to lower cost options. If there are none, an inflexible process can use resources freed by the curtailment of others.
>
> Process optimization does not refer only to industry; consumers are important elements of flexibility in an economies response to increased scarcity. In this context, even "final goods" are inputs to the consumer's satisfaction process, and a change in resource costs will lead, eventually, to a change in usage of final goods which incorporate that resource in significant amounts.
>
> Many of the relevant constraints on process optimization are institutional,

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> and subject to change by political action. This is another element of flexibility to be considered by a society seeking to minimize the negative effects of increased resource scarcity. (An example is the deregulation or reduced regulation of natural gas, allowing those process managers with little flexibility with respect to natural gas to register their priorities in the market place.)

The role hydrogen actually realizes in the future economy will be conditioned by markets as diverse as food, fuels (synthetic and conventional), and refined ores; and by institutions as disparate as the United Nations (food production and distribution), OPEC, and the Federal Power Commission. An example that suggests the complexity that will characterize this realization is the importance of hydrogen as both an input to the petroleum industry, and an important user of petroleum products. For this reason, it is difficult to conclude *a priori* whether an increase in the price of petroleum will result in an increase or a decrease in the demand for hydrogen. The effects realized will depend on the flexibilities confronted by the process optimizers who use and/or produce hydrogen. Attempts to predict the sensitivity of hydrogen application to different fossil-availability scenarios will thus require consideration of a range of processes quite beyond the scope of a single-resource study. An important element of any such study will be determining the optimal extent of government intervention in, or modulation of, process management by private interests. The effects of decentralized responses to resource scarcity do not correspond to the national interest. Government can be expected to influence those responses, either by direct participation in, or control of, the relevant processes, or by altering the constraints under which those processes are optimized. In either case, intelligent public policy will require the ability to conceptualize the interdependent selections of resource options by energy producers and users. To make valid optimization choices, the policy makers must have the highest level of technical data made available to them.

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APPENDICES

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APPENDIX A

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I. DIRECT PARTICIPANTS

The study effort which has resulted in the preparation of this report required the participation of a number of people at many stages. Direct participants were a) members of the NASA Working Panel whose primary functions were to provide the coordination of NASA center support and to advise the study team, b) the JPL Study Team whose primary responsibilities were to coordinate and document the study results, c) Supporting Personnel whose primary responsibilities were to collect and evaluate supporting data in their areas of specialty and d) the Review Group whose primary function was to critique the report and to bring to the study the broader perspectives afforded by their diverse backgrounds. Special contributors, individuals who by nature of their recent work or professional affiliation, were asked to make presentations on specific subjects of concern to the study. Individual contacts were made informally to obtain specific information. All of these people are named below.

The Program Manager at NASA Headquarters, whose guidance and help have been extremely valuable to this study, is Mr. David R. Stone, Code NE, Office of Energy Programs.

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APPENDIX B

RECENT AND ONGOING HYDROGEN-RELATED WORK IN THE U. S.

I. SCOPE

As a portion of the Hydrogen Energy Systems Technology (HEST) Study, those efforts of other groups in the U. S. which have assessed the hydrogen energy concept on an overall systems-level basis have been consulted for guidance and technical content. The HEST Study also evaluated past and present work in hydrogen in the specific areas of utilization, production, transmission, storage and distribution. The broad spread of hydrogen systems and devices is also being reviewed. Section B. 2 lists hydrogen energy system studies and Section B. 3 cites specific hydrogen-related research and technology work.

Surveys and bibliographic publications in hydrogen energy are also being covered elsewhere, as are those major conferences and workshops in which hydrogen has been a topic of special note.

This listing does not cover the numerous U. S. energy systems assessments and projections provided over the past several years, even though the subject of hydrogen energy plays some part in the energy scenarios developed. Such is beyond the scope of the brief presentation to follow.

The current federal Research and Development (R&D) expenditures on hydrogen energy systems are estimated in Table B-1. These expenditures do not include those in related areas such as coal gasification development and basic supporting research.

II. SYSTEMS-LEVEL STUDIES OF HYDROGEN ENERGY SYSTEMS (TABLE B-2)

This section reviews the rather limited number of assessments of hydrogen energy systems which have been carried out on an overall, or "systems-level" of investigation. This is as opposed to a specific production, delivery or utilization system, subsystem or device, e. g., thermochemical water-splitting processes, hydrogen-fueled automotive engines. Such items, where particularly notable, are separately listed.

III. SPECIFIC HYDROGEN-RELATED WORK

Important studies concerned with hydrogen-related work are reviewed in this section. The studies have been categorized as: production; coal processing; storage; transmission, and distribution; utilization; and materials, safety and related topics.

Table B-1. Estimated Federal R&D on Hydrogen Energy Systems, $1000

	FY 1975
Production	500
Transmission	100
Storage	550
End Uses	
Utility	850
Transportation	800
System Studies	1500
Total	4300

These studies are listed in Tables B-3 to B-7 respectively, and are based on data from the Smithsonian Science Information Exchange.

The Synthetic Fuels Panel, [Atomic energy Commission, 1972], established in 1972 under the aegis of The President's Office on Science and Technology, reported hydrogen to be a leading contender among synthetic fuel options as evidenced by the title of their report: "Hydrogen and Other Synthetic Fuels."

The Institute of Gas Technology's broad-ranging 1972 assessment of "A Hydrogen Energy System" [Gregory, 1972b] for the American Gas Association concludes that there are no insurmountable barriers which would preclude the production, delivery and utilization of hydrogen as a universal energy form analogous to today's natural gas and electricity systems.

In May 1973 a special government/industry working symposium, held at the NASA Langley Research Center, confirmed the attractiveness of liquid hydrogen fuel for aviation from a technical performance and environmental standpoint.

A joint NASA/American Society of Engineering Educators (ASEE) special task-force comprehensively assessed "Hydrogenergy" during the summer of 1973 [Johnson Space Center, 1973]; their findings were broadly published and constituted an early input to this study.

Beginning in 1973 the U. S. Naval Ship Research and Development Center in Annapolis has supported contracted studies and in-house laboratory experimental efforts on nautical uses of hydrogen.

Two hydrogen bibliography services have recently been established, the National Bureau of Standards (NBS) Boulder Laboratory's quarterly, "Hydrogen Future Fuel," and the University of New Mexico's "Hydrogen-Energy" series. Also published by NBS on this subject is "Selected Topics on Hydrogen Fuel" [Hord, 1975].

Three national/international technical conferences devoted solely to hydrogen have now taken place. These meetings took place at Cornell University in 1973 and at the University of Miami in 1974 and 1975. In 1974 the International Association for Hydrogen Energy was founded and has scheduled the "First World Hydrogen Energy Conference" for March 1976.

A number of technical evaluations have been carried out by aircraft companies, notably Lockheed, of hydrogen-fueled subsonic and supersonic transport aircraft. NASA has been the principal supporter of these efforts.

Contemporary with the HEST study, several other efforts have been made and are being carried out by different supporting and implementing organizations. Examples are given in Table B-2.

Table B-2. Hydrogen-Energy System Studies and Conferences

Year	Study Group	Sponsor	Title or Reference	Scope	Areas Emphasized	Reported (where/when)
1964-66	Allison, GM	Army Engrs.	"Energy Depot"	Nuclear H_2 to NH_3 fuel	Production, E/C T/C	ORNL reports, Army at THEME
1968	Air Prod. & Chem.	NASA-ARC	HST fueling NAS 2-3894	LH_2 from global bases	Production from Fossil Fuels, liq.	Final Report CR 73, 226 (196)
1971	IGT	A.G.A.	H_2 System	Prod. econom.	E/C	A.G.A. L21173 Aug. 72
1972	IGT	A.G.A.	H_2 System	All aspects	Prod., trans., storage, utiliz.	A.G.A. L21173 Aug. 72
1972	GE-TEMPO		ECO-ENERGY	Explored Alternatives	Prod., delivery	GE 72TMP-15, Sept. 72 (rev.)
1972	Brookhaven Nat. Lab.	ORNL	Ref. Energy Systems	Basis for Sys. Comp.	Total energy flows for several "time cuts"	BNL AET-8 April 1972
1972	Synthetic Fuels Panel	OST (ORNL)	H_2 & Other Syn. Fuels	Total system	Production & Utilization	AEC TID-26136 (+ ORNL TM-4305, 4307, etc.)
1973	Govt/Indstry. Panel	NASA-LaRC	Wkng. Symp. on LH_2 fueled aircrft.	Aircraft technology	Aircraft design, LH_2 prod. & log.	Proceedings April 1973
1973	Cornell Symp. on H_2 Econ.	Cornell U. (NSF)		Broad, most aspects	Prod. & utiliz.	Proceedings (still in process)
1973	SRI	NSF	Tech. Assess. of H_2 Econ.	Broad	Societal impact	Report in process (due Spring 75)
1973	IGT	A.G.A.	H_2 System	Prod. & Delivery	T/C Prod., pipeline opt., matrls., and utilz. survey	Final Rpt. to A.G.A. (not released)
1973	BNL/AEC	AEC/DAT	H_2 Storage & Production in Utility Systems	Utility Sys.	Storage, Production, Fuel Cell	First Annual Rpt. Available
1973	JSC & Univs.	NASA-ASEE	Hydrogenergy	Broad	Societal & Implementation	Report (2 vol.) Sept. 73
1973	NBS Boulder Lab.	Dept. of Commerce	Hydrogen-Future Fuel	Prod. & Utiliz.	Cryogenic tech.	Report available
1973	Futures Group	Northeast Utilities	H_2 as syn. energy-carrier	Prod. & delivery	Utility viewpoint	Report available
1973	JPL	NASA/EPA/DOT	High eff., low-poll. car	H_2 add. to gasoline	Auto. pwr. system	Interim Rpts. available
1974	U of Miami	NSF/ARPA	THEME	Gen. conf. Inrntl.	Entire system	Proceedings (out of supply) formal edition: Jan. 75
1974	GE-TEMPO	NSRDC/ARPA	H_2 Mission plan.	Navy viewpt.	Prod. & logistics	Report (available?)
	Stevens Inst.	NSRDC/ARPA	Eng. problms.	Navy viewpt.	Engines, E/C, pipeline opt.	Report available
	NSR DC	NSRDC/ARPA	Embrittlement & turbine boat demo.	In-house	Pract. eng. solutions	Visitations available
1974	Lockheed-Cal.	NASA-ARC	LH_2 AST	Tech. & econ. study	Feas. & rel. \$ re kerosene ver.	Final rpt. CR 114 718 (avail Fall 74)
1974	Lockheed-Cal.	NASA-LRC	LH_2 subsonic transports	Tech. & econ. study	Feas. & rel. \$ re kerosene ver.	Final oral Nov. 74 (rpt in publ.)
1974	U of Miami	IAHE	H_2 energy fundamentals	Survey/ Instruct.	All	Prelim. Proceed avail. Final Rpt. Summer 75
1974	IGT	NASA-MSFC	Survey prod. & util.	Survey/plan.	Prod. & util.	Aug. 1975
1974	Linde-UCC	NASA-LaRC	H_2 from coal	Tech. & econ. assessment	Prod.	Report available
1974	IGT	EPRI	Off-Peak Power to Produce Indust. H_2	Prod. & Delivery	Produce & market analyses	Report in prep.
1975	Battelle NW Labs	NASA-KSC	LH_2/LO_2 explosive initiation phenom.	Tech. invest.	Combustion, detonation & safety	NAS 10-91 Final Report
1975	Gen. Atomic Co.	NASA-LeRC	Nuclear H_2 prod.	Tech. & econ. study	WHTR & T/C	Late 75/Early 76
1975	Westinghouse	NASA-LeRC	Nuclear H_2 prod.	Tech. & econ. study	WHTR & combined T/C + E/L	Late 75/Early 76
1975	Denver Res. Inst.	JPL(HEST)	Env. & Soc. aspects of H_2 system	Define methodology	Prop. & Util.	Incl in HEST Rpt.
1975	IGT	NASA-LaRC	H_2, CH_4 and JET A from Coal	Tech. & econ. study	Thermal eff. & cost	Jan. 76

Table B-3. Specific Hydrogen-related Work: Production

Year	Study Group	Sponsor	Title or Reference
73	Univ. of Illinois	Dept. of Agriculture	Metabolic Activities of Rumen Microorganisms
73	LeRC	NASA	Terrestrial Applications of Solar Energy
73	Univ. of Mass.	NSF	Ocean-Sited Power Plants
73	Univ. of Kentucky	NASA/LeRC	Thermochemical Fuels from Solar Energy
73	Carnegie-Mellon U.	NSF	Solar Power Ocean-Based Plants
74	IGT	AGA	Thermochemical Hydrogen Production
74	Univ. of Florida	EPA	Methanogenic Bacteria in Sludge
74	General Atomic	General Atomic	Production of Hydrogen from Water
74	General Electric	GE	Advanced Energy Generation
74	Indiana Univ.	NSF	Biophotolysis Hydrogen Production Workshop
74	Univ. of Pennsylvania	NSF	Direct Energy Conversion Research
74	Case Western Reserve U.	NSF	Hydrogen Production by Photosynthesis and Hydrogenase Activity
74	SUNY	NSF	Redox Reactions of Coordination Compounds
74	Union Carbide Corp.	Union Carbide Corp.	Resource Recovery from Solid Waste
74	Univ. of Idaho	NSF	Radiation Enhanced Electrocatalysis
75	Univ. of Hawaii	Dept. of Defense	Power: Hydrogen Generation from Sea Water
75	Univ. of California; San Diego	NSF	Bioconversion of Solar Energy and Production of Hydrogen by Photolysis

Table B-4. Specific Hydrogen-related Work: Coal Processing

Year	Study Group	Sponsor	Title or Reference
72	FMC Corp.	Dept. of Interior	Project Coed
72	AVCO Corp.	Dept. of Interior	ARC Processing
72	Univ. of Wyoming	Dept. of Interior	Multiple Catalyst Fluidized Reactions
72	Applied Tech Corp.	Dept. of Interior	A program with AGA-OCR to Develop its ATGAS Process
72	IGT	Dept. of Interior	Pipeline Gas by Hydrogasification
72	Col. School of Mines	Dept. of Interior	Removal of Sulfur from Coal by Treatment with Hydrogen
72	Bur. of Mines	Dept. of Interior	Gasification of Shale Oil
72	Univ. of Miss.	NSF	The Conversion of Model Coal Liquids Compounds to Naphtha Species
73	Stevens Inst. of Tech.	NSF	Fractionation of Coal
73	Univ. Oil Prod. Co.	Univ. Oil Prod. Co.	Coal Conversion
73	Univ. of Utah	Dept. of Interior	Intermediate Coal Hydrogenation Process
74	Standard Oil Co. of Indiana	Standard Oil Co. of Indiana	Selective Hydroconversion Studies on Coal
74	Hydrocarbon Research Inc.	Standard Oil Co. of Indiana	H-Coal Process Development
74	U.S. Dept. of the Interior	EPA	Solvent Refined Coal Product Evaluations
74	Consolidated Coal Co., Chicago, Ill.	Dept. of Interior	Carbon-Dioxide-Acceptor Coal-Gasification Process
74	Iowa State University	Dept. of Interior	Electrofluidic Coal Processing
74	Univ. of Wyoming	Univ. of Wyoming	Hydrogenation of Coal in Molten Media

Table B-4. Specific Hydrogen-related Work: Coal Processing (contd)

Year	Study Group	Sponsor	Title or Reference
74	Univ. of No. Dakota	Dept. of Interior	Premium Fuels from Northern Great Plains Lignite-Project Lignite
74	Dept. of Interior	Dept. of Interior	Coal Liquefaction by Catalytic Hydrogenation
74	Dept. of Interior	Dept. of Interior	Hydrogenation of Coal to High BTU Gas
74	Dept. of Interior	Dept. of Interior	Hydrogenation of Coal to Liquids - Hydrodesulfurization
74	Dept. of Interior	Dept. of Interior	Production of Hydrogen
74	Dept. of Interior	Dept. of Interior	Hydrogen Production from Residues of Coal Hydrogenation
74	IGT	AGA	Improved Shift Conversion Catalyst
74	Pittsburgh & Midway	Dept. of Interior	Solvent Refined Coal
74	IGT	Dept. of Interior	Pipeline Gas By Hydrogasification
74	Univ. of Utah	Dept. of Interior	Intermediate Coal Hydrogenation Process
74	Westinghouse Electric Corp.	Dept. of Interior	Clean Power Generation from Coal
74	U. S. Steel Corp.	Dept. of Interior	Clean Coke Process
74	Univ. of Kentucky	NSF	Synthetic Oil from Coal
74	CUNY	NSF	Studies Toward Improving Techniques for Gasifying Coal
75	Chem. Syst. Inc.	Dept. of Interior	Slurry Methanation Process

Table B-5. Specific Hydrogen-related Work: Storage, Transmission and Distribution

Year	Study Group	Sponsor	Title or Reference
73	Brookhaven National Laboratory	Consolidated Edison Company	Development of Storage Device for Hydrogen as a Hydride
73	Futures Group	Northeast Utilities Service Company	Feasibility of Energy Delivery System Based on Hydrogen
73	Northeast Utilities Service Company	Northeast Utilities Service Company	Storage of Hydrogen
73	IGT	AGA	"A Hydrogen Energy System"
73	Arthur D. Little	U.S. National Science Foundation	Energy Distribution Advisory Committee FPC 1974 National Power Survey
74	Oklahoma State University School of Engineering	Arkansas Power & Light Company	Energy Conservation and Storage
74	Brookhaven National Laboratory	Department of Defense - Army	Hydrogen Storage and Purification Systems
73	Univ. of Calif.	Dept. of Transportation	University Research on Hydrogen Storage
73	IGT	AGA	A Hydrogen Energy Distribution System
73	Oklahoma State	Oklahoma State University	Energy Conversion, Energy Storage and Reconversion
74	Associated Universities Inc.	Environmental Protection Agency	Motor Vehicle Storage of Hydrogen Using Metal Hydrides
74	Brookhaven National Laboratories	U.S. Dept. of Defense Army	Hydrogen Storage and Purification Systems
74	McDonnell-Douglas Corp.	NASA LaRC	A Fuselage/Tank Structure Study for Actively Cooled Hypersonic Cruise Vehicles
75	Bell Aerospace Co.	NASA LaRC	Development and Validation of Purged Thermal Protection Systems for Liquid Hydrogen Fuel Tanks

Table B-6. Specific Hydrogen-related Work: Utilization

Year	Study Group	Sponsor	Title or Reference
73	Englehard Industries, Inc.	U.S. Dept. of Defense - Army	Electrode-Electrolyte System for H_2-Air Fuel Cell
73	NASA/LeRC	NASA/LeRC	Advanced H-O Power System Technology
73	Caltech/JPL	NASA	High-Efficiency, Low-Pollution Engine for Aircraft
73	Futures Group	Northeast Utilities Serv. Co.	Feasibility of Energy Delivery System Based on Hydrogen
73	G. E.	NASA	Modified Engine for Methane and Hydrogen
74-	Pub. Serv. Elec. & Gas Co.	Pub. Serv. Elec. & Gas Co.	Chemical Energy Storage
74	NASA/LeRC	NASA/LeRC	Hydrogen-Oxygen Power Systems
74	NASA/LeRC	NASA/LeRC	High Temp. Alloys for Adv. Energy Conversion Systems
74	Cornell Univ.	Dept. of Transportation	Combustion of Hydrogen-Fueled Transportation System
74	Univ. of California	Dept. of Transportation	Research Studies Pertaining to Hydrogen Car Development
74	Univ. of Kansas	Univ. of Kansas	Livestock Manure Disposal Via Hydrogasification
74	Oklahoma State University	Oklahoma State University	Energy Conversion, Energy Storage and Reconversion
74	NASA/LeRC	NASA/LeRC	Hydrogen-Oxygen Combustion Magnetohydrodynamic Generators

Table B-6. Specific Hydrogen-related Work: Utilization (contd)

Year	Study Group	Sponsor	Title or Reference
74	NASA/LeRC	NASA/LeRC	Hydrogen-Oxygen Power Systems
74	NASA/LeRC	NASA/LeRC	Hydrogen-Oxygen Auxiliary Systems Tech.
74	NASA/LeRC	NASA/LeRC	Advanced H_2-O_2 Engine Turbomachinery Tech.
74	Boeing Co.	Boeing Co.	Hydrogen Fuel Systems
73	Energy Res. Corp.	Communications Satellite Corp.	Regenerative Fuel Cell
74	United Aircraft Corp.	Dept. of Defense (USAF)	Regenerative Fuel Cells Follow-On for Satellite Secondary Power
74	Okla. State University	NSF	Development of an Electrical Generator and Electrolysis Cell for a Wind Energy Conversion System
74	University of Hull	Dept. of Defense (USAF)	Kinetics of Hydrogen-Oxygen and Hydrocarbon-Oxygen Systems
74	United Aircraft Corp.	Dept. of Defense (USAF)	High Power Density Fuel Cell for Aircraft High Power
74	Comm. Ed. Co.	North American Rockwell	Non-Polluting Engine Program
74	Oklahoma State Univ.	Arkansas Power & Light Co.	Energy Conversion & Storage
74	Univ. of Florida	Univ. of Florida	Combustion Properties of Hydrogen in an Internal Combustion Engine

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APPENDIX C

EUROPEAN ACTIVITIES IN THE HYDROGEN ENERGY FIELD

J. E. Chirivella

This appendix is a synopsis of the study and physical research activities in the Hydrogen Energy field in the European community. It is based entirely on observations made on visits to several countries in Europe known to be active in hydrogen related work during the winter of 1974-75.

In a series of informal interviews with individual leaders in Austria, Belgium, England, the Federal Republic of Germany, France and Italy, the U.S. hydrogen activity was described by introducing the HEST study. Numerous European reports and other technical publications were received for analysis and assimilation by the project team.

The following brief review of the visits made is organized by country, in alphabetical order.

AUSTRIA

Dr. Cesare Marchetti - International Institute for Applied Systems Analysis (IIASA) Schloss-Laxemburg, formerly of Euratom, Ispra, Italy, is the noted European pioneer of the 'Hydrogen Economy" concept. From his earlier focus on thermochemical production of hydrogen, he has considerably broadened his activities to encompass long-range projections of the world's future energy supply and demand trends. He believes that hydrogen will become the principal enery medium in the longer-range picture. For the U.S., Dr. Marchetti foresees continued dependence on fossil fuels until the year 2000 and beyond, with a substantial conversion to nuclear energy systems underway by the late 1980s. Solar energy is seen to become dominant in the U.S. no earlier than late in the 21st century.

Professors E. Broda and N. Getoff of the University of Vienna are members of the Biology and Chemistry Departments, and were contacted at the recommendation of Dr. Marchetti.

Professor Broda, in his evaluation of the possibilities of conducting basic water-splitting reactions through photosynthesis-related processes suggests, a critical study of genetic changes in plants for the purpose of enhancing plant processes to favor hydrogen production. He believes that an evaluation of very early plant development will be fruitful in the development of an understanding of photosynthetic water-splitting and is presently working with elemental green bacteria and blue algae.

Professor Getoff's work on hydrogen production via radiolysis and photolysis is concentrated on experimental analysis of the phenomenon of molecular level energy transfer during water splitting via photon participation.

BELGIUM

Mr. Leon Valette, of S.C.I.E.N.C.E., Brussels, is one of a number of professional people, formerly in the General Directorate of the Commission of the European Communities, who make up the staff of S.C.I.E.N.C.E., a private research organization. The DELPHI study, a continuing worldwide survey on "Hydrogen as an Energy Vector" is the most relevant project to the HEST area of interest. Several questionnaries have been distributed and recollected in an attempt to form a publishable "consensus" on many aspects of hydrogen energy. Schedules and funding levels were discussed with Mr. Valentine, who administers the European Economic Community (EEC) Hydrogen Program and an impressive grasp of the complex techno-socio-political status and direction of Europe's energy situation were displayed.

ENGLAND

Dr. J.K. Dawson, Energy Technology Support Unit, United Kingdom Atomic Energy Authority (UKAEA) is a leading authority in hydrogen energy in the British Isles. His group is presently evaluating an electrolytic hydrogen production scheme for the British Government in which very large scale production plants are envisioned. Pertinent R & D recommendations will be made based on this study. The apparent low-level of interest in hydrogen energy is because the country has higher priority problems to solve. Hydrogen will probably have little impact in the energy area here until after the turn of the century.

Dr. Tony Hart and Dr. Peter Hampson, Central Electricity Research Laboratory of the Central Electricity Generating Board, Leatherhead (near London) are evaluating hydrogen in the context of the British electricity system. Several papers have been presented focusing on the energy transmission aspect. Electrical energy transmission is economically more favorable than pipeline hydrogen for distances of interest to the British Isles. They are following coal-to-hydrogen technology and believe that Englands technology is adequate. Labor problems affect the reliability of supply and economics of coal production.
Dr. Hart was organizing a technical conference on electrolytic hydrogen production at the time of the visit (subsequently held) and advanced electrolyzer topics were pursued in discussion. Hart evidenced some degree of pessimism regarding the possibility of an early development of advanced High Temperature Reactors (HTR) under UKAE. The CERL people are well up on the activities of EURATOM and the EEC.

FEDERAL REPUBLIC OF GERMANY

Drs. J. Schulten and H. Barnert, Institute for Reactor Technology, Juelich are involved with

HTR work supported by the German Government with emphasis on the "pebble bed" type reactor which Juelich has pioneered. It has been demonstrated (with uncertain reliability) at temperatures of 1200°C. The use of the HTR in coal gasification is of primary interest, as well as other examples of nuclear process heat applications. The EVA-ADAM chemical heat pipe concept is also associated with HTR primary energy. Other discussions centered on: helium gas turbines, coal gasification demonstration plant, and hydrogen energy.

Through a cooperative arrangement with the University of Aachen thermo-chemical production cycles are being explored; Professor Knoche of Aachen is leading this work which has examined iron-chloride and sulfur cycles, all of which apparently remain in the laboratory stage. The Juelich researchers believe in the evolution of a full-scale hydrogen energy system.

Dr. Udo Ohrt and Dr. Dieter Hassel, Technischer Uberwachungs--Verein Rheinland, e. V., Cologne, are active in the alternative automotive power systems and fuels area. They are interested in hydrogen as a long range automotive fuel, and the hydrogen injection (to gasoline) approach being evaluated by JPL and others. An impressive document, "New Fuels on the Way", which the group coordinated on behalf of numerous industry, government and university contributors, reflects Germany's major interest in methanol (from domestic coal) in the near term, and hydrogen from non-fossil sources, for the far term.

FRANCE

Dr. Francois Joly and Dr. Bernard Cochet-Muchy, Pechiney Ugine Kuhlmann, Paris, are Directors of the Nuclear Reactor and Chemical Products Divisions, respectively of this large, worldwide industrial company. It is heavily involved with basic metals and chemicals, and has more recently added, nuclear energy. Joly is quite interested in nuclear thermochemical production of hydrogen. The company is working with the Government in associated technological area and makes inputs to EURATOM, Ispra (discussed later). He believes that thermochemical production remains a long way off, and that the associated capital investments will be much higher than are presently estimated or conjectured. Hence, electrolysis will be the established route for non-fossil production for some time to come.
Dr. Cochet-Muchy is interested primarily in hydrogen as a chemical feedstock.

Mr. Paul Gelin, Nuclear Center at Saclay, CEA-CEN, DEDR/EMT, Ivette, described studies of hydrogen as an alternative to hot water produced from nuclear waste heat as a means of general space heating. The center, under the direction of Mr. Rastoin, houses an HTR. There is expressed interest and the beginnings of research on thermochemical hydrogen production cycles, but Gaz de France (GDF) is depended on for basic information in this area.

Mr. Paul Godin, Electricite de France (EDF), Chatou, works at the EDF Center for Research and Studies has been involved in studies of electrical load-leveling. Hydrogen is favored as the storage means once France develops a broad nuclear base-load capability. Both reconversion of hydrogen to electricity and direct sale as a feedstock commodity are being considered. Hydrogen cannot compete with electricity for energy transmission however, in the EDF view. Godin estimates that by 2000, France will have approximately 15 percent of its nuclear capability in fast breeder reactors. Hydrogen production is through electrolysis at EDF and considerable activity was evident.

Professor Paul Haggermueller, Department of Science, University of Toulous, was conversed with by phone. He is particularly active in organizing meetings and symposia on subjects relating to hydrogen energy. As Director of the Department, Haggermueller is presently involved in studies of thermochemical cycles and metal hydrides for hydrogen storage.

Jean Pottier, Branch Chief of New Studies and Techniques, Gaz de France (GDF), Paris, is working in a Government-requested study of hydrogen as an energy carrier. The fundamental elements of the program plan covered aspects of delivery and utilization although emphasis is clearly on production. Work by GDF on thermochemical cycles for hydrogen production began three years ago and focused upon cycles depending on the oxidation of metals. Presently, fairly basic research with potassium is emphasized (to establish properties of the oxides for cycle purposes).

There have been limited industrial activities. According to Pottier, for example the "Institute Francoise de Petrole" has been looking into hydrogen and its carriers such as methanol for automotive fueling. There is little interest in hydrogen from coal and coal gasification since coal is so scarce in France. Were a hydrogen production and delivery system to be developed, GDF feels that the private industrial sector will automatically develop the requisite utilization devices.

Pottier explained that GDF is conducting cooperative studies with the Comisariat a la Energie Atomique (CEA) in which GDF performs the thermochemical work and CEA the reactor-oriented studies. In this way the nuclear/thermochemical interface is being thoroughly evaluated before spending large amounts of effort on either component of the system. GDF believes that thermochemical production will eventually displace methane steam reforming, and that it is also favored over electrolytic production. A demonstration thermochemical plant is forecasted for approximately 15 years from now. Studies of transmission and distribution of hydrogen in which basic engineering aspects will be examined are planned for the near future.

Dr. L. Thieret, Commision a la Energie Atomique, Paris, heads the systems group of the French program of HTR development, and is particularly concerned with non-electrical applications in this field. The use of nuclear heat in reforming natural gas to hydrogen is emphasized with the belief that in the future large supplies will be available from Holland and the North Sea. Frances aggressive and well-designed effort in developing nuclear energy for its basic energy needs shows this program to be at least 5 years ahead of that of the United States, according to Dr. Thieret, and he estimates a 20 to 30 percent dependence on the fast breeder by 2000.

ITALY

Drs. G. Behgi and C. DeBeni, EURATOM Joint Nuclear Research Center, Ispra, are the recognized European pioneers in thermochemical production of hydrogen. Dr. DeBeni provided an in-depth description of the various cycles Ispra has examined up through "Mark 9", dwelling on a number of the practical problems encountered in their research. Presently the emphasis is on the Mark 9 or some other variation of the iron-chlorine family of cycles. Recently unclassified information on their work is now available and much information was acquired for subsequent analysis in the HEST effort. The estimated 12 years to a sizable pilot plant makes EURATOM the clearcut leader in European work in the thermochemical hydrogen production.

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APPENDIX D

HYDROGEN USES

R. Manvi

This Appendix offers brief descriptions of some of the present and future uses of hydrogen, organized according to industrial synthesis and process uses and applications to other sectors of the national economy.

I. AMMONIA

Large quantities of hydrogen are required to produce ammonia, which is one of the world's most important chemicals. Ammonia's uses include fertilizers, refrigeration, nitric acid, water treatment, synthetic plastics and fibers, animal feeds, explosives, rocket fuels, ore refining, and many others. There are no substitutes for nitrogen as a fertilizer. The importance of ammonia to the U.S. economy is shown by the fact that in 1973, production was 141.77×10^8 kg (15.627 million tons) (Bureau of Mines, 1975)[*] with a value of $1.016 billion, and probably this was greater than that for any other chemical.

Most of the ammonia production is concentrated along the Gulf Coast. Manufacture of all synthetic ammonia is carried out by passing the correct combination of nitrogen and hydrogen (1:3 molar ratio) over an iron oxide catalyst promoted with aluminum or potassium oxide, at near 644° K (700° F) and about 25.3 MN/m^2 (250 atm) pressure. The hydrogen consumption with a yield between 0.85 and 0.95 is roughly 2.2 - 2.5 m^3/kg (70,000 - 80,000 scf/ton). Most plants obtain their hydrogen by steam reforming of natural gas, during which enough air is added to obtain the required amounts of nitrogen. The largest ammonia plant in the U.S. is of 461.3×10^6 kg/yr (0.51×10^6 tons/yr) capacity. Geographic location of U.S. ammonia plants is shown in Fig. D-1 (Biederman and Darrow, 1975).

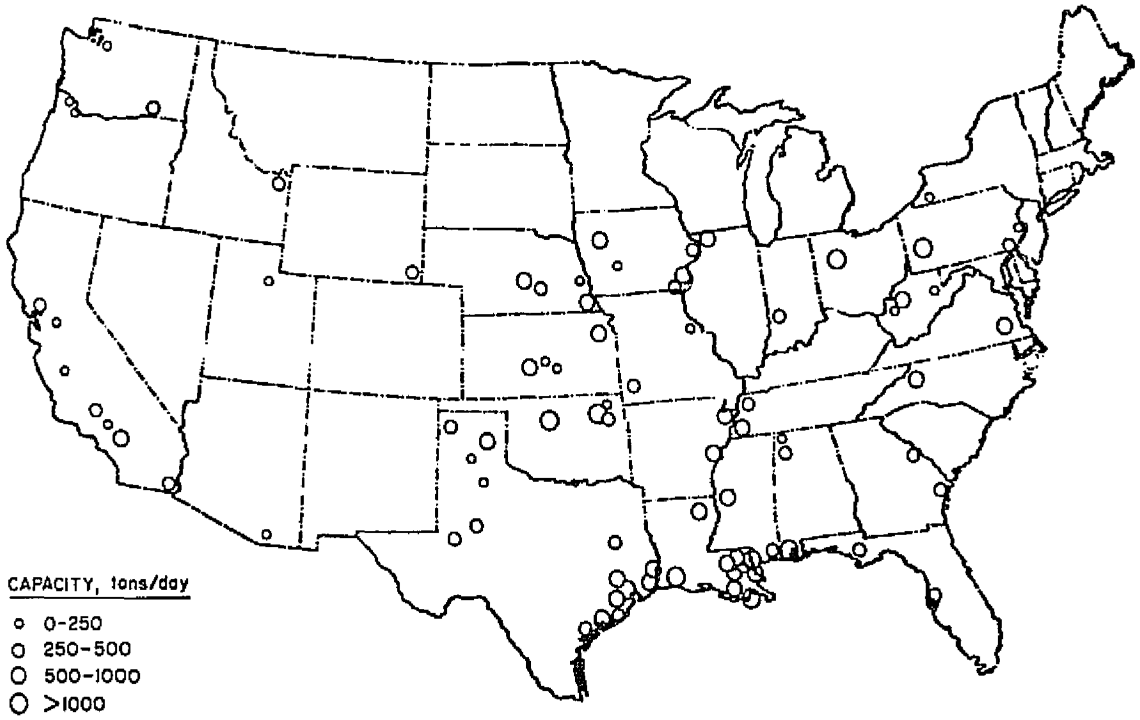

Fig. D-1. Geographic Dispersion of U.S. Ammonia Plants (Biederman and Darrow, 1975)

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[*] References are listed alphabetically at the end of this appendix.

II. PETROLEUM

Because every petroleum refinery has both processes which consume and generate hydrogen, accurate determination of quantities of hydrogen used in refineries is extremely difficult. The net effect in an individual refinery is dependent upon the type of hydrogen processing as well as the feed and output composition. Listed below are some of the hydrogen uses in petroleum processing (Bland and Davidson, 1967).

	Process	Purpose
(1)	Hydrotreating:	Desulfurization of distillate feeds; color and stability improvement of lube oils; reduce sulfur content of high sulfur stocks. Hydrogen consumption: 0-8.9 m^3/m^3 (0-50 scf/barrel).
(2)	Hydro-desulfurization:	Remove sulfur, nitrogen, oxygen, metal compounds from distillates. Hydrogen consumption: 14-267.2 m^3/m^3 (80-1500 scf/barrel).
(3)	Hydro-fining:	Refine byproducts from gasoline steam cracking; hydrogenate polycyclic aromatics; selective hydrogenation; remove heavy metals from catalytic cracking feed. Hydrogen consumption: 17.8-107 m^3/m^3 (100-600 scf/barrel).
(4)	Hydrocracking:	Upgrade and desulfurize heavy sour crude and residue; upgrade distillates to gasoline or middle distillates; to produce premium gasoline, jet fuel, mid-barrel products; reduce heavy stocks to gasoline. Hydrogen consumption: 320.6-445.3 m^3/m^3 (1800-2500 scf/barrel).
(5)	Hydrodealkylation:	To produce napthalene, benzene, and toluene. Hydrogen consumption: Less than 107 m^3/m^3 (600 scf/barrel).
(6)	Catalytic Reforming:	A process in which light hydrocarbon components are converted into middle range gasoline fractions. Hydrogen is generated by steam reformers. Hydrogen generated: 107 m^3 - 142 m^3/m^3 (600 scf - 800 scf/barrel).

Many petroleum refineries without extensive hydrocracking operations are self sufficient in generating hydrogen. Since refineries with hydrocracking facilities retrieve large quantities of hydrogen, they generally obtain "deficit" hydrogen from steam reforming if they cannot obtain all the hydrogen they need from their catalytic reformers. Figure D-2 shows the geographic location of refineries with hydrocracking. The largest hydrocracking unit in the U.S. has approximately 9380 m^3/day (59,000 barrel/day) capacity.

III. METHANOL

Methanol is one of the largest volume organic chemicals produced synthetically. Industrially, methanol is used chiefly as a solvent and precursor in the manufacture of plastics, resins, and organochemicals; it has been used as an automotive antifreeze and racing fuel. Today, nearly all methanol is made using natural gas as a feedstock by steam reforming. In the Lurgi high pressure process, CO and H$_2$ in a Molar ratio of 1:2 are allowed to react in the presence of chromium-oxide – zinc oxide catalyst at 30.4 MN/m^2 (300 atm) pressure and at about 283° K (660° F). The recent low pressure ICI process operates at 5.1 MN/m^2 (50 atm) and 533° K (500° F), using active copper as a catalyst.

In 1973, the U.S. methanol plant capacity was reported to be 4542 $\times 10^3$ m^3/yr ~ (1200 million gal/yr) (Statistical Summary 1973). However, the actual production was estimated to be 363 $\times 10^4$ m^3 (960 million gal) (Biederman and Darrow, 1975). Hydrogen consumption for methanol production is estimated to be 1.62 m^3 - 2.34 m^3/kg (52,000 sft^3 - 75,000 sft^3/ton). At the current prices of about $\$106/\text{m}^3$ ($\$0.40$/gal) the methanol market is worth $\$400 \times 10^6$. The geographic location of methanol plants is shown in Fig. D-2. The largest plant is 871 $\times 10^3$ m^3/yr (230 $\times 10^6$ gal/yr) capacity.

IV. FOOD (Air Products, 1975)

A. Hydrogenation of Edible Organic Oils

The edible organic oils in soybeans, fish, cotton seed, corn, peanuts, and coconuts are treated with hydrogen in the hydrogenation process. This process retards the tendency of the oil to oxidize and turn rancid, improves consistency (producing a solid fat such as margarine and shortening instead of a liquid oil) and reduces the reactivity of the oils. Major edible oil producers have on-site hydrogen generating facilities. The opportunity to replace self-generating hydrogen plants increases as on-site production costs and purity requirements increase.

B. Hydrogenation of Inedible Tallow and Grease

Inedible tallow and grease are treated with hydrogen for the production of soap and animal feed.

V. METALWORKING, FERROUS REDUCING ATMOSPHERE (Air Products, 1974)

Ferrous metals are heat-treated in controlled atmosphere furnaces to change certain physical properties of the metal. Some specific reasons for heat treatment follow: Develop ductility;

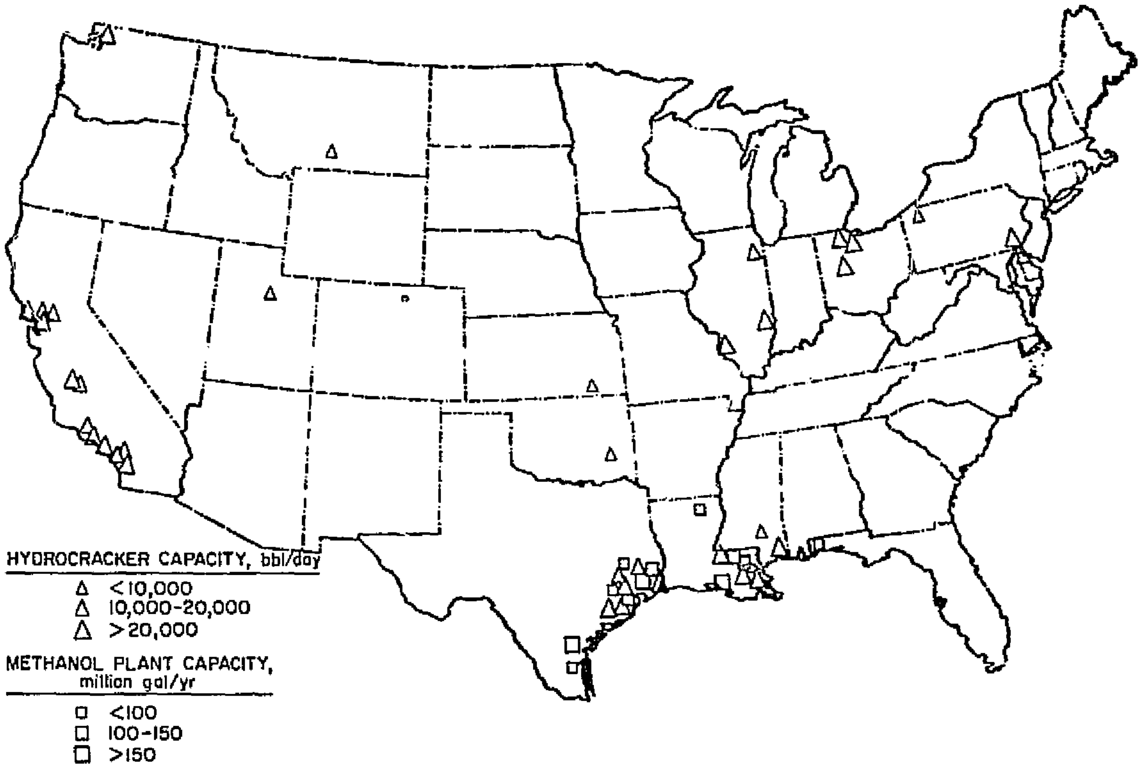

Fig. D-2. Geographic Dispersion of Hydrocracking Refineries and Methanol Plants (Biederman and Darrow, 1975) improve the machining quality; relieve the stresses; change the grain size; harden; increase the tensile strength; change the chemical composition of the metal surface as in case hardening; alter the magnetic properties; modify electrical properties; and recrystallize and soften cold worked metal.

Stringent product specification can be met with a furnace controlled atmosphere. The atmosphere composition and the temperature of the metal are two key variables that must be controlled in the furnace.

A hydrogen-nitrogen (HN) atmosphere (reducing atmosphere) is often used to prevent metal oxidation.

Annealed steel is produced in a hydrogen-nitrogen atmosphere furnace. Annealing is a term frequently used in heat treating. Generally, annealing refines the grain and softens the metal. An annealing operation may be performed to:

(1) Allow for cold working of steel

(2) Make steel machinable

(3) Reduce stresses and strains produced while metal is being shaped or welded

Bright annealing produces a lustrous surface as required for all grades, including stainless steel and tubing.

For most uses, the ratio of hydrogen to nitrogen varies in an HN atmosphere from 3% hydrogen and 97% nitrogen to 30% hydrogen and 70% nitrogen.

Dissociated ammonia gas and partially burned fuel gas may be used instead of an HN atmosphere; however, HN systems offer greater purity, flexibility, safety as well as higher quality and reproducibility. This can be done without the capital investment that is required for generators.

VI. METALWORKING, NON-FERROUS REDUCING ATMOSPHERE

(Air Products, 1974)

The refining process to recover tungsten, molybdenum and magnesium requires hydrogen gas to reduce oxides and prevent oxidation of the metal.

An HN reducing atmosphere is also used for annealing or heat-treating nonferrous metals. This prevents oxidation and therefore improves the surface brightness of the metal. Free or reactive carbon or carbon compounds do not form in a reducing atmosphere. The ratio of hydrogen to nitrogen in the gas blend varies from one operation to another. The blend ranges given above for ferrous metals also apply to nonferrous metals.

A reducing atmosphere of relatively pure hydrogen is used in tungsten processing when oxide compacts are sintered (heated to become a coherent non-porous mass).

Molybdenum is produced from concentrated molybdite, which is heated to form molybdenum trioxide. The molybdenum trioxide is reduced in a furnace with hydrogen at 1273° K (1830°F) to produce metal powder, and extruded and formed into rods under pressure. The rods are sintered with direct current in a hydrogen reducing atmosphere. The sintered rods can be readily forged, rolled or drawn.

Magnesium can be obtained by two different methods. Magnesium chloride can be electrolyzed or magnesium oxide can be thermally reduced. Hydrogen is consumed in the electrolysis of magnesium chloride. The electrolysis is done in a heat resisting crucible made of a ferrous metal. A flow of coal gas or hydrogen carries off oxygen and chlorine which would otherwise become attached to the molten magnesium.

Hydrogen is also used in powder metallurgy to make small metal parts. The powdered metal is placed in a mold and then heat and pressure are applied in a hydrogen atmosphere.

VII. FABRICATED METAL PRODUCTS

(Air Products, 1974)

A. Plasma Arc Welding

A plasma is a stream of ionized particles. The plasma torch provides an electric arc between a tungsten electrode and a water-cooled copper nozzle. Gases such as hydrogen, helium and argon are heated and ionized when they are forced through the arc and nozzle. Advantages of this system include directional control of the flame, a gas shield at the metal surface, and a higher temperature of the electric arc.

Intense heat plasma torches are employed for cutting, welding, and smelting operations.

B. Fuel

Oxy-hydrogen torches replace oxy-acetylene torches in underwater cutting when pressurized acetylene exceeds safe limits.

Oxy-hydrogen is used largely in brazing operations, welding aluminum, magnesium, lead, and sometimes for cutting lead. This type of welding provides a 2477° K (4000° F) flame temperature which is well suited for low temperature brazing and welding. Hydrogen is employed in "bell jar brazing" of small parts where a controlled atmosphere is required.

C. Forming Gas

This is a mixture of 70% hydrogen and 30% nitrogen and is commonly used in small scale in metallurgy.

VIII. ELECTRONICS (Air Products, 1974)

A. Reducing Atmosphere

Brazing is a bonding process in which the materials being joined are heated but not melted. The brazing filler metal melts and flows at temperature above 700°K (800°F). This process is also employed for ceramic-to-metal bonding applications.

Brazing in the manufacture of vacuum tubes, light bulbs and other electronic equipment is a high-temperature operation accomplished in controlled atmosphere furnaces. As a result of the high temperature, the metals involved are reactive and easily oxidized, therefore, hydrogen is used to prevent oxidation. Alternatives to hydrogen include use of other non-reactive atmospheres (argon, nitrogen), and partial combustion of oil or gas. Crystal growing also requires hydrogen gas.

B. Fuel

Oxy-hydrogen torches are used for glass tube sealing and fabrication. The oxy-hydrogen torch burns with a carbon-free flame. This is not possible with a hydrocarbon fuel.

IX. ELECTRICAL COOLANT FOR ELECTRICAL GENERATING EQUIPMENT
(Air Products, 1975)

Public Electric Utilities require hydrogen as a coolant for large generators, motors and frequency changers. Hydrogen's greater thermal conductivity provides more efficient cooling than standard air. Hydrogen is circulated through heat exchangers in the shell of the generator to cool the rotor, and is also circulated through the stator windings. Though this is a closed recirculating system, consumption due to losses is normally estimated at 1 scf of hydrogen per day, per megawatt of capacity.

X. CHEMICAL-INDUSTRIAL (Air Products, 1975)

A. Chemical Processes which Consume Hydrogen

- Production of hydrogen peroxide by autooxidation requires H_2 and O_2.
- Aldehydes and ketones are formed from carbon monoxide and hydrogen.
- The manufacture of high density polyethylene and polypropylene resins requires hydrogen.
- Considerable quantities of hydrogen are required to selectively hydrogenate feedstocks to a uniform degree and to regulate molecular weight.
- Alcohols are formed by reducing aldehydes and ketones through reaction with hydrogen and a catalyst.
- Hydrogen chloride gas is formed by reacting hydrogen and chlorine gas under pressure.
- Hydrogenation of coal and coke produces gasoline, fuel oils, toluene, xylene and benzene.
- Napthalene production requires supplemental hydrogen.
- Substitute natural gas (SNG) production requires hydrogen. Although hydrogen is usually produced on-site, supplemental hydrogen may be required.

Although all of the above processes require on-site hydrogen generators, supplemental bulk quantities may be purchased to avoid periodic processing shutdowns for generator maintenance or cleaning.

B. Pharmaceutical

Hydrogen is used extensively by pharmaceutical companies to manufacture certain drugs.

XI. GLASS (Air Products, 1975)

Glass Cutting

- Hydrogen is consumed in the oxy-hydrogen cutting of glass.
- Hydrogen is also used in working leaded glass. The hydrogen content must be carefully controlled to prevent burning the lead out of the glass.

XII. NUCLEAR ENERGY

- Hydrogen is used in processing nuclear fuels.

XIII. AEROSPACE

A. Manned Space Program

Liquid hydrogen is used as a propellant in rockets. Hydrogen is reacted chemically with oxygen, yielding a very high heat of reaction for propulsion. Hydrogen, the lightest known element, was selected as the rocket fuel because it produces the maximum thrust per pound of fuel.

B. Other Missiles and Rockets

Hydrogen is used as a propellant when the weight-to-energy ratio is sufficiently critical to justify the hydrogen expense. Alternative propellants are solid chemicals and other liquid fuels such as kerosene.

C. High Energy Physics

Experiments on subatomic particles of matter are conducted in liquid hydrogen bubble chambers. The liquid hydrogen serves both as a target for the high energy particles (cold trap) and to detect the movement of the high energy particles. Photographs are taken of the bubbles produced by particles passing through the liquid hydrogen bath.

D. Fuel Cells

Hydrogen is required in the use of fuel cells.

XIV. DIRECT REDUCTION OF ORES
(Synthetic Fuels Panel, 1972)

Energy is required for each step of metal products manufacture. The first and the biggest step is in the reduction of ores. Iron production in the U.S. in 1973 was estimated at 79.6×10^9 kg (87.7 million tons) with a total consumption of 133.3×10^9 kg (146.9 million tons) (Bureau of Mines, 1975). This far exceeds the production of all other metals combined. Direct reduction of iron ores without coke, long in development and in small-scale use the past 15 years, is now being carefully studied. A variety of direct reduction processes use hydrogen, carbon monoxide and carbon in some combination. Most commonly, natural gas is reformed to a mixture of CO and H_2. While it is accepted that hydrogen is easiest to handle and is the most effective reductant, its reaction with iron is endothermic. Carbon monoxide reacts exothermally, so a compromise is to accept mixtures of H_2 and CO that react almost athermally.

The Japanese are spending $\$30 \times 10^6$ on marrying the nuclear energy to steel making and Great Britain is advancing the similar "Dragon Project." In these, the electrical energy from an atomic plant could provide, by electrolysis of water, hydrogen and oxygen.

The hydrogen would be used in the direct reduction facilities to make sponge iron; and oxygen, although not required in the electric furnace refining of sponge iron, could be used to fuel existing BOP. The remaining energy from the power plant would furnish heat and electricity. It has been estimated that hydrogen consumption would be $0.624\ m^3/kg$ (20,000 sft^3/ton) of ore. Hydrogen reduction for nonferrous metallurgy (copper, zinc, uranium, and lead) is equally feasible but would be less hydrogen-consuming. Direct reduction processes offer several advantages such as flexibility of plant location, reduced use of fossil fuels, reduced pollution problems, and absence of costly equipment such as blast furnaces, etc.

XV. TRANSPORTATION

Hydrogen with air from the atmosphere or with oxygen supplied on board is very attractive for fueling future transportation systems. Hydrogen fueled prime movers could be of the following types (Carhart, et al, 1974).

A. Piston Engines

One of the important factors in the choice of a fuel for a piston engine of the type used in land vehicles is the compression ratio. Higher compression ratios generally favor higher outputs and efficiencies. Compression ratios are determined by, among other factors, important fuel characteristics such as flame speed and limits of flammability. Hydrogen has very wide limits of flammability when mixed with air (4% to 75% H_2), which enables an engine to operate with the mixture far from the stoichiometric proportion of 29.6%. Hydrogen has a tendency to "knock" because of its high flame speed. However, flame speeds for all fuels are lower near limits of flammability, and a fuel air mixture that has high flame speed (H_2-air) exhibits an acceptable burning rate at a relatively lean mixture ratio. The tendency of H_2 to "knock" and to back fire can be eliminated if a mixture is adjusted to contain at least 25% excess air. An engine designed for, and operated with, H_2 at a compression ratio of about 10:1 will not build up engine deposits from the combustion of fuel, but engine oil deposits are possible. Tests using H_2 showed very small quantities of nitrogen oxides in the exhaust. Besides lubrication, there seems to be no significant obstacles to using hydrogen in the conventional engine. Such an engine could be a high-performance, high-compression ratio engine with a clean water vapor exhaust and an extended life resulting from the absence of deposit buildup. However, because of low volumetric energy density of H_2, sizable problems are evident relative to fuel tankage and logistics.

B. Gas Turbine Engines

Not much experimental work has been done with H_2 burning engines. However NASA-LaRC successfully flew a B-57 aircraft with one of the J65 engines fueled with H_2. Combustion problems should be minor for turbine engines because hydrogen has a very high flame velocity and can be prevaporized and premixed with air. These facts point to smaller, lighter engines than are possible with petroleum fuels. Carbon deposits in combustors would be greatly reduced and possibly eliminated if bearing lubricant leaks can be eliminated.

Because of this and because of the H_2-air flame radiates at low intensities, radiation to the combustor walls could be minimized. Hence, the material problems would be greatly relieved for high temperature combustors. Aircraft heat exchangers would have longer life because of the lack of fuel deposits from H_2, and the combustor nozzle life would be extended for the same reason. Furthermore, H_2 has a unique advantage for hypersonic flight because it has a high specific heat and can be heated to high temperatures without degradation or decomposition. However, H_2 as a liquid presents some design and operating problems because of its low density (~1/10 of jet fuel) and low temperature of 20°K (-423°F).

C. Fuel Cell Powered Vehicles

Hydrogen-fueled, fuel-cell powered vehicles offer many advantages such as high efficiency, and low pollution. However, some of the problems to be encountered are heavy weight and large volume, limited operating life, costly components and materials, and complicated procedures for startup and shutdown. In the long run, these problems would be solved and the potential for fuel-cell powered systems using hydrogen as a fuel looks promising.

XVI. RESIDENTIAL (Johnson Space Center, 1973)

The residential and commercial demand for fuel energy can be satisfied by hydrogen. The development of consuming devices can be of the following types.

A. Flame Burners

Most burners mix air with gas prior to burning. The gas-air mixture must travel toward the open end of the burner at a rate higher than the rate of flame propagation in the mixture. This prevents "flash-back" or ignition inside the burner. If the velocity of the gas flow exceeds the burning velocity at all points, the flame that is blown off H_2 has a very high flame velocity, particularly at less than stoichiometric air contents, such as in the primary gas-air mixture, but the design and construction of appliances that use H_2 present no severe problems. H_2 burners are more prone to "flash back" than to "blow off." Experiments at IGT have shown that simple conversion techniques can be used to convert today's standard burners to satisfactory operation with H_2. Since with H_2 the only product of combustion is water, a H_2 furnace does not need a flue. If the amount of water vapor produced is excessive, dehumidification control can be provided.

B. Catalytic Burners

A novel property of hydrogen that gives it a marked advantage over other fuels is its ability to react with the oxygen in air when in contact with a catalyst. This property allows the fabrication of unusual flameless heating devices. These are two types of catalytic burners for H_2. The low temperature burner is a ceramic plate with porosity about 70%. The internal surface of the plate is coated with a catalyst; a platinum metal is best, but cheaper materials may be found. Air is mixed with the H_2 and fed through the porous plate. Flameless combustion occurs within the plate. At low output, the burner can operate at 422 to 533°K (300 to 500°F) with no fire hazard. The high temperature catalytic burner, which operates at temperatures above 811°K (1000°F), requires a backing for the catalytic surface. Advantages of catalytic burners are: water is the only combustion product and appliances do not require venting, greater heat transfer efficiency in appliances, elimination of pilot lights, and inherent safety. However, development efforts on catalytic burners are far from complete.

XVII. INDUSTRIAL PROCESS HEAT

In 1974, large quantities 10×10^{18} J ($\sim 10 \times 10^{15}$ Btu) of process heat in the form of steam were required by the industrial sector. (16-17% of the total energy consumption in the U.S.). Hydrogen may be burnt conventionally in boilers or, with development, special purpose hydrogen-oxygen direct steam generation systems may provide an environmentally clean, compact source of process steam over a wide temperature range. Exhausts from hydrogen-oxygen fired steam cycle power plants (HOTSHOT) suggested by GE TEMPO could also supply low quality steam for certain needs. On the other hand, if a dual pipe (H_2 - O_2) system were available, a simple pipe-combustor-attemporator would be substituted for the current massive water tube steam generators. Advantages of such a system would be considerable savings in capital cost, and no pollution.

If low-cost hydrogen is made available, then there are no significant technical restrictions to the use of hydrogen consumption as a source of industrial process steam.

XVIII. ELECTRIC POWER GENERATION (Synthetic Fuels Panel, 1972)

The electric utilities must meet daily load variations where the peak demand can be more than twice the minimum demand. This wide variation in demand is also seasonally dependent (summer or winter). Electric power companies supply the widely varying loads by means of base load, intermediate load, and peaking plants. Hydrogen as a fuel offers distinct advantages for these companies. It could serve as a common element making it possible to generate, store, and reuse all forms of energy in most efficient, low polluting way.

Hydrogen systems are implementable for future solar, geothermal, wind and other power plants in two ways. First, the energy that comes intermittantly (tides, wind, solar) could be converted into hydrogen whenever its available, regardless of the need at the time. Then the hydrogen could be stored or piped to where it's needed — when demand is great — or later reconverted to electricity. Second, present nuclear or fossil fuel electric plants are wasteful. That's because they have to be big enough to meet the demand during peak periods, so they are practically idling when demand is low. But if they are operated at constant high load, the frequently unneeded power can be stored as hydrogen and the efficiencies could increase considerably. Regardless of the generating source, unused power turned into hydrogen could thus become energy in the "bank."

Reconversion of hydrogen to electricity may be accomplished by any of the following.

(1) Fuel cells

(2) Gas turbines (HOTSHOT)

(3) MHD power plants.

All the above devices, if operated on hydrogen and oxygen promise very high operating efficiencies, and are virtually pollution-free. A considerable amount of research and development work is required in the area of hydrogen reconversion to electricity. Hydrogen reconversion is closely related to hydrogen storage (cryogenic, gas, metal hydride systems). Brookhaven National Lab/ERDA along with Northeast utilities is actively pursuing the electrolyzer-fuel cell systems (Johnson Space Center, 1973).

XIX. SYNTHETIC FUEL PRODUCTION

Although economically feasible operation has not yet been demonstrated, there are several processes which are available to convert coal to liquid and gaseous fuels. Large quantities of hydrogen are required in these processes. Typical of these are:

A. Coal to Synthetic Liquid Fuel

The Pittsburgh Energy Research Center (U.S. Bureau of Mines) is emphasizing development of the "synthoil" process, which in one quick step hydrodesulfurizes coal to produce a nonpolluting fuel oil that is essentially free of sulfur and readily de-ashed (Chemical Engineering Progress (CEP), 1975). In this process, coal, conveyed in recycled "carrier" oil, is propelled by turbulent flow of hydrogen through a fixed bed of cobalt molybdenum catalyst pellets, accomplishing over 94% conversion to oil in just 2 min of reaction time. Unused H_2 is recycled to provide the turbulence necessary for good mixing and prevention of plugging. A 9.1×10^3 kg/day (10 ton/day) pilot plant is now being designed based on extensive applicability tests with a 45.4 kg/day (100 lb/day) unit. Process conditions are 28.58 MN/m^2 (4000 psig) at 723°K (450°C). Oil yields are high, over 5×10^{-4} m^3/kg (3 barrels/ton), corresponding to 94 to 98% conversion of organic coal to oil. Overall energy efficiency is estimated to be 74.9% and is defined as the energy in the product oil divided by the total energy input including coal for liquefaction, for H_2 generation, for power and heat needs. Hydrogen consumption is reported to be 0.468 m^3/kg (15,000 scf/short ton) of coal, or ~ 891 m^3/m^3 crude ($\sim 5,000$ scf/barrel crude).

B. Coal to Substitute Natural Gas (SNG)

The first step in most SNG processes is the steam-coal reaction, which takes place in the primary gasifier to produce the synthesis gas-CO + H_2. Next, extra H_2 is made by "shifting" some of the synthesis gas to H_2 and CO_2. The CO_2 is then removed, and the extra H_2 is used to readjust the carbon/hydrogen ratio of the synthesis gas. Finally, the product fuel, mostly methane, is synthesized in the methanator. In a typical LURGI gasification scheme (CEP, 1975), to produce 7.08 × 10^6 m^3/day (250 × 10^6 scf/day) SNG, about 20 × 10^6 kg/day (22,000 tons/day) of coal are required. Part of the carbon in this coal feed is used up in the shift reactor to generate needed additional hydrogen.

Most of the SNG processes such as HYGAS, SYNTHANE, etc., could be used to produce SNG from coal and a noncoal hydrogen source. This would result in a much more efficient utilization of the U.S. coal resources than would be the case if hydrogen were generated using additional coal. It is estimated that the separate manufacture of H_2 from external means would allow up to 2.5 times more SNG to be produced from the same amount of coal. Total hydrogen consumption in SNG processes ic calculated to be 1.0-1.560 m^3/m^3 (1.000-1.560 scf/scf) of SNG.

C. Shale to Gasoline

Hydrogen is required for refining and hydrotreating the intermediate shale oil. The requirements are estimated to be 232 m^3/m^3 (1300 sft^3/barrel) of syncrude.

XX. EXOTIC USES

Use of hydrogen to raise the wreck of the S.S. Titanic has been proposed. It is planned to raise the wreck by remote controlled equipment. She lies 3 km (2 miles) deep off Newfoundland. Sea water would be electrolyzed by using a 20 MW generator and the hydrogen evolved will fill 200 nylon reinforced PVC pontoons for the proposed operation (Chemical Engineering News, 1970).

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APPENDIX E

THERMOCHEMICAL CYCLES*

The study and development of thermochemical cycles for producing hydrogen has been the concern and interest of a relatively small number of chemical researchers within a technically limited, geographically dispersed scientific community. Survey material regarding the subject is very difficult to find. This appendix is being included for those readers who desire fundamental information on the subject of thermochemical cycles and some insight into the thermodynamics and chemistry of a few specific cycles. It presents some of the contents of a NASA-Lewis sponsored program which has been underway since 1973. The objective of the program is to develop the fundamental principles underlying thermochemical processes and to prepare an evaluation technique which may be used to rapidly analyze various cycles. Further results of this program are presented in References 1 - 4.

I. THERMOCHEMICAL PRODUCTION OF HYDROGEN

Thermochemical production of hydrogen implies the production of hydrogen from water splitting by means of heat. The processes, or set of processes, by which this is achieved are known as thermochemical cycles. A closed cycle accepts only water and heat and yields oxygen and hydrogen with some heat rejected to a lower temperature reservoir. An open thermochemical cycle may also accept other feedstock materials, and reject one or more species to the atmosphere.

Open-cycle thermochemical processes are based on the use of carbon-based fuels, water and heat, and yield hydrogen, carbon dioxide and low-grade heat. Steam reforming and partial oxidation are examples as well as more complex processes such as the steam-iron route to hydrogen from coal.

In closed thermochemical cycles, water and heat are the input and only hydrogen and oxygen, along with some degraded heat, are rejected to the atmosphere. The mechanism of water splitting by closed thermochemical cycles is shown in Figure E-1. Water is injected in a closed system which takes heat from a reservoir at a temperature T_H and rejects part of it to another reservoir at T_C, yielding hydrogen and oxygen as the only products. Funk and Reinstrom began exploring the theoretical energy requirements for various processes in 1966 (Ref. 5), and established some comparisons with electrolysis. They considered multistep processes in which water reacts with another material, say a metal, to produce hydrogen and metal oxide. Subsequent reduction of the metal by thermal decomposition would recycle the metal for repeated use. They did not find any suitable two step reactions that would occur at temperatures within reach of nuclear reactors. When considering, on the other hand, three, four, and even five-step processes, they projected ultimate efficiencies as low as 18%. These pessimistic results, together with the ample supplies of inexpensive feedstocks, kept the interest in thermochemical cycles for water splitting rather low for a number of years.

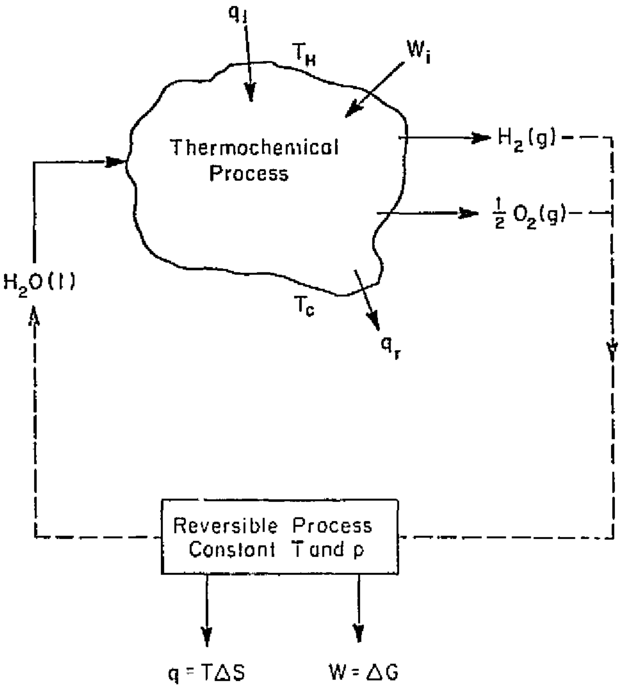

Figure E-1. Water Splitting by a Closed Thermochemical Cycle

Early in the 70's, it became obvious worldwide that there is a limit to the amount of petroleum which can be extracted from the earth. Hydrogen was recognized as a potential means of handling large amounts of energy, and an effort was initiated throughout the world to pursue thermochemical hydrogen generation by using closed cycle schemes. Predominant among such centers are the Euratom facilities in Ispra, Italy, the Nuclear Research Center in Juelich, West Germany, and Mitsubishi Heavy Industries in Tokyo, Japan. In the USA, the AEC is funding work in its laboratories at Los Alamos, Brookhaven, and Argonne National Laboratories. NASA has been funding the University of Kentucky to develop a thermochemistry program to evaluate thermochemical cycles, and very recently a contract was issued to Westinghouse to investigate experimentally the possibilities of a thermochemical cycle based in the chemistry of sulphur with electrical assistance in one of the steps. The American Gas Association (AGA) has

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*Compiled by Drs. J. E. Funk, M. A. Soliman, R. H. Carty, W. L. Conger, and K. E. Cox, University of Kentucky and D. Lawson, Jet Propulsion Laboratory.

sponsored significant work at the Institute of Gas Technology (IGT) and, also, several private laboratories have been supporting in-house work, including G. E., and Gulf General Atomic.

1. Thermodynamics of Water Splitting

The processes under consideration are those which accept liquid water at reference conditions — 298°K and 0.1 MN/m^2 — and produce hydrogen and oxygen at the same conditions. Actual processes, of course, may have different input and output conditions, but the choice of reference conditions greatly facilitates the analysis and comparisons of water decomposition processes.

The efficiency, η, of a hydrogen producing process is defined as the ratio of:

- the enthalpy of decomposition of liquid water, ΔH_o (the higher heating value of the hydrogen produced)

to

- the thermal energy equivalent of the total* energy (in all forms) entering the hydrogen producing process, Q_t.

$$\eta = \frac{\Delta H_o}{Q_t} \qquad \text{(E-1)}$$

Thermodynamic and energetic considerations lead to limitations on the value of the thermal efficiency and show the effect of operating temperatures.

2. Thermodynamics of the Overall Process

The upper portion of Figure E-1 shows a control volume enclosing some thermochemical process which accepts thermal energy, or heat, q_i, at some high temperature, T_H, and rejects heat, q_r, at some temperature, T_C. The process also requires a certain amount of useful work, W_i. It is recognized that the heat may be supplied and rejected at many different temperatures, but for purposes of this analysis a single temperature for each is assumed. Liquid water at 0.1 MN/m^2 and T_C (assumed to be 298°K) flows into the process and hydrogen and oxygen at 1 atm and T_C leave the process. Now imagine as shown in the lower portion of Figure E-2, that the hydrogen and oxygen are caused to undergo a reversible flow process at constant temperature, T_C, and pressure, 1 atm, to produce liquid water (e.g. as in an ideal fuel cell). The entire system is now "closed" and is operating as a thermally regenerative fuel cell.

If the entire system shown in Figure E-1 is enclosed in a control volume, the situation will appear as shown in Figure E-2. The first law of thermodynamics may be written to obtain

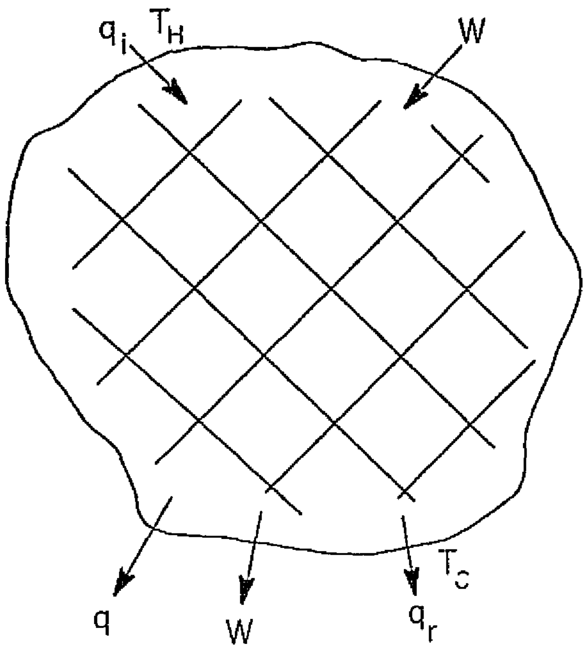

Figure E-2. Overall system as a black box

$$q_i + W_i = q + W + q_r \qquad \text{(E-2)}$$

For the reversible process,

$$\left.\begin{aligned} q &= T_c \Delta S_o \\ W &= \Delta G_o \\ \Delta H_o &= q + W \end{aligned}\right\} \qquad \text{(E-3)}$$

The second law is

$$\frac{q_r + q}{T_c} - \frac{q_i}{T_H} \geq 0 \qquad \text{(E-4)}$$

and

$$\eta \leq \begin{cases} \dfrac{1}{1 + \dfrac{q_r}{\Delta H_o} + \left(\dfrac{W_i}{\Delta H_o}\,\dfrac{1-\epsilon}{\epsilon}\right)\left(1 + \dfrac{1}{\epsilon}\,\dfrac{W_i}{G_o}\,\dfrac{T_H - T_C}{T_H} - \epsilon\right)} \\[2ex] \dfrac{\Delta H_o}{\Delta G_o}\,\dfrac{T_H - T_C}{T_H} \end{cases} \qquad \text{(E-5)}$$

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*If electricity is bought from the grid, the corresponding efficiency has to be the annual average value; as this value varies from year to year it should be specified. If in the end of the process, energy is delivered to another plant, this should not be deducted from the total.

The term $T_H - T_C/T_H$ is the "Carnot" efficiency of a heat engine working between T_H and T_C and will always exceed ϵ, the efficiency of converting heat to useful work. The denominator of the bracketed term in Eq. (E-5) will, therefore, always be positive.

Equation (E-6) fixes the upper limit on η (when q_r and W_i are = 0) such that

$$\eta \leq \begin{cases} 1.0 \\ \dfrac{\Delta H_o}{\Delta G_o} \dfrac{T_H - T_C}{T_H} \end{cases} \tag{E-6}$$

This result was first published in 1966 (Ref. 5) and has been verified several times since.

a. The Single Stage Process. The simplest single step process is water electrolysis. If electrolysis is done reversibly at 298°K and 0.1 MN/m^2, the electricity requirement is equal to ΔG_o (56.7 kcal/g mole H_2) and the heat requirement is $T_C \Delta S_o$ (11.6 kcal/g mole H_2) -- the difference between ΔH_o and ΔG_o for water.

Actual operating data indicate that water electrolysis cells consume 159-214 x 10^6 J/kg of H_2 generated. The cell efficiency, based on a ΔG_o of 119 x 10^6 J/kg H_2, is then in the range 55-75%.

A one-step process is shown on a T-S diagram in Figure E-3 being operated reversibly along two different paths, A and B. From the first law it is readily shown that

$$\text{Work} \Big|_{I \text{ path A}}^{F} = \Delta H - T\Delta S = \Delta G \tag{E-7}$$

$$\text{Work} \Big|_{I \text{ path B}}^{F} = \Delta H - \int_{I \text{ path B}}^{F} TdS \tag{E-8}$$

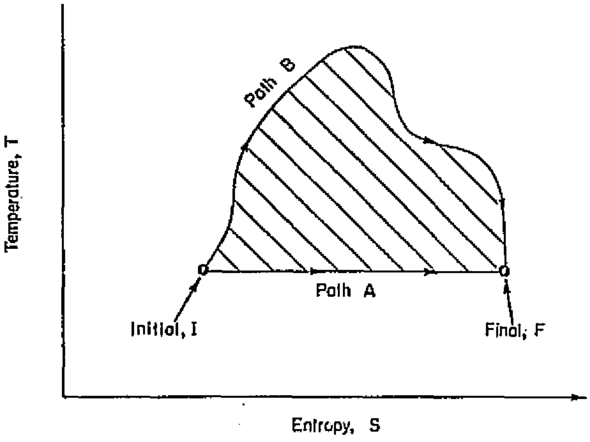


Figure E-3. Single-Stage T-S Diagram

From Eqs. (E-7) and (E-8) it may be seen that the reduction in work required to go from I to F reversibly via path B rather than A is equal to the area enclosed by the process path on the temperature-entropy diagram (the shaded area in Figure E-3). The heat requirement increases by a like amount. A reduction in the reversible work requirement results when the entropy change for the process is positive. The opposite occurs when the entropy change is negative.

It may be shown directly that if the decomposition reaction is done at some temperature, T_H, higher than 298°K, the useful work and heat requirements W_H and Q_H are

$$W_H = \Delta G_H = \Delta G + \int_{T}^{T_H} \frac{\partial \Delta G}{\partial T} \, dt \tag{E-9}$$

and

$$Q_H = T_H \Delta S_H \tag{E-10}$$

If ΔH and ΔS are independent of temperature, the reduction in useful work relative to 298°K is

$$W - W_H = \Delta G - \Delta G_H = \Delta S(T_H - T) \tag{E-11}$$

The increase in heat required is

$$Q_H - Q = (T_H - T)\,\Delta S \tag{E-12}$$

The entropy change for water decomposition, after the liquid to vapor phase change has occurred, is approximately 0.01 kcal/g mole °K which is simply too small to achieve a substantial reduction in the work requirement at currently achievable operating temperatures. Another way of saying this is that the equilibrium composition does not shift in favor of H_2 rapidly enough with increasing temperature to suggest that a single step thermal decomposition process offers great promise for the near term. At 2000°K and 0.1 MN/m^2 the equilibrium mixture of H_2O - H_2 - O_2 contains a mole fraction of H_2 equal to only 0.036 corresponding to only a 3.6% conversion of water. High temperature gas cooled reactors which may be able to provide process heat in the near future are operating in the range of 1200-1300°K.

b. Multistage Processes. It is possible for a multistage process to satisfy the first and second laws of thermodynamics along with the constraint that no useful work be expended in the process (Ref. 6). In order to visualize such a situation imagine a general thermochemical process comprising an arbitrary number of steps as shown in Figure E-2. Each reaction exhibits some change in enthalpy, ΔH, entropy, ΔS, and Gibbs function or free energy, ΔG. If the entire process is operated reversibly at 298°K and 0.1 MN/m^2, the work and heat requirements will be exactly the same as for an ideal electrolysis cell since the work requirement, ΔG, and the heat requirement, $T\Delta S$, are the same for any and all reversible processes. In this sense, the reversible constant temperature and pressure thermochemical process is the same as the reversible water electrolysis cell. The work requirement for electrolysis can be reduced only slightly by going to higher temperatures, as has been discussed earlier, but by choosing the operating temperatures in the thermochemical process properly it is possible, at least in principle, to reduce the useful work requirement to zero. In the chemical process the work requirement manifests itself mainly in work of separation required in the various reaction steps.

The total process useful work requirement may be reduced by operating some of those reaction steps shown in Figure E-4 at high temperatures and some at low temperatures. If the work requirement for the reaction step is taken to be the change in the Gibbs function for the reaction, the object is to operate those reactions with positive entropy changes at high temperatures. Neglecting the effect of temperature on enthalpy and entropy changes, and realizing that phase changes must be treated with care, the following analysis may be made.

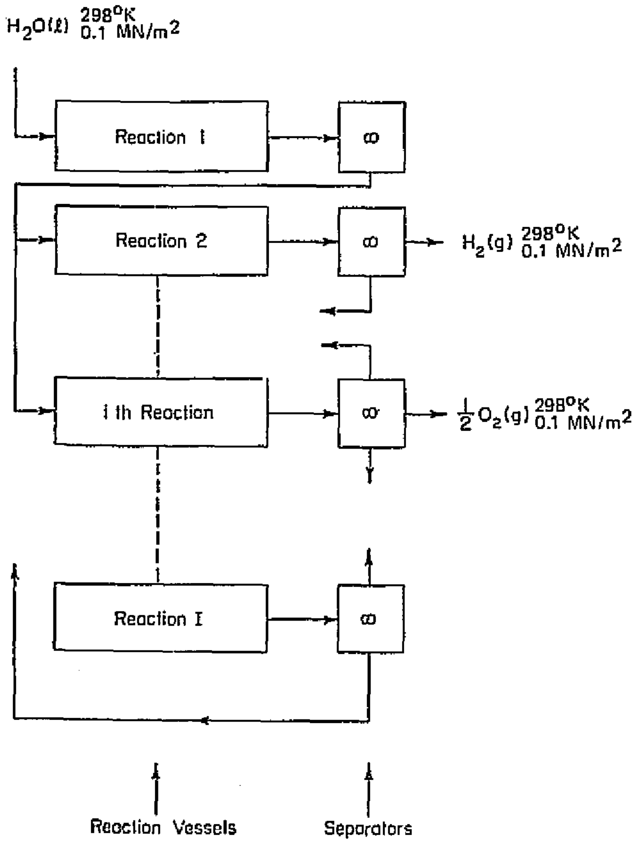


Figure E-4. A General Multistage Process

The work and heat requirements for ith reaction are given by

$$W_i = W_i^{T_o} - \Delta S_i (T_i - T_o) \qquad \text{(E-13)}$$

$$q_i = q_i^{T_o} + \Delta S_i (T_i - T_o) \qquad \text{(E-14)}$$

where the o subscript refers to a reference or standard temperature, say 298°K.

The effect of the sign of the reaction entropy change is apparent. The total heat and work requirements are obtained by summing, so that

$$W_T = \Delta G_o - \sum_{i=1}^{I} \Delta S_i (T_i - T_o) \qquad \text{(E-15)}$$

$$q_T = \sum_{i=1}^{I} T_i \Delta S_i \qquad \text{(E-16)}$$

Now, suppose that J reactions have positive entropy changes and are operated at high temperatures, T_i and L reactions have negative entropy changes and are operated at T_o. The total work, W_T, will be zero when

$$\sum_{i=1}^{J} \Delta S_i (T_i - T_o) = \Delta G_o \qquad \text{(E-17)}$$

If only one high temperature, say T_H, is employed, the result is

$$\sum_{i=1}^{J} \Delta S_i = \frac{\Delta G_o}{T_H - T_o} \qquad \text{(E-18)}$$

In principle, there is no reason why Eq. (E-17) or (E-18) cannot be satisfied along with

$$\sum_{i=1}^{I} \Delta S_i = \sum_{j=1}^{J} \Delta S_j + \sum_{i=J+1}^{J+L} \Delta S_i = \Delta S_o \qquad \text{(E-19)}$$

This conclusion cannot be reached for a one step process. In that case, the zero work requirement must be accomplished by a temperature manipulation rather than the selection of a suitable sequence of chemical reactions.

c. The Two-Stage Process. Suppose a two-reaction process has been found which requires no useful work. One reaction is operated at T_c and the other at T_H. Choose $T_c = 373°K$ and $T_H = 1173°K$ and assume that ΔH and ΔS are independent of temperature. For water, $\Delta H = 58.1$, $\Delta G = 53.8$, and $\Delta S = 0.0116$; and H_2O is assumed to enter the process in the vapor phase. Since the work required is zero, $\Delta G_c = \Delta G_H = 0$ and

$$\Delta H_H = T_H \Delta S_H \qquad \text{(E-20)}$$

$$\Delta H_C = T_C \, \Delta S_C \qquad \text{(E-21)}$$

From Eq. (E-18) it is found that

$$\Delta S_H = \frac{53.8}{950-100} = +0.0633 \text{ kcal/gm mol °K}$$

and, from Eq. (E-20)

$$\Delta H_H = (1223)(0.0633) = +77.4 \text{ kcal/gm mol}$$

Since the ΔS's must sum to 0.0116 kcal/gm mol °K

$$\Delta S_C = -0.0517 \text{ kcal/gm mol °K}$$

From Eq. (E-21)

$$\Delta H_C = (373)(-0.0517) = -19.3 \text{ kcal/gm mol}$$

Abraham and Schreiner (Ref. 6) indicate that the positive entropy change required for the high temperature reaction (+0.0633) is too large for real substances. Funk and Reinstrom (Ref. 5) have expressed the opinion that it is unlikely that compounds will be found to operate in sufficient two-step processes.

II. METHODS OF CALCULATION USED IN THE HYDRGN PROGRAM

Many closed thermochemical cycles have been proposed and several investigators are at work producing others. The number of possible cycles is almost limitless, therefore, a quick and relatively simple method for rating them is needed. The HYDRGN computer program attempts to provide such a ranking of these cycles so that the obviously poor ones may be eliminated from further consideration.

An analysis of any process may be made in various degrees of detail, including a complete description of the process containing a flow sheet, sizing of equipment, and costing. In the present case, it was necessary to analyze the processes with minimum data. This means that many idealizations of actual mechanisms had to be made.

The HYDRGN program uses thermodynamic data for the pure components involved in each chemical reaction to calculate the standard state enthalpy, entropy, and Gibbs-free energy changes for each chemical reaction as well as for the heating and cooling steps. Using these properties and the extent of reaction at equilibrium, the heat and useful work needed for each step is calculated. The program also calculates the number of moles of each reactant in the recycle streams at various fractions of equilibrium conversion. The total process heat needed by the cycle which must be supplied by external sources is obtained by a heat exchange routine that determines the amount of heat liberated by the exothermic steps in the cycle which cannot be either utilized internally by the endothermic steps or used to produce useful work. Finally, the program calculates figures of merit which are used in evaluating the process.

Consider a reaction of the form:

$$r_1R_1 + r_2R_2 + r_3R_3 + \ldots \rightarrow p_1P_1 + p_2P_2 + \ldots \qquad \text{(E-22)}$$

We now assume that this reaction is conducted as shown in Fig. E-5 and is isothermal, isobaric, and all products and reactants are ideal gases and form ideal gaseous solutions.

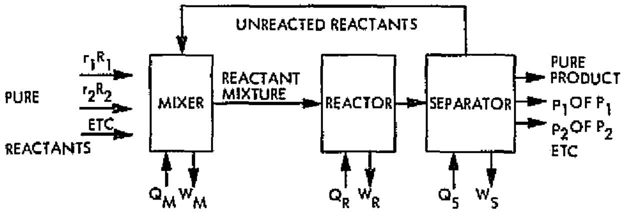


Fig. E-5. Schematic Diagram of the Reactants Flow

Defining

$\Delta H°$ = Standard state enthalpy change for reaction

$\Delta S°$ = Standard state entropy change for reaction

$\Delta G°$ = Standard state Gibbs Free Energy change for reaction

Q_T = Total heat input

W_T = Total useful work input

T = Temp. of the reaction

the first law for a flow system, neglecting kinetic and potential energy, is:

$$\Delta H° = Q_T - W_T \qquad \text{(E-23)}$$

where:

$$Q_T = Q_M + Q_R + Q_S$$

$$W_T = W_M + W_R + W_S$$

We can now analyze each element within Fig. E-5 to determine the heat and work requirements.

1. Mixer. Since the pure gaseous reactants are mixed to form an ideal solution at constant temperature and pressure,

$$\Delta H_M = 0 = Q_M - W_M$$

If the mixing is conducted in a manner such that no work other than PV work is done on the process, $W_M = 0$ and

$$Q_M = \Delta H_M = 0.$$

2. Separator. For an ideal solution,

$$\Delta H_S = 0 = Q_S - W_S$$

The minimum amount of energy which must be expended in this separation will be for the case of a completely reversible process. Therefore,

$$Q_S = T\Delta S_S = W_S \qquad \text{(E-24)}$$

and for an ideal mixture of gases,

$$\Delta S_S = R\sum_i n_i \ln X_i \qquad \text{(E-25)}$$

where:

n_i = number of moles of species i in mixture

X_i = mole fraction of species i in mixture

Combining Eqs. (E-24) and (E-25), we get:

$$W_S = RT\sum_i n_i \ln X_i = Q_S \qquad \text{(E-26)}$$

This relationship shows that an amount of work, W_S, must be added to the separator and an equal amount of heat, Q_S, is extracted from the process.

3. Reactor. Assuming no work other than PV work is done within the reactor itself,

$$W_R = 0$$

and from the first law:

$$\Delta H_R = Q_R \qquad \text{(E-27)}$$

Combining the heat and work terms for each element of the process,

$$\begin{aligned} Q_T &= Q_M + Q_R + Q_S \\ &= 0 + \Delta H_R + TR\sum_i n_i \ln X_i \end{aligned}$$

If it is further assumed that the heat liberated by the separation process is unrecoverable as would probably be the case,

$$Q_T = \Delta H_R$$

and since

$$\Delta H^\circ = \Delta H_M + \Delta H_R + \Delta H_S$$

and

$$\Delta H_M = \Delta H_S = 0$$

then

$$Q_T = \Delta H^\circ \qquad \text{(E-28)}$$

That is, the total heat of the reaction is equal to the standard state enthalpy change. Also,

$$W_T = W_M + W_R + W_S$$

$$= 0 + 0 + RT\sum_i n_i \ln X_i$$

$$W_T = RT\sum_i n_i \ln X_i \qquad \text{(E-29)}$$

If all elements of the reaction are conducted reversibly such as in an electrochemical cell, the heat and work relationships become:

$$Q_T = Q_M + Q_R + Q_S$$

$$Q_T = T(\Delta S_M + \Delta S_R + \Delta S_S) = T\Delta S^\circ \qquad \text{(E-30)}$$

$$W_T = W_M + W_R + W_S$$

$$W_T = -(\Delta G_M + \Delta G_R + \Delta G_S) = -\Delta G^\circ \qquad \text{(E-31)}$$

4. Heterogeneous Reactions. For a heterogeneous reaction, Eqs. (E-28) and (E-29) are applicable with a modification to the work of separation. In this case, the work of separation is based only on the gas phase. Therefore, n_i and X_i in Eq. (E-29) refer to the number of moles and the mole fractions based on the gas phase.

Referring to Eq. (E-22) we shall derive the general equations for the work of separation for gases. If we define

L_i = relative number of moles of species i in reactor mixture

ϵ = number of moles of component R_1 reacting/mole of R_1 entering the reactor

and require that stoichiometric amounts of products be produced, then:

$$\text{moles of } R_1 \text{ entering separator} = r_1\left(\frac{1-\epsilon}{\epsilon}\right)$$

$$\text{moles of } R_i \text{ entering separator} = \left[\frac{r_1 \frac{L_i}{L_1} - \epsilon r_i}{\epsilon}\right].$$

R_1 will be referred to as the "base reactant." The choice of the base reactant is optional so long as consistency is maintained between the calculation of ϵ and the moles of recycle.

For a heterogeneous chemical reaction in which each condensed compound is assumed to be present as a pure phase, the change in the standard state Gibbs free energy is given by:

$$\Delta G^\circ = -RT\left[\sum_j p_j \ln X_{P_j} - \sum_i r_i \ln X_{R_i}\right] - RT\left(\sum_j p_j - \sum_i r_i\right)\ln P_T \qquad \text{(E-32)}$$

where the summations are over all gaseous species. For the complete separation of all the gases in the equilibrium reaction mixture, the work of separation is:

$$W_{sep} = RT\left[\sum_j p_j \ln X_{P_j} + \sum_i \left(\frac{r_1\left(\frac{L_i}{L_1}\right) - \epsilon r_i}{\epsilon}\right)\ln X_{R_i}\right] \qquad \text{(E-33)}$$

Adding (E-72) and (E-33), we get

$$W_{sep} = -\Delta G^\circ + RT\sum_i\left(\frac{r_1 L_i}{L_1 \epsilon}\right)\ln X_{R_i} - RT\left(\sum_j p_j - \sum_i r_i\right)\ln P_T \qquad \text{(E-34)}$$

From Eq. (E-34) it is seen that for a complete separation of the gaseous species, at one atmosphere, the work needed for separation must be greater than or equal to the standard state Gibbs free energy change.

Since the reactants will be recycled and remixed before entering the reactor, all the gaseous reactants may be summed and treated as a single component in calculating the work of separation. This has been done in the analysis of the HYDRGN program. In this case, Eq. (E-33) becomes:

$$W_{sep} = RT\left\{\sum_j p_j \ln X_{P_j} + \left[\ln\left(\sum_j X_{R_i}\right)\right]\left[\sum_i\left(\frac{r_1 L_i}{L_1 \epsilon} - r_i\right)\right]\right\} \qquad \text{(E-35)}$$

If there is a single gaseous product, the pressure of the gas at equilibrium is:

$$P_T = e^{-\Delta G^\circ/RTp_i} \qquad \text{(E-36)}$$

If ΔG° is negative, the pressure of the gas, P_T, is greater than one atmosphere and no work is needed to remove the pure product. However, if ΔG° is positive, the pressure as given by Eq. (E-36) is less than 0.1 MN/m^2. Therefore, in order to cause the reaction to proceed, the work of compression must be expended in pumping the gas from P_T to one atmosphere. The work of separation in this case becomes:

$$W_{sep} = -p_i RT \ln(P_{atm}/P_T)$$

$$= -(p_i RT)\frac{\Delta G^\circ}{RTp_i} = -\Delta G^\circ \qquad \text{(E-37)}$$

By a similar analysis, if there is only one gaseous reactant, Eq. (E-36) becomes:

$$P_T = e^{\Delta G^\circ/RTr_i} \qquad \text{(E-38)}$$

From this relationship, it is seen that if ΔG° is less than zero, P_T is less than 1 atm and no work of compression is needed. Likewise, if ΔG° is greater than zero, the equilibrium pressure of the reaction is greater than 1 atm and an amount of work equal to $-\Delta G^\circ$ must be expended to compress the gaseous reactant to this higher pressure.

For a reaction in which there are more than one gaseous product and no gaseous reactants, the HYDRGN program assumes that the reaction is conducted at a temperature where the equilibrium pressure of the reaction is 1 atm so that there is no work of compression. Likewise, the program assumes the pressure is 1 atm for the case of multiple gaseous reactants and no gaseous products.

If there are no gaseous species in the reaction, either as reactants or products, the program assumes the minimum amount of work expended is $-\Delta G^\circ$ if ΔG° is greater than zero.

It is planned to modify the program in the future to handle pressures different than 0.1 MN/m^2.

5. Calculation of Thermodynamic Properties. For each species involved in the cycle the heat capacity, enthalpy, entropy, and Gibbs free energy are computed by the following relationships:

$$\frac{C_p^\circ}{R} = a_1 + a_2T + a_3T^2 + a_4T^3 + a_5T^4 \tag{E-39}$$

$$\frac{H_T^\circ}{RT} = a_1 + \frac{a_2}{2}T + \frac{a_3T^2}{3} + \frac{a_4T^3}{4} + \frac{a_5T^4}{5} + \frac{a_6}{T} \tag{E-40}$$

$$\frac{S_T^\circ}{R} = a_1 \ln T + a_2T + \frac{a_3T^2}{2} + \frac{a_4T^3}{3} + \frac{a_5T^4}{4} + a_7 \tag{E-41}$$

$$G^\circ = H^\circ - TS^\circ$$

The coefficients are obtained from either molecular constant data or thermodynamic data (Ref. 7) using the PAC-2 computer program. For each species, two sets of coefficients are obtained for temperature intervals of 300 to 1000°K and 1000 to 5000°K. A library of these thermodynamic coefficients is included with the program for over 700 species (solid, liquid, and gas phases of a compound are counted as separate species).

We have arbitrarily assumed $H^\circ_{298.15} = (\Delta H_f^\circ)_{298.15}$ for each compound. For reference elements, $H^\circ_{298.15} = 0$.

6. Heat Transfer. The total theoretical amount of heat necessary to complete any thermochemical cycle which decomposes 1 g mole of water is 68.31 kcal. This figure assumes that all heat released by the exothermic steps can be used by the endothermic parts of the process. Since the exothermic chemical reactions usually occur at the lower temperatures in the cycle, this assumption is seldom if ever true. Therefore, an analysis of the temperatures and enthalpy changes of all of the steps in the cycle is necessary in order to determine which exothermic and endothermic steps are compatible for the exchange of heat. This process of "matching" the steps in the cycle for the purpose of heat exchange is based on the first and second laws of thermodynamics and is done in the MATCH subroutine.

Considering the heat exchange between two steps of the cycle to take place in a constant pressure-countercurrent heat exchanger as shown in Fig. E-6, the following relationship follows from the first law of thermodynamics:

$$N_A(H_{A_1} - H_{A_2}) + N_B(H_{B_2} - H_{B_1}) + Q = 0 \tag{E-42}$$

where N is the number of moles of material in the stream and Q is the amount of heat exchanged with the surroundings (assumed to equal zero).

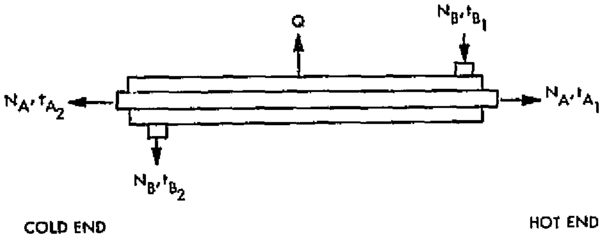


Fig. E-6. Counter Current Heat Exchanger

If A is the endothermic stream, the second law requires that at every point in the exchanger the following inequality hold:

$$t_B > t_A \tag{E-43}$$

It is, however, assumed that t_A may equal t_B at either the inlet or the outlet of the heat exchanger (no temperature offset).

In order to maximize the amount of heat recovered from the exothermic steps, the total enthalpy change for a step may have to be accomplished by matching with more than one of the other appropriate steps within the cycle. The HYDRGN program uses two methods for this division of the total enthalpic change of a step between multiple heat exchange matches.

As seen in Eq. (E-42), one method is to change the number of moles of one or both of the streams involved in a match. This is called stream splitting and is used primarily for isothermal steps but may also be used for some nonisothermal cases.

In the second method, which is used only for nonisothermal steps, the number of moles remains constant for all the heat exchanges in which the step is involved. However, the total temperature change required by the step is divided between the various matches according to the requirements imposed by Eqs. (E-42) and (E-43) for each exchange.

If there is to be any heat from exothermic steps which cannot be applied to the endothermic steps, it is desirable to have this excess heat available at the higher temperatures. Using 298°K as the first value, a listing in ascending order is is made of the temperatures at which the isothermal steps occur. The temperatures in this list are referred to as the "temperature levels" of the process and determine the order in which matching of the steps is to be done.

At each level, all exothermic steps with initial temperatures equal to this level are found. An attempt is then made to match all of this available heat to the appropriate endothermic parts of the process before proceeding to the next higher temperature level.

Using the criteria imposed by Eqs. (E-42) and (E-43) and the assumptions described above, the order of matching at each temperature level is:

(1) The heat liberated by nonisothermal steps is first matched to the appropriate isothermal steps. If all of the available heat from these steps cannot be matched in this manner, attempts are made to apply it to appropriate nonisothermal steps in the cycle.

(2) The heat liberated by isothermal steps is now matched in the same manner.

As part of the matching process, the constraint expressed by Eq. (E-43) is initially imposed only at the inlet and outlet conditions of the two streams. If either or both of the steps involved in the match are isothermal, no further calculations are needed. In the case of two nonisothermal streams being matched, it is possible to meet these conditions and still have a violation of the second law at some point within the heat exchanger.

This possibility usually, but not always, occurs if there is a phase change in one of the streams. For this reason, the ROUTE subroutine sets up all phase changes as separate isothermal steps. However, it is still necessary to check matches between nonisothermal steps for second law violations. The method used consists of dividing the total heat transferred in the exchanger into 25 increments and determining the temperature of each stream at these points. If $t_B < (t_A + 5.0)$, the match between the two steps is flagged with an asterisk in the output as an indication that there may be a violation of the second law.

In performing the above calculations, a form of Eq. (E-40) must be solved for T at a particular value of H for the material involved in the step. It should be noted that each nonisothermal step consists of heating or cooling only a single compound.

If (H_1, T_1) and (H_2, T_2) are the inlet and outlet conditions of one of the steps in the match, the first enthalpy value at which the match is checked is:

$$H^* = H_1 + (H_2 - H_1)/2 \qquad \text{(E-45)}$$

Using Eq. (E-40), the general equation to be solved for T^* at the value H^* is:

$$H = f(T) \qquad \text{(E-46)}$$

Subtracting H^* from both sides of Eq. (E-46), we get:

$$H - H^* = f(T) - H^* \qquad \text{(E-47)}$$

This relationship is now of a form to be solved by the secant method of iteration (Ref. 8). The iteration is repeated until the absolute error for the value of H is less than 0.01 cal.

While the above methods will not necessarily lead to the optimum heat exchange matches for the final design of the process, they do give the value for the minimum amount of heat which must be provided from an external source. This minimum value of external heat needed, Q^*, is obtained by summing the heat to be supplied to the endothermic steps after all possible heat matches have been made. Any exothermic heat available above 500°K after the matching process, is assumed to be converted into work with an efficiency of 0.3. This work generated by the process, W_{gen}, is subtracted from the work needed by the cycle.

Figures of Merit. The figure of merit, η, which this program uses to evaluate the relative merits of a thermochemical cycle is defined as:

$$\eta = \frac{\Delta H^\circ_{298}}{Q_{total}} \qquad \text{(E-48)}$$

where ΔH°_{298} is the molar heat of decomposition of liquid water at 298°K and Q_{total} is the total energy which must be supplied to the cycle from an external source to produce 1 mole of hydrogen. The value of $\Delta H^\circ 298$ is 68.31 kcal for all cycles. Q_{total} includes both the heat and work energy required by the process. Since ΔH°_{298} is constant, the value of the figure of merit depends on the method used to calculate Q_{total}.

The HYDRGN program computes a maximum and a minimum value for the figure of merit under two different sets of conditions. The maximum and minimum values for each of the two figures of merit are the result of using the respective minimum and maximum values of the work for each reaction.

As seen in Eq. (E-49), the first estimate of the figure of merit is made assuming total recovery of all exothermic heat and 100% efficiency for the work of separation. In all calculations the efficiency of conversion of heat to work is taken as 0.3.

The second estimate of η, shown in Eq. (E-50), is obtained after heat exchange matching. The heat needed by the cycle, Q^*, is the sum of the endothermic heats remaining after the matching process. The work of separation is reduced by the total work generated by unmatched exothermic heat and it is further assumed that the separation processes are only 50% efficient.

$$\eta_1 = \frac{\Delta H^\circ_{298}}{\Delta H^\circ_{298} + (W_{sep}/0.3)} \qquad \text{(E-49)}$$

$$\eta_2 = \left(\frac{\Delta H^\circ_{298}}{Q^* + \dfrac{2W_{sep} - W_{gen}}{0.3}} \right) \qquad \text{(E-50)}$$

III. PRELIMINARY CRITERIA FOR THE EVALUATION OF THERMOCHEMICAL CYCLES

A. Thermodynamic Criteria

1. $$\Sigma Qi\left(\frac{T_{hi} - T_{ci}}{T_{hi}}\right) \geq \Delta G_{H_2O}$$

   $= 56.7$ Kcal/mole

2. $\Delta G_i \leq 5$ K cal/mole
3. HYDRGN Program, Fig. of Merit

   (first) ≥ 0.50

B. Engineering and Economic Criteria

1. a. Materials Handling.
   b. Cost of Inventory.
2. Cost of Losses (or Makeup)
   a. Establish level of loss for gases, solids and liquids.
   b. Cost of losses.
   c. Pollution problems caused by losses
3. Separation Problems
   a. Nature and phase of reactant species
   b. Nature and phase of product species
   c. Proposed separations; solid/fluid desirable
4. Side or Competing Reactions
   a. Possibility of side reactions based on literature, and thermodynamics
5. Heat Transfer
   a. Heat transfer to reactants. mechanism. Desirable to have one of the reactants gaseous.
   b. Area for heat transfer. $, cost of area/MBtu.
6. Materials
   a. Compatibility of materials with reactants.
   b. Compatibility of materials with hydrogen. Desirable to have H_2 production step at low temperature and high pressure?
7. Steps
   a. No. of steps, approximately 5 or less.
   b. No. of <u>elements</u> in cycle, 5 or less.
   c. T of highest reaction $\leq$ 1000 to 1300°K.
8. At what step in the process is the H_2 produced? What are the step conditions? Desirable features of this step should be:
   a. Temperature should be low (<500°K). This will minimize materials problems.
   b. Pressure should be high (30-50 atm.). This will avoid compression costs.

   Note: The above criteria makes hybrid (mixed thermal-electrolytic) processes look more attractive.
9. Possibility of a high temperature <u>topping</u> cycle in the process? This could be the case if the heat source is a HTGR.
10. Work extracted from a topping cycle could be added at <u>100% efficiency</u> as the reject heat at $T = 1000$°K is used for the thermochemical steps. Makes overall figure of merit improve.

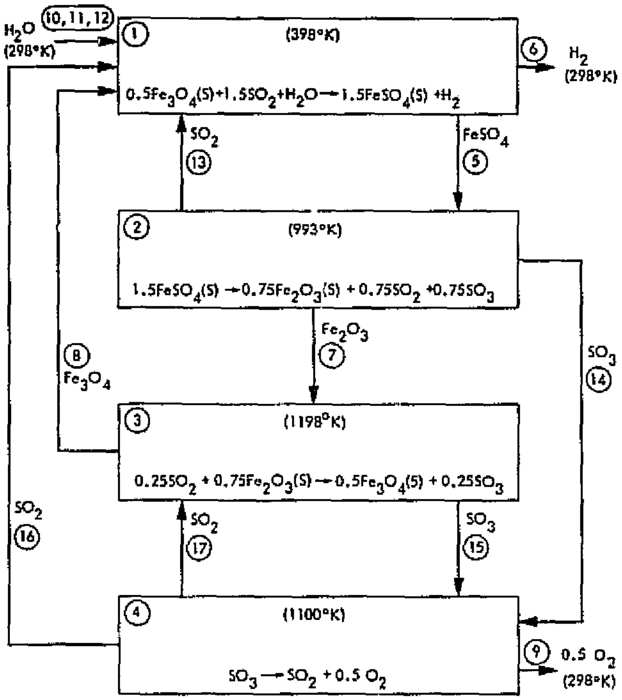
C. Practical Criteria

1. Reaction feasibility from:
   a. Literature
   b. Laboratory testing
   c. Rate of desired reactions
   d. Reaction with recycled, i.e. impure reactants.

IV. SPECIFIC CYCLE DESCRIPTIONS

The open literature contains descriptions of several specific thermochemical cycles. Descriptions of them are included here so that a deeper insight into how they work can be gained.

<u>Iron Sulfur Cycle.</u> This is one of a family of thermochemical cycles using oxides of iron and sulfur (Ref. 9). The decomposition of sulfur trioxide is common to many thermochemical processes. This cycle has four major steps and involves the handling of gases, liquids and solids with a high grade heat input to the cycle of 1198 K (1697°F). Figure E-7 diagrams the process showing both the intermediate steps and reactant temperatures.



NOTE: THE NUMBERS CIRCLED ARE THE STEP NUMBERS USED IN TABLE E-2.

Figure E-7. Iron sulfur cycle diagram

Tables E-1 and E-2 summarize the data on the iron-sulfur process. The commercial productions of hydrogen by this process is most unlikely because of the high material inventory required for the cycle. This is due to a low equilibrium conversion in one of the steps and most likely will be even poorer, when kinetic rates are accounted for in the overall cycle. The total heat requirements are modest at 2.68 times the theoretical value required to split water. From a chemical standpoint the formation of black magnetic iron oxide (Fe_3O_4) may present some problems in yield requirements for the cycle.

Iron Chloride Cycle. This family of cycles employ oxides and chlorides of iron (Ref. 10) and are being studied in Europe and the U.S. The cycle has four major steps and involves the handling of gases, liquids and solids with the heat source to drive the reaction of 923 K (1202°F). Figure E-8 is the process diagram for the cycle.

Tables E-3 and E-4 summarize the data on the iron-chlorine cycle. From a mass or material handling standpoint this cycle is not as demanding as the iron sulfur cycle. To get one kilogram of hydrogen gas 11×10^3 kg of chemicals are needed to be processed (Table E-3). When kinetic rates are considered this figure will no doubt increase the material handling problem. The heat requirements for the cycle are 5.36 times the theoretical aimpoint required to split water into hydrogen and oxygen. The nonstoichiometric nature of iron-chlorine compounds will cause some problems in the over all cycle yields. In this process materials of construction matched with the high temperatures will be a major problem.

Table E-1. Mass and Heat Processed-
Iron Sulfur Process

I. Stoichiometric Mass of Material per Unit Mass H_2 Product, without recycle

$$W_1 = 673$$

II. Mass of Material per Unit Mass H_2 Product Considering Equilibrium Conversion in all Reactions

$$W_2 = 849,265$$

no kinetic considerations

III. Total Heat Transferred from External Source Relative to ΔH_{298} for H_2

$$q_1 = 1.47$$

IV. Total Heat Transferred from Internal Sources Relative to ΔH_{298} for H_2

$$q_2 = 0.57$$

V. Total Heat from All Sources Relative to ΔH_{298} for H_2

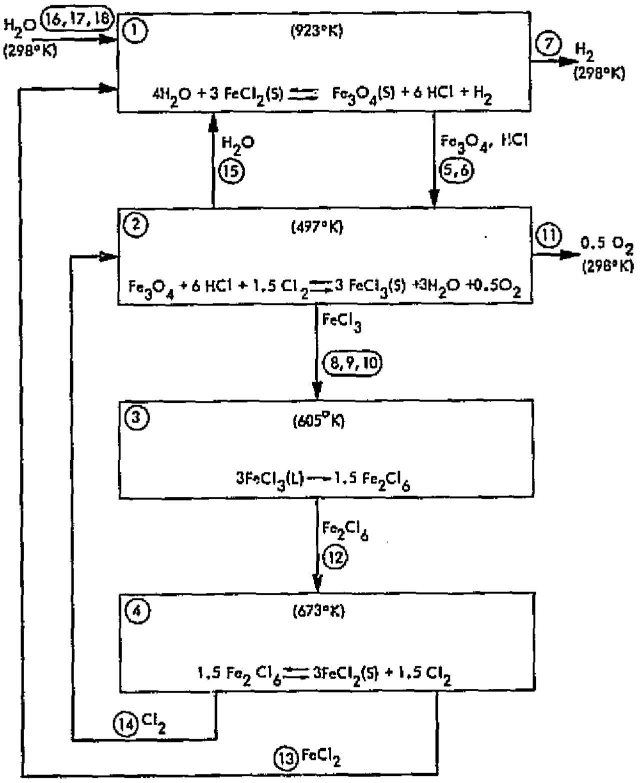
$$q = q_1 + q_2 = 2.04$$

Hybrid Sulfuric Acid Cycle. The hybrid sulfuric acid cycle is not a true closed thermochemical cycle as defined earlier. It is intended to be used with a nuclear reactor as a combined work plus heat cycle. The hybrid cycle involves (see Fig. E-9) the electrolysis of sulfurous acid (H_2SO_3) to sulfuric (H_2SO_4), thus in principle in a 1 molar sulfuric acid, sulfur dioxide (SO_2) could be oxidized at the anode and hydrogen evolved at the cathode of an electrolysis cell under a potential of 0.17 V. This compares with a voltage of 1.23 V (or more) for a normal water electrolysis cell (a factor of about 7.2 in voltage). The removal of water from the dilute sulfuric acid and the need for a double reaction scheme in the decomposition of the acid are complicating factors. Figure E-10 is the process diagram for the cycle.

Tables E-5 and E-6 summarize the data on the hybrid sulfuric acid cycle. From a material handling standpoint this cycle is good in that 103 Kg (lb) of material need to be processed for 1 Kg (lb) of hydrogen gas. The heat requirements are 3.64 times the theoretical amount required to split water. This hybrid cycle may be attractive as a topping cycle in a nuclear-electrical system. In some special situations the direct use of sulfuric acid for other chemical processes may be economically feasible. A problem with this cycle is the need to get the concentration of the sulfuric acid high in the electrolyzer cell so that a minimum amount of water is handled in the cycle.

Table E-2. Overall Iron Sulfur Process Summary

STAGE	SUMMARY 1	2	3	4	Σ
1. ΔH_{298}, Heat of Reaction, (kcal)	-24.23	60.91	8.20	23.64	68.3
2. ΔH_T, Heat of Reaction at Temp. T, (kcal)	-34.56	59.08	8.29	23.24	
3. T, Temp. of Reaction, (°K)	398	993	1198	1110	
4. W_s, Theor. Work of Separation, (kcal)	1.18	2.05	5.8	3.97	13.0
5. Theor. Work of Separation, (%) $(W_s/\Sigma W_s)\ 100$	9.0	16.0	44.6	30.4	100.0
6. $Q_s = W_s/0.15$, Heat Required to Generate Work of Separation, 15% efficiency, (kcal)	7.87	13.67	38.67	26.47	86.68
7. Q, Heat Requirement, (kcal)	0.6	74.9	1.92	18.68	96.1
8. Q_j, Total Heat Requirement, (kcal) $Q_j = Q_s + Q$	8.47	88.57	40.59	45.15	182.78
9. Total Heat Requirement, (%) $(Q_j/\Sigma Q_j)\ 100$	4.6	48.5	22.2	24.7	100.0
10. Q_{rej}, Heat Rejected (kcal)	25.5	0	1.2	1.1	27.8
11. η_j, Figure of Merit	-2.88	0.69	0.202	0.524	
12. (11) x (9) $\Sigma(\eta_j)(Q_j/Q_T) = \eta$	-1.335	0.333	0.045	0.129	0.374
13. ϵ_j, Loss Coefficient $\epsilon_j = (Q_s + Q_{rej})/68.3$	0.488	0.20	0.584	0.404	1.676



NOTE: THE NUMBERS CIRCLED ARE THE STEP NUMBERS USED IN TABLE E-4.

Figure E-8. Iron Chloride Cycle Diagram

Table E-3. Mass and Heat Processed — Iron Chloride Process

I. Stoichiometric Mass of Material per Unit Mass H_2 Produced, without recycle

$$W_1 = 991$$

II. Mass of Material per Unit Mass H_2 Product Considering Equilibrium Conversion in all Reactions, No Kinetic Considerations

$$W_2 = 11,106$$

III. Total Heat Transferred from External Source Relative to ΔH_{298} for H_2

$$q_1 = 1.72$$

IV. Total Heat Transferred from Internal Sources Relative to ΔH_{298} for H_2

$$q_2 = 0.96$$

V. Total Heat Transferred from All Sources Relative to ΔH_{298} for H_2

$$q = q_1 + q_2 = 2.68$$

Table E-4. Overall Iron Chloride Process Summary

	SUMMARY				
STAGE	1	2	3	4	Σ
1. ΔH_{298}, Heat of Reaction, (kcal)	118.34	-91.38	51.87	-10.50	68.3
2. ΔH_T, Heat of Reaction of Temp. T, (kcal)	79.57	-57.88	15.68	-7.92	
3. T, Temp. of Reaction, (°K)	923	400	605	673	
4. W_s, Theor. Work of Separation, (kcal)	25.39	8.0		9.35	42.74
5. Theor. Work of Separation, (%) $(W_s/\Sigma W_s)$ 100	59	19		22	100
6. $Q_s = W_s/0.15$, Heat Required to Generate Work of Separation, 15% Efficiency, (kcal)	169.3	53.3		62.3	284.9
7. Q, Heat Requirement, (kcal)	84.3	-8.0	38.18	0.77	117.53
8. Q_j, Total Heat Requirement, (kcal) $Q_j = Q_s + Q$	254.6	45.3	38.2	63.1	400.2
9. Total Heat Requirement, (%) $(Q_j/\Sigma Q_j)$ 100	63.6	11.3	9.5	15.7	100.0
10. Q_{rej}, Heat Rejected (kcal)	1.57	47.64			49.21
11. η_j, Figure of Merit	0.465	-2.017	1.36	-0.17	
12. (11) x (9) $\Sigma(\eta_j)(Q_j/Q_T) = \eta$	0.296	-0.2284	0.1292	-0.0267	0.1701
13. ϵ_j, Loss Coefficient $\epsilon_j = (Q_s + Q_{rej})/68.3$	2.5	1.47	0	0.91	4.88

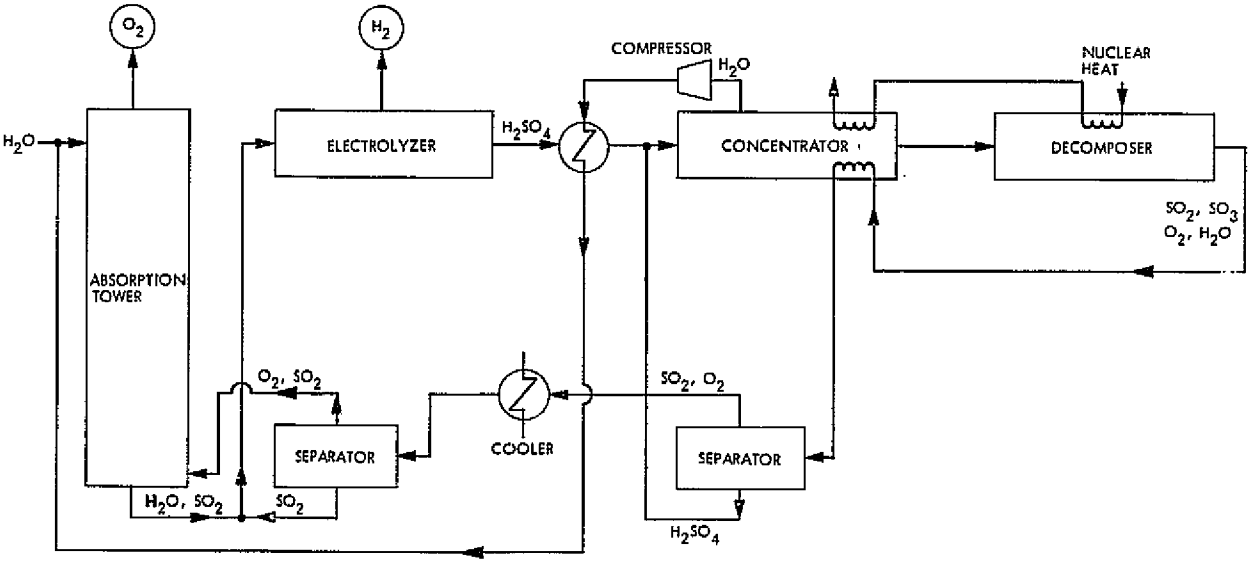
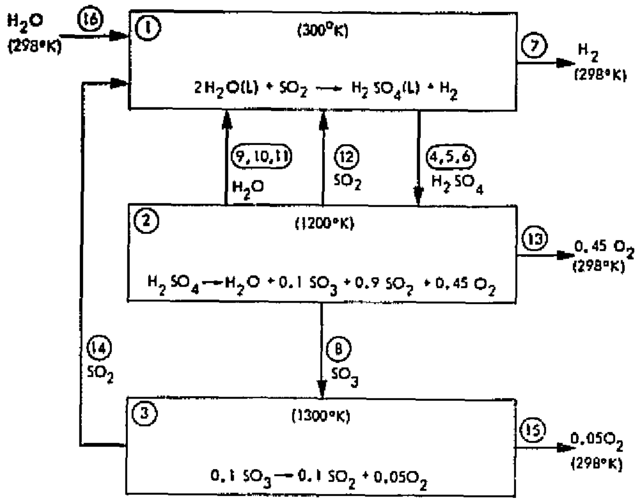


Figure E-9. Hybrid Sulfuric Acid Cycle Hardware Schematic



NOTE: THE NUMBERS CIRCLED ARE THE STEP NUMBERS USED IN THE TABLES.

Figure E-10. Hybrid Sulfuric Acid Cycle

Table E-5. Mass and Heat Processed — Hybrid Sulfuric Acid Cycle

I. Stoichiometric Mass of Material per Unit Mass H_2 Produced, without recycle

$$W_1 = 103$$

II. Mass of Material per Unit Mass H_2 Product Considering Equilibrium Conversion in all Reactions, no kinetic considerations

$$W_2 = 103$$

III. Total Heat Transferred from External Source Relative to ΔH_{298} for H_2

$$q_1 = 0.961$$

IV. Total Heat Transferred from Internal Sources Relative to ΔH_{298} for H_2

$$q_2 = 0.336$$

V. Total Heat Transferred from all Sources Relative to ΔH_{298} for H_2

$$q = q_1 + q_2 = 1.297$$

Table E-6. Overall Hybrid Sulfuric Acid Cycle Summary

	SUMMARY				
STAGE	1	2	3	4	Σ
1. ΔH_{298}, Heat of Reaction, (kcal)	13.04	52.92	2.36		68.3
2. ΔH_T, Heat of Reaction at Temp. T, (kcal)	13.02	43.02	2.3		
3. T, Temp. of Reaction, (°K)	300	1200	1300		
4. W_s, Theor. Work of Separation, (kcal)	20.24	6.87	0.32		27.43
5. Theor. Work of Separation, (%) $(W_s/\Sigma W_s)$ 100	74.0	25.0	1.0		100.0
6. $Q_s = W_s/0.15$, Heat Required to Generate Work of Separation, 15% Efficiency (kcal)	134.94	45.8	2.13		182.87
7. Q, Heat Requirement, (kcal)	11.56	52.47	1.58		65.59
8. Q_j, Total Heat Requirement, (kcal) $Q_j = Q_s - Q$	146.5	98.27	3.69		248.48
9. Total Heat Requirement, (%) $(Q_j/\Sigma Q_j)$ 100	59.0	39.6	14.9		100.0
10. Q_{rej}, Heat Rejected (kcal)	12.06	5.26	0.18		17.50
11. η_j, Figure of Merit	0.089	0.5385	0.6396		
12. (11) x (9) $\Sigma(\eta_j)(Q_j/Q_T) = \eta$	0.0525	0.2130	0.0095		0.2750
13. ϵ_j, Loss Coefficient $\epsilon_j = (Q_s - Q_{rej})/68.3$	2.152	0.7476	0.0338		2.933

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APPENDIX F

PRODUCTION COST METHODS AND DATA*

R. E. Jeffe, T. Fujita

I. PRODUCTION COST METHODOLOGY

The costing method employed by the HEST study is based on the public utility method developed by the American Gas Association (AGA) General Accounting Committee and modified slightly by the Panhandle-Eastern Pipeline Co. The costing equations were taken from work prepared by the Synthetic Gas-Coal Task Force of the Federal Power Commission National Gas Survey.

GENERAL GAS COST EQUATION FOR UTILITY FINANCING

Basis:

- 20-yr project life
- 5%/yr straight line depreciation on total capital requirement excluding working capital
- 48% federal income tax rate
- Escalation rates (when applicable) are 4%/yr during 1971-1975, 3.5%/yr during 1976-1980, and 3%/yr thereafter.

Definition of Terms:

C = Total capital requirement, million \$

W = Working capital, million \$

N = Total net operating cost in first year, million \$/yr

G = Annual gas production (10^6 Btu/yr)

d = Debt fraction

i = Interest on debt

r = Return on equity

p = Return on rate base

e = Escalation rate, annual fraction

n = Year, 1 to 20

Rate Base in nth year

Depreciable investment = $C-W$

Accrued depreciation at midpoint of yr
$= 0.05\,(n-0.5)\,(C-W)$

Rate base $= C - 0.05\,(n-0.5)\,(C-W)$

Return on Rate Base

$$p = (d)i + (1-d)r$$

Cost Breakdown in nth yr

Total cost in nth year =

$$p\left[C - 0.05\,(n-0.5)\,(C-W)\right] \sim \text{Return on Base Rate}$$

$$+\left(\frac{48}{1-48}\right)r\,(1-d)\left[C-0.05\,(n-0.5)\,(C-W)\right] \sim \text{Income Tax}$$

$$+\,0.05\,(C-W) \sim \text{Depreciation}$$

$$+\,N\,(1+e)^{n-1} \sim \text{Operating Costs (including escalation)}$$

Cumulative Costs over 20-year Project Life

Total 20-year Costs

$$= \sum_{n=1}^{20} (\text{total cost in } n^{th} \text{ yr})$$

$$= \sum_{n=1}^{20} N\,(1+e)^{n-1} + (C-W) + 10\left[p + \frac{48}{52}\,(1-d)r\right](C+W)$$

Average Yearly Unit Cost

$$\text{Average gas cost} = \frac{(\text{total 20-yr costs}/20)}{G}$$

$$= \frac{N(F_e)+0.05\,(C-W)+0.5\left[p+\frac{48}{52}\,(1-d)r\right](C+W)}{G}$$

where F_e is an escalation factor defined as

$$F_e = 0.05\sum_{n=1}^{20}(1+e)^{n-1} = 0.05\left[\frac{(1+e)^{20} - 1}{(1+e)}\right]$$

Based on previously given escalation rates for the general gas equation, the escalation factor is 1.37 for plants starting in 1975 and 1.34 for plants starting in 1980 and beyond.

APPLICATION TO HYDROGEN PRODUCTION

In applying the general cost equation to hydrogen production, the following minor modifications and assumptions were made:

(1) The setting of working capital (W) to zero.

(2) The subdividings of operations cost into two parts, 1) operations and maintenance and 2) feedstock cost.

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*The basic energy or energy-equivalent unit employed in this Appendix is 10^6 Btu. Such quantities may be converted to 10^9 J by multiplying by 1.056. To the accuracy required in this Appendix, the 6% change in values is not significant.

(3) The expansion of all terms to allow for the incorporation of specific hydrogen process characteristics.

Referring to the general equation, subdivision of operating costs is accomplished by letting

$$N = OG + HX$$

where

O = Operations and maintenance cost per unit plant output

H = Unit feedstock costs

X = Annual feedstock consumption

Expressing X and G in units of energy, the process efficiency is

$$E = \frac{G}{X}$$

If the process is broken down into several steps, E is the product of the efficiencies of the intermediate steps.

Expansion of cost terms basically involves introduction of unit cost values and load factors, i.e.,

$$C = IS$$

$$G = LS$$

where

I = Unit capital cost of the plant normalized to rated output

S = Plant size expressed in terms of rated output

L = Annual load factor or actual output over rated output

If the process is decomposed into stages, the value of the product IS for each such stage can be determined and summed to determine the capital cost, C.

II. COST DATA

A detailed listing of input data, including a base, high and low value and the resulting costs are given herein for the six processes discussed in Chapter VII. The following data (Table F-1) is common to all six cases.

In the general gas cost equation, the income tax rate was fixed at 48% and the depreciated life and plant life were taken to be equal and fixed at a value of 20 years. To show the effect of changes in tax rate as well as the effect of differing depreciation rates (not equal to plant life), high-low changes in these parameters have been introduced in Table F-1.

For simplicity, the price escalation rate is assumed to be zero in all cases. This in effect allows a relative comparison of all the processes where the plants are presumed to be operating in the same time frame. This was deemed appropriate for purposes of the present study, particularly since other major cost parameters are subject to a wide range of estimates.

When assessing unit gas costs (cost per unit gas delivered), the relevant input cost factors are unit capital, operating, and feedstock costs as well as efficiencies and load factors. These data are presented in Tables F-2a through F-7a. The resulting calculated hydrogen costs are summed from the major cost elements of the particular production methods. These results are given in Tables F-2b through F-7b.

Table F-1. Cost Factors Common to All Calculations

Cost Factor	Symbol	Unit of Measure	Base Value	High Cost Value	Low Cost Value
Debt fraction	d		0.75	0.65	0.85
Interest rate	i	year^{-1}	0.09	0.12	0.09
Return on equity	r	year^{-1}	0.15	0.20	0.15
Income tax rate	T	year^{-1}	0.48	0.55	0.45
Plant life	n	years	20	20	20
Depreciated life	m	years	20	15	25
Price escalation rate	e	years^{-1}	0	0	0

Table F-2a. Cost factors for steam reforming

Cost Factor[a]	Symbol	Unit of Measure	Base Value	High Cost Value	Low Cost Value
Plant Investment	I	$\$/10^6$ Btu/yr	0.85	0.90	0.80
Operations Cost	O	$\$/10^6$ Btu	0.05	0.10	0.05
Feedstock Cost	H	$\$/10^6$ Btu	1.00	4.00	0.60
Process Efficiency	E		0.75	0.60	0.80
Load Factor	L		0.90	0.85	0.95

[a] Feedstock costs are given per unit of primary energy. All other costs are normalized to hydrogen-output energy content.

Table F-2b. Cost of hydrogen from steam reforming

Cost Element	Symbol	Base Value		High Value		Low Value	
		$\$/10^6$ Btu	%	$\$/10^6$ Btu	%	$\$/10^6$ Btu	%
Depreciation	GC	0.05	3	0.07	1	0.03	4
Capital Charges	GCC	0.07	5	0.12	2	0.05	6
Operations Cost	GO	0.05	3	0.10	1	0.05	5
Feedstock Cost	GF	1.33	89	6.67	96	0.74	85
Total		1.50	100	6.96	100	0.87	100

Table F-3a. Cost factors for partial oxidation of oil

Cost Factor[a]	Symbol	Unit of Measure	Base Value	High Cost Value	Low Cost Value
Plant Investment	I	$\$/10^6$ Btu/yr	2.50	5.00	2.00
Operations Cost	O	$\$/10^6$ Btu	0.10	0.15	0.05
Feedstock Cost	H	$\$/10^6$ Btu	1.60	3.00	1.00
Process Efficiency	E		0.70	0.50	0.73
Load Factor	L		0.85	0.75	0.90

[a] Feedstock costs are given per unit of primary energy. All other costs are normalized to hydrogen-output energy content.

Table F-3b. Cost of hydrogen from partial oxidation of oil

Cost Element	Symbol	Base Value		High Value		Low Value	
		$\$/10^6$ Btu	%	$\$/10^6$ Btu	%	$\$/10^6$ Btu	%
Depreciation	GD	0.15	6	0.44	6	0.09	5
Capital Charges	GCC	0.20	7	0.78	11	0.13	8
Operations	GO	0.10	4	0.15	2	0.05	3
Feedstock	GF	2.28	83	6.00	81	1.37	84
Total		2.73	100	7.37	100	1.64	100

Table F-4a. Cost factors for coal gasification

Cost Factor[a]	Symbol	Unit of Measure	Base Value	High Cost Value	Low Cost Value
Plant Investment	I	$\$/10^6$ Btu/yr	3.60	7.50	2.75
Operations Cost	O	$\$/10^6$ Btu	0.25	0.50	0.15
Feedstock Cost	H	$\$/10^6$ Btu	1.00	1.60	0.60
Process Efficiency	E		0.55	0.50	0.70
Load Factor	L		0.80	0.70	0.85

[a] Feedstock costs are given per unit of primary energy. All other costs are normalized to hydrogen-output energy content.

Table F-4b. Cost of hydrogen from coal gasification

Cost Element	Symbol	Base Value		High Value		Low Value	
		$\$/10^6$ Btu	%	$\$/10^6$ Btu	%	$\$/10^6$ Btu	%
Depreciation	GD	0.27	10	0.57	11	0.13	3
Capital Charges	GCC	0.38	14	1.00	19	0.19	6
Operations	GO	0.30	11	0.40	8	0.15	4
Feedstock	GF	1.82	65	3.20	62	0.86	87
Total		2.77	100	5.17	100	1.33	100

Table F-5a. Cost factors for nuclear-electrolysis (Process: Nuclear reactor provides electrical energy to electrolysis plant)

Cost Factor[a]	Symbol	Unit of Measure	Base Value	High Cost Value	Low Cost Value
Plant Investment (NR)[b]	I_{nr}	$\$/10^6$ Btu/yr	25.00	35.00	17.00
Operations Cost (NR)	O_{nr}	$\$/10^6$ Btu	0.20	0.60	0.20
Feedstock Cost (NR)	H_{nr}	$\$/10^6$ Btu	0.25	0.50	0.15
Plant Investment (EL)[b]	I_{el}	$\$/10^6$ Btu/yr	1.80	6.70	1.30
Operations Cost (EL)	O_{el}	$\$/10^6$ Btu	0.20	0.60	0.20
Process Efficiency (NR)	E_{nr}		0.25	0.25	0.35
Process Efficiency (EL)	E_{el}		0.80	0.50	1.00
Load Factor	L		0.85	0.50	0.90

[a] Feedstock costs are given per unit of primary energy. All other costs are normalized to hydrogen-output energy content.
[b] NR = nuclear reactor; EL = electrolysis plant.

Table F-5b. Costs of hydrogen from nuclear-electrolysis

Cost Element	Symbol	Base Value		High Value		Low Value	
		$\$/10^6$ Btu	%	$\$/10^6$ Btu	%	$\$/10^6$ Btu	%
Depreciation (NR)[a]	GD_{nr}	1.84	29	9.33	27	0.76	27
Capital Charges (NR)	GCC_{nr}	2.57	40	16.34	48	1.11	39
Operation Costs (NR)	GO_{nr}	0.25	4	1.20	3	0.20	7
Feedstock Costs (NR)	GF_{nr}	1.25	20	4.00	12	0.43	15
Depreciation (EL)[a]	GD_{el}	0.11	2	0.89	3	0.06	2
Capital Charges (EL)	GCC_{el}	0.15	2	1.56	5	0.08	3
Operations (EL)	GO_{el}	0.20	3	0.60	2	0.20	7
Total		6.37	100	33.92	100	2.84	100

[a] NR = nuclear reactor; EL = electrolysis plant.

Table F-6a. Cost factors for nuclear-thermochemical (Process: Nuclear reactor supplies heat energy to thermochemical plant)

Cost Factor[a]	Symbol	Unit of Measure	Base Value	High Cost Value	Low Cost Value
Plant Investment (NR)[b]	I_{nr}	$\$/10^6$ Btu/yr	7.50	12.00	5.50
Operations Cost (NR)	O_{nr}	$\$/10^6$ Btu	0.10	0.30	0.10
Feedstock Cost (NR)	H_{nr}	$\$/10^6$ Btu	0.25	0.50	0.15
Plant Investment (TC)[b]	I_{tc}	$\$/10^6$ Btu/yr	5.70	10.50	3.30
Operations Cost (TC)	O_{tc}	$\$/10^6$ Btu	0.60	1.20	0.30
Process Efficiency (NR)	E_{nr}		0.80	0.70	0.90
Process Efficiency (TC)	E_{tc}		0.30	0.20	0.60
Load Factor	L		0.75	0.50	0.85

[a] Feedstock costs are given per unit of primary energy. All other costs are normalized to hydrogen-output energy content.
[b] NR = nuclear reactor; TC = thermochemical.

Table F-6b. Cost of hydrogen from nuclear-thermochemical

Cost Element[a]	Symbol	Base Value		High Value		Low Value	
		$/10^6 Btu	%	$/10^6 Btu	%	$/10^6 Btu	%
Depreciation (NR)[a]	GD_{nr}	1.67	24	8.00	25	0.43	19
Capital Charges (NR)	GCC_{nr}	2.33	34	14.01	43	0.63	29
Operation Costs (NR)	GO_{nr}	0.33	5	1.50	5	0.17	8
Feedstock Costs (NR)	GF_{nr}	1.04	15	3.57	11	0.28	13
Depreciation (TC)[a]	GD_{tc}	0.38	5	1.40	4	0.16	7
Capital Charges (TC)	GCC_{tc}	0.53	8	2.45	8	0.23	10
Operation Costs (TC)	GO_{tc}	0.60	9	1.20	4	0.30	14
Total		6.88	100	32.13	100	2.20	100

[a] NR = nuclear reactor; TC = thermochemical plant.

Table F-7a. Cost factors for photovoltaic-electrolysis
(Process: Solar photovoltaic plant supplies electrical energy to electrolysis plant)

Cost Factor[a]	Symbol	Unit of Measure	Base Value	High Cost Value	Low Cost Value
Plant Investment (PV)[b]	I_{pv}	$/10^6 Btu/yr	35.00	175.00	17.00
Operations Cost (PV)	O_{pv}	$/10^6 Btu	0.30	0.60	0.30
Plant Investment (EL)[b]	I_{el}	$/10^6 Btu/yr	1.80	6.70	1.30
Operations Cost (EL)	O_{el}	$/10^6 Btu	0.20	0.60	0.20
Process Efficiency (EL)	E_{el}		0.80	0.50	1.00
Load Factor	L		0.35	0.30	0.40

[a] Energy source (feedstock) cost is zero for solar energy and water costs are included in operations costs for the electrolysis plant.

[b] PV = photovoltaic solar plant; EL = electrolysis plant.

Table F-7b. Cost of hydrogen from photovoltaic-electrolysis

Cost Element	Symbol	Base Value		High Value		Low Value	
		$/10^6 Btu	%	$/10^6 Btu	%	$/10^6 Btu	%
Depreciation (PV)[a]	GD_{pv}	6.25	39	77.78	35	1.70	34
Capital Charges (PV)	GCC_{pv}	8.72	54	136.32	62	2.50	50
Operations (PV)	GO_{pv}	0.38	2	1.20	1	0.30	6
Depreciation (EL)[a]	GD_{el}	0.27	2	1.49	1	0.13	2
Capital Charge (EL)	GCC_{el}	0.36	2	2.61	1	0.19	4
Operations (EL)	GO_{el}	0.20	1	0.60	0	0.20	4
Total		16.18	100	220.00	100	5.02	100

[a] PV = photovoltaic power plant; EL = electrolysis plant.

III. COST MATRIX PROCEDURE

The cost matrix procedure allows one to compute quickly hydrogen costs for any set of assumptions relative to the defined cost factor parameters.

In developing the cost matrix procedure, the general gas equation giving average yearly unit costs is represented as the sums of the following four basic components:

Depreciation:

$$GD = \frac{1}{m}\frac{C}{G} = \frac{I}{mL}$$

Capital:

$$GCC = 0.5\left[p + \frac{T}{1-T}\,(1-d)r\right]\frac{C}{G}$$

$$= 0.5\left[p + \frac{T}{1-T}\,(1-d)r\right]\frac{I}{L}$$

Operation:

$$GO = F_eO\frac{G}{G} = F_eO$$

Feedstock:

$$GF = F_eH\frac{X}{G} = F_e\frac{H}{E}$$

In the general cost equation, the plant depreciation period is m = 20 years which corresponds to a 5% per year depreciation. Also, the federal income tax rate is nominally T = 48%. The above capital component of cost is the sum of the return on base rate and federal income tax.

When the process is broken down into intermediate stages, cost components can be evaluated separately for each stage and then summed. The cost components for a stage will be based on the output of that stage and the output can in turn be related to the final output via stage efficiencies, where all outputs are expressed in units of energy.

Use of the cost matrix to compute costs basically requires only that the user:

(1) Identify among the list of cost factors those base values he wishes to change.

(2) Identify all row cells in which the given cost factor is required (i.e., row cell is white).

(3) Divide the new cost factor value by the base value, putting the resultant into the appropriate row cells.

(4) Multiply row-wise the row cell values together, putting the product into Column X.

(5) Multiply the row products (Column X) times the row base to arrive at a new row cost.

(6) Sum the new row costs to arrive at the total cost.

The procedure is illustrated in Table F-8 which pertains to nuclear-electrolysis. In this example, four changes will be made. The six steps identified above as applied to the example are as follows:

Step 1 - Identify all cost factors to be changed.

(1) I_{nr}: a change to 12.5 from 25.

(2) H_{nr}: a change to 0.5 from 0.25.

(3) E_{el}: a change to 1.0 from 0.80.

(4) L: a change to 1.0 from 0.85.

Step 2 - Identify all row cells in which the given cost factor is required.

(a) I_{nr} - rows 1 and 2

(b) H_{nr} - row 4

(c) E_{el} - rows 1 through 4

(d) L - rows 1, 2, 5, and 6

Step 3 - Divide the new cost factor value by the base value

	Cost Factor	New Value	Base Value	Ratio
(a)	I_{nr}	12.5	25	0.5
(b)	H_{nr}	0.5	0.25	2.0
(c)	$1/E_{el}$	1	1/.80	0.80
(d)	1/L	1	1/.85	0.85

Step 4 - Multiply row-wise the row cell values together and record in column X. For example, for Row 1, multiply 0.5 x .80 x .85 to get .34 and record 0.34 in Column X.

Step 5 - Multiply the row products (Column X) times the row base. For example, for Row 4, multiply 1.60 x 1.25 to obtain 2.00, which is then recorded in the new cost column.

Step 6 - Sum the row costs to arrive at the new total cost of $4.12/10^6 Btu.

In the present version, the user cannot directly change the base cost factor values for d, i, r, e, T, and n. Changes in these parameters can be evaluated by substitution into the equation given earlier.

The cost matrix tables used for the six technologies costed out in this study are shown as Tables F-9 through F-14. Base values from Tables F-2 to F-7 are used.

Table F-8. Example of cost matrix calculation ($\$/10^6$ Btu)

Factors	1/m	I_{nr}	O_{nr}	H_{nr}	$1/E_{nr}$	I_{el}	ϕ_{el}	$1/E_{el}$	1/L			
Base Values	1/20	25	.20	.25	1/.25	1.80	.20	1/.80	1/.85	X	Base	New Cost
① GD_{nr}		0.5	▨	▨	▨	▨	▨	.80	.85	.34	1.84	.63
② GCC_{nr}	▨	0.5	▨	▨	▨	▨	▨	.80	.85	.34	2.57	.87
③ GO_{nr}	▨	▨		▨	▨	▨	▨	.80	▨	.80	.25	.20
④ GF_{nr}	▨	▨	▨	2.0		▨	▨	.80	▨	1.60	1.25	2.00
⑤ GD_{el}	▨	▨	▨	▨	▨		▨	▨	.85	.85	.11	.09
⑥ GCC_{el}	▨	▨	▨	▨	▨		▨	▨	.85	.85	.15	.13
⑦ GO_{el}	▨	▨	▨	▨	▨	▨	▨	▨	▨	1.00	.20	.20
									Grand Total			4.12

Table F-9. Computation of H_2 cost using steam reforming ($\$/10^6$ Btu)

Factors	1/m	I	O	H	1/E	1/L			
Base Values	1/20	.85	.05	1.00	1/.75	1/.90	X	Base	New Cost
① GD			▨	▨	▨			.05	
② GCC	▨		▨	▨	▨			.07	
③ GO	▨	▨		▨	▨	▨		.05	
④ GF	▨	▨	▨			▨		1.33	
						Grand Total			

Table F-10. Computation of H_2 cost using partial oxidation of oil ($\$/10^6$ Btu)

Factors	1/m	I	O	H	1/E	1/L			
Base Values	1/20	2.50	.10	1.60	1/.70	1/.85	X	Base	New Cost
① GD			▨	▨	▨			.15	
② GCC	▨		▨	▨	▨			.20	
③ GO	▨	▨		▨	▨	▨		.10	
④ GF	▨	▨	▨			▨		2.28	
						Grand Total			

Table F-11. Computation of H_2 cost using coal gasification ($\$/10^6$ Btu)

Factors	1/m	I	O	H	1/E	1/L			
	1/20	3.60	.25	1.00	1/.55	1/.80	X	Base	New Cost
① GD			▨	▨	▨			.27	
② GCC	▨		▨	▨	▨			.38	
③ GO	▨	▨		▨	▨	▨		.30	
④ GF	▨	▨	▨			▨		1.82	
								Grand Total	

Table F-12. Computation of H_2 cost using nuclear-electrolysis ($\$/10^6$ Btu)

Factors	1/m	I_{nr}	O_{nr}	H_{nr}	$1/E_{nr}$	I_{el}	O_{el}	$1/E_{el}$	1/L			
Base Values	1/20	25	.20	.25	1/.25	1.80	.20	1/.80	1/.85	X	Base	New Cost
① GD_{nr}			▨	▨	▨	▨	▨				1.84	
② GCC_{nr}	▨		▨	▨	▨	▨	▨				2.57	
③ GO_{nr}	▨	▨		▨	▨	▨	▨		▨		.25	
④ GF_{nr}	▨	▨	▨			▨	▨		▨		1.25	
⑤ GD_{el}		▨	▨	▨	▨		▨	▨			.11	
⑥ GCC_{el}	▨	▨	▨	▨	▨		▨	▨			.15	
⑦ GO_{el}	▨	▨	▨	▨	▨	▨		▨	▨		.20	
											Grand Total	

Table F-13. Computation of H_2 cost using nuclear-thermochemical ($\$/10^6$ Btu)

Factors	1/m	I_{nr}	O_{nr}	H_{nr}	$1/E_{nr}$	I_{tc}	O_{tc}	$1/E_{tc}$	1/L			
Base Values	1/20	7.5	.10	.25	1/.80	5.70	.60	1/.30	1/.75	X	Base	New Cost
① GD_{nr}			▨	▨	▨	▨	▨				1.67	
② GCC_{nr}	▨		▨	▨	▨	▨	▨				2.33	
③ GO_{nr}	▨	▨		▨	▨	▨	▨		▨		.33	
④ GF_{nr}	▨	▨	▨			▨	▨		▨		1.04	
⑤ GD_{tc}		▨	▨	▨	▨		▨	▨			.38	
⑥ GCC_{tc}	▨	▨	▨	▨	▨		▨	▨			.53	
⑦ GO_{tc}	▨	▨	▨	▨	▨	▨		▨	▨		.60	
											Grand Total	

Table F-14. Computation of H_2 cost using photovoltaic-electrolysis ($\$/10^6$ Btu)

Factors	$1/m$	I_{pv}	O_{pv}	I_{el}	O_{el}	$1/E_{el}$	$1/L$			
Base Values	1/20	35.00	.30	1.80	.20	1/.80	1/.35	X	Base	New Cost
① GD_{pv}			▨	▨	▨				6.25	
② GCC_{pv}	▨		▨	▨	▨				8.72	
③ GO_{pv}	▨	▨		▨	▨		▨		.38	
④ GD_{el}		▨	▨		▨	▨			.27	
⑤ GCC_{el}	▨	▨	▨		▨	▨			.36	
⑥ GO_{el}	▨	▨	▨	▨		▨	▨		.20	
Grand Total										

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APPENDIX G

CRYOGENIC STORAGE

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I. INTRODUCTION

A major category of any large-scale liquid hydrogen production plant or large distribution center is storage of the liquid cryogen. In the following text, an attempt has been made to (1) discuss the different types of storage techniques available; (2) point out examples of their use; (3) assess their present as well as future potential for LH_2 storage; and (4) point out areas for further technology development.

The discussion is divided according to the following subject outline:

- I. Aboveground Storage
  - A. Single-Wall Tanks
    - 1. Externally Insulated
    - 2. Internally Insulated
  - B. Double-Wall Tanks (Both Walls Rigid)
    - 1. Purged Perlite
    - 2. Evacuated, Perlite
    - 3. Evacuated, Multilayer Insulation
  - C. Double-Wall Tanks (One Flexible Wall)
    - 1. Evacuated, Hollow Glass Spheres
- II. Underground Storage
  - A. Frozen in Ground or Mined Cavern
  - B. Prestressed Concrete

The majority of the text is devoted to aboveground storage. This is because underground storage units have not proven very successful from a heat-leak standpoint in recent years. Several examples of abandoned constructions are given in the section on underground storage.

Another major question with large storage vessels is that of safety, in the event of a failure. In such a case the two main considerations are restriction of pool diameter and downwind dispersion of the boil-off gases. Dikes and secondary retaining walls can be used to restrict pool diameter. Dispersion of vapors from the top of an aboveground storage container provides a higher degree of safety against ground level dispersion of hazardous concentrations of vapor than discharge from an underground storage vessel.

For some of the storage techniques discussed, construction cost figures are given and their source noted. Some estimates that were made in previous years have been scaled up to 1975 dollars. For lack of a better scaling parameter, the following ratio was used:

$$\begin{bmatrix}\text{Estimated Cost}\\ \text{In Previous Year}\end{bmatrix} \times \begin{bmatrix}\dfrac{\text{Gross National Product in Current Dollars for 1975}}{\text{Gross National Product in Constant Dollars for 1975}}\end{bmatrix} = \begin{bmatrix}\text{Estimated Cost}\\ \text{in 1975}\end{bmatrix}$$

If an original estimate was made in year "x" then that year was considered as the base year for construction of the multiplier. The data to construct the multiplier was taken from "Statistical Abstract of the United States," 1974 edition.

II. ABOVEGROUND STORAGE

A. Single Wall Tanks

1. Externally Insulated. This technique of insulated storage is well within the present state of the art for small scale tankage and lines used with the "shallow" cryogenics (e. g. NH_3, LNG). As pointed out by Hallet, 1968, board-type or sprayed-on foam can be employed as the insulating material for commercial applications. This technique has also been used for LH_2 tankage (albeit for small test tankage under relatively controlled conditions) as pointed out by Sumner, 1969. A schematic representation of a possible large scale application is shown in Fig. G-1. Proper design work, using existing mechanical property data, could result in large scale storage containers for LH_2. Special attention must be given to the metal tank wall, as it must be leak-tight and also serve as the pressure boundary of the system.

A major component of this insulation system is the vapor/vacuum barrier on the insulation exterior. Fabrication of this barrier can be accomplished using "off-the-shelf" fabrics or films (Steeves) but the lifetime of such a barrier, especially when exposed to the elements, is an area for further testing. Permeability, or leak tightness of this barrier is necessary to prevent formation of frozen/liquid air within the insulation. Once such condensation starts, the insulation, in addition to allowing a greater passage of heat, can become a container for an explosive mixture if H_2 leakage from the metal storage container becomes mixed with the condensed air.

At present, this technique of construction, for deep cryogenic storage tanks, has not been employed by the major storage vessel manufacturers[1]. Cost data for this type of construction was estimated in 1968 by Hallett. These data have been scaled up to 1975 dollars and the results

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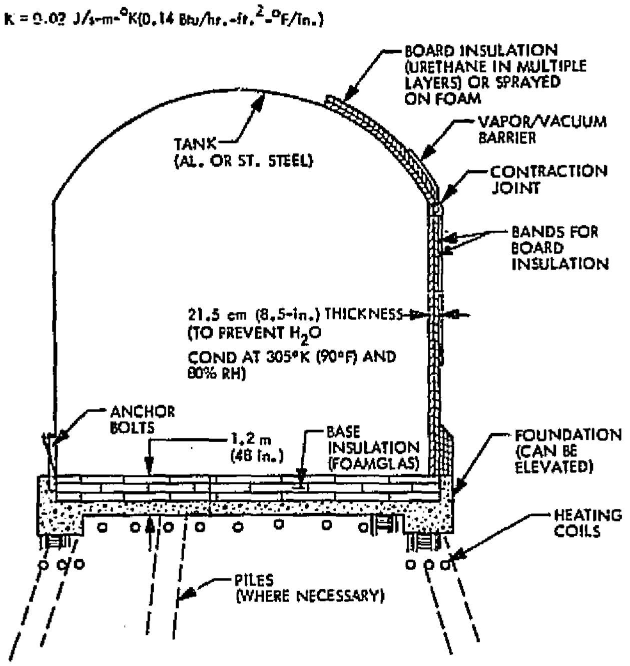
[1] Chicago Bridge and Iron, Oak Brook, IL; Pittsburgh Des Moines Steel Co., Pittsburgh, PA; Graver Tank and Manufacturing Co., El Monte, CA; and Preload Technology Inc., Garden City, N. Y.



(FROM HALLET, 1968)

Fig. G-1. Single-Wall Externally Insulated Tank

shown in Table G-1. Technology work which could be accomplished to provide a better basis for using this storage scheme would be:

(1) an experimental effort to determine air permeability, sealing techniques, abrasive resistance, and weather aging data for some of the most current metalized ripstop fabrics.

(2) to specify techniques for nondestructive leak testing of large scale metal structures to be used for LH_2 storage.

2. Internally Insulated. This type of storage vessel (approximated in Figure G-2) was tried for LNG service in recent years. The most single critical feature is the liquid seal membrane on the inner surface of the insulation. A 72×10^3 m^3 (600,000-barrel) unit (18.9×10^6 gal) was fabricated on Staten Island, New York. The outer walls, floor, and roof were concrete. Polyurethane foam blocks were mounted on the inner walls of the structure and were sealed with a liquid/vapor barrier of aluminized mylar. The barrier was then covered by a second coating of polyurethane insulation. (Additional specifics of the construction probably could be obtained from Texas Eastern Gas Transmission Corp. for whom the tank was built). When the container was put into operation, the vapor barrier did not function as anticipated. The heat flow into the vessel was high and some external leakage of methane was observed. The tank was drained and an attempt was made to repair the vapor barrier. During repair, an industrial accident occurred (Feb. '73). An intense fire, fueled by the urethane insulation resulted in overpressurization of the dome and its subsequent collapse. Forty three men were lost (Latshaw).

Table G-1. Cost of Externally Insulated Single-Wall Tanks

Proposed Quantity of LH_2 Stored	Estimated Cost of Construction: Quantity of LH_2 Stored (1968$)	Estimated Cost of Construction: Quantity of LH_2 Stored (1975$)
3.86×10^3 m^3 (1.02×10^6 gal)	\$140/m^3 (\$0.53/gal)	\$190/m^3 (\$0.72/gal)
11.6×10^3 m^3 (3.06×10^6 gal)	\$82/m^3 (\$0.31/gal)	\$111/m^3 (\$0.42/gal)
23.2×10^3 m^3 (6.12×10^6 gal)	\$66/m^3 (\$0.25/gal)	\$90/m^3 (\$0.34/gal)
46.2×10^3 m^3 (12.2×10^6 gal)	\$58/m^3 (\$0.22/gal)	\$79/m^3 (\$0.30/gal)

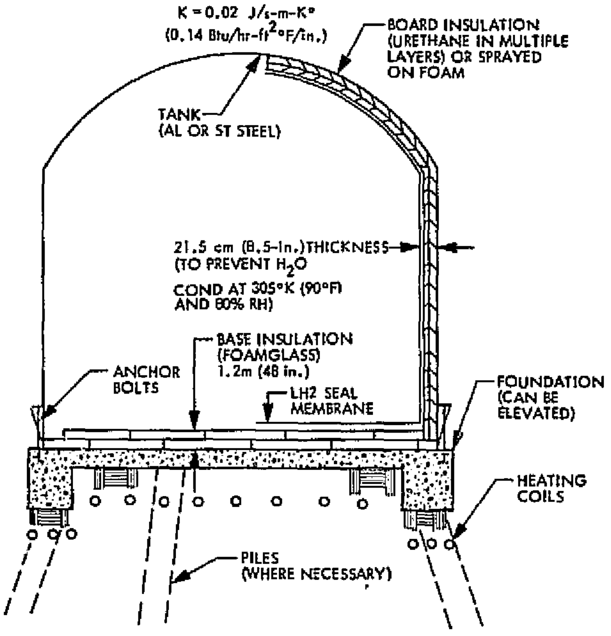


Fig. G-2. Single-Wall Internally Insulated Tank

To prevent such disasters in the future, NASA, through KSC, and in conjunction with Boeing and IBM, is supervising safety studies on large scale LNG operation. A risk management plan is presently being compiled for large-scale shipment and storage of LNG for New York City.

For the deep cryogenics (e.g. LH_2) internal tank insulation has been used on the inside surface of the SIVB stage LH_2 tank. The insulation was composed of thread-reinforced foam blocks which were edge interlocked with each other when they were adhesively bonded to the inner wall of the tank. A polyurethane resin spray coating was applied to the insulation surface to serve as a liquid barrier against hydrogen. Even though this system worked satisfactorily, it was an aerospace application - subject to all the care and craftmanship that usually is expended with one-of-a-kind spaceflight hardware. The consistency of materials and the quality control for this job would be difficult to predict from a cost standpoint if such a system was employed for large-scale LH_2 storage tank insulation.

Another internal tank insulation system for LH_2 tankage was recently developed by Martin Marietta Corp. (Gille, 1973). This system was based on using surface tension or capillary forces to position a layer of hydrogen vapor in a cellular structure between the LH_2 and the tank wall. The installation used silicone adhesives, Kapton and Teflon films, and fiberglass batting filler within the cellular structure. Methods and tooling for insulation panel fabrication, as well as an approach for the installation of the panels in a complete tank, were satisfactorily developed. Boil-off measurements during the first test with LH_2 showed that the thermal conductivity was approximately 0.132 J/s-m°K (0.076 Btu/hr-ft-°R). The thermal performance of the installation showed degradation after pressure-temperature cycling of the tank. Post-test evaluation, however, showed this was the result of a design inadequacy which could be overcome by a material change. Even though this insulation system falls into "aerospace hardware" it could be developed to the point where it would be useable in large LH_2 storage vessels. Additional work toward developing the capillary internal insulation concept for other applications has been conducted on Contract NAS8-25974 and on the following programs:

(1) Contract NAS8-21130, "Development of Advanced Materials for Integrated Tank Insulation System for the Long-Term Storage of Cryogens in Space;"

(2) Contract NAS3-12425, "Insulation Systems for Liquid Methane Fuel Tanks for Supersonic Cruise Aircraft;" and

(3) Martin Marietta Corporation internal program to develop an insulation system for storing and transporting liquified natural gas.

A survey of the four major cryogenic storage vessel fabricators revealed that none is presently considering this type of insulation system for use in a saleable product. The consensus of opinion is that the integrity of linear materials is not state of the art for large scale vessels. However, cost data for this type of construction were estimated in 1968 (Hallet, 1968) and has been scaled up to 1975 dollars. These data, shown in Table G-2, are not considered accurate on an absolute basis - only relative numbers comparable to scaled values previously shown for externally insulated tanks.

Table G-2. Cost of Internally Insulated Single-Wall Tanks

Proposed Quantity of LH_2 Stored	Estimated Cost of Construction	
	Quantity of LH_2 Stored (1968$)	Quantity of LH_2 Stored (1975$)
$3.86 \times 10^3 m^3$ (1.02×10^6 gal)	\$148/m^3 (\$0.56/gal)	\$201/m^3 (\$0.76/gal)
$11.6 \times 10^3 m^3$ (3.06×10^6 gal)	\$90/m^3 (\$0.34/gal)	\$122/m^3 (\$0.46/gal)
$23.2 \times 10^3 m^3$ (6.12×10^6 gal)	\$74/m^3 (\$0.28/gal)	\$100/m^3 (\$0.38/gal)
$46.8 \times 10^3 m^3$ (12.2×10^6 gal)	\$66/m^3 (\$0.25/gal)	\$90/m^3 (\$0.34/gal)

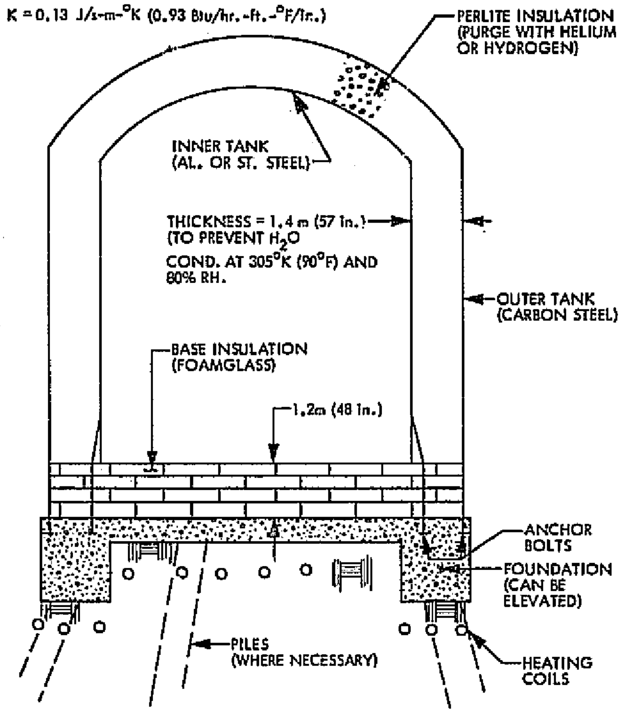
Technology work which must be accomplished to provide a better basis for using this storage scheme would be:

- at LH_2 temperature determine hydrogen permeability, cracking resistance, aging characteristics, and mechanical property data for some of the most current laminates and specially processed biaxial flex metal membranes
- techniques of field fabrication, and leak tightness, of large scale liner assemblies
- detailed design and costing information for application of the S-IVB and Martin schemes to large scale LH_2 storage containers

B. Double-Tall Tanks (Both Walls Rigid)

1. Purged Perlite. This technique, shown schematically in Fig. G-3, is in general use today though not with the deep cryogenics such as LH_2. This type of storage scheme is employed only with LOX, LN_2, and the more shallow cryogenics such as LNG due mainly to the thickness of insulation required for lower temperature fluids. If this system were used in the future for storing LH_2, the purge gas would have to be GH_2 or GHE. However, the only major requirement for a purge gas is that it be noncondensible (and of course nonreacting) at the stored temperature of the liquid cryogen (e.g. LNG tanks use boiled-off liquid as a purge and LOX tanks use GN_2).

As a single example of such construction, the Graver Tank and Mfg. Co. has constructed $530 m^3$ (140,000 gal) and $2461 m^3$ (650,000 gal) spherical LOX storage vessels in the past (Hothan). Both walls of these vessels were metal and each of the storage vessels had a 1.2m (4-ft) insulation annulus which was purged with dry N_2 gas. The present limit on size of these double-metal wall storage vessels is thought to be only structural. For example, the quality control of metal plate, as well as welding for closures,



(FROM HALLET, 1966)

Fig. G-3. Double-Wall Purged Perlite Insulation

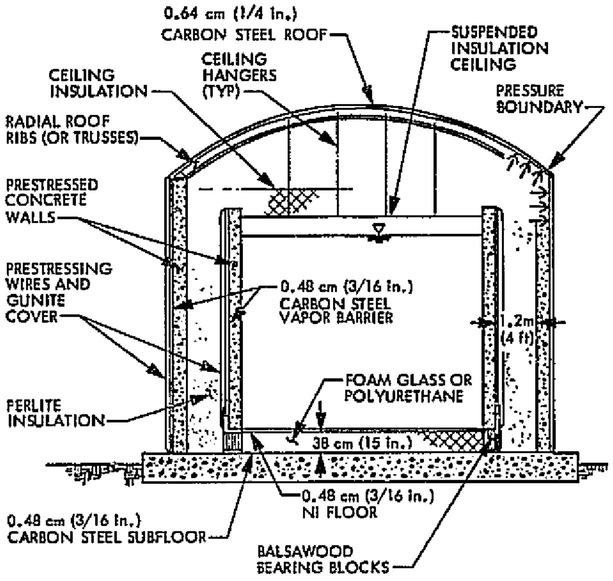


Fig. G-4. Double-Wall Prestressed Concrete Tank for the Storage of LNG Typical Cross Section (Not to Scale)

becomes somewhat questionable for thickness greater than 5.1 cm (2 in.). In addition, the storage-vessel shape becomes more difficult to maintain simply because of the weight of construction materials involved. A third consideration is that, granted present day construction methods, there exists a practical design maximum for the insulation annulus of approximately 1.5m (5 ft) (Martz). Beyond this value the cost/size of the storage unit has a much steeper slope. When any of these "limits" are reached it is felt that pressure-stabilized structures would have to be introduced if the construction geometry remained spherical. The only other alternative, for larger storage vessels, would be ones of cylindrical design. Considering only spherical units (which have the most contained volume for a given surface area) an "off the top of the head" upper limit diameter figure is approximately 24m (80 ft). This computes to a stored volume of approximately 8 x 10^3 m^3 (2 x 10^6 gal) (Hothan).

Another example of this storage technique is used by Preload Technology Inc., which deals in prestressed concrete structures. Considerable headway has been made in recent years with cylindrical tanks. The general construction method, along with some specific notes, is shown in Fig. G-4 (Legatos). As can be seen, at least for this LNG application, the insulation purge gas is boil-off from the main pool of stored liquid. Preload Technology Inc. has constructed LNG storage units[2] as large as 108 x 10^3 m^3 (900,000 barrels) (28.4 x 10^6 gal) and feel that they can project their construction technique to LNG units as large as 143 x 10^3 m^3 (1.2 x 10^6 barrels) (37.8 x 10^6 gal). Further, the walls of these structures can be made as thick as desired, with good quality control, to withstand high external impact loads which could result because of accidents (e.g., impact by an airliner).

At present, Preload Technology has not given much design consideration for prestressed concrete storage units for LH_2. Their feeling is that a need exists for design information, at LH_2 temperature, regarding (a) mechanical properties of concrete and (b) the development of large-scale lighter weight vapor barriers.

Cost data for the double-metal-wall purged perlite insulation system, for use with LH_2 storage vessels, was estimated in 1968 by Hallet, and has been scaled up to 1975 dollars. The data appear in Table G-3. Also, a rough estimate, obtained from W. E. Latshaw, is shown for LN_2 and LOX storage vessels. Finally, Preload Technology has furnished a rough estimate for prestressed concrete storage vessels used for LNG.

Technology work which would lead to more understanding of this promising storage technique can be summarized, generally, as follows:

(1) a study to determine construction limitations for large scale spherical cryogenic containers

(2) determination of the mechanical properties of concrete at LH_2 temperature

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[2] Located in New York City metropolitan area; completed in 1974; Distrigas Corp., owner.

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Table G-3. Cost of Purged Perlite Insulated Double Wall Vessels

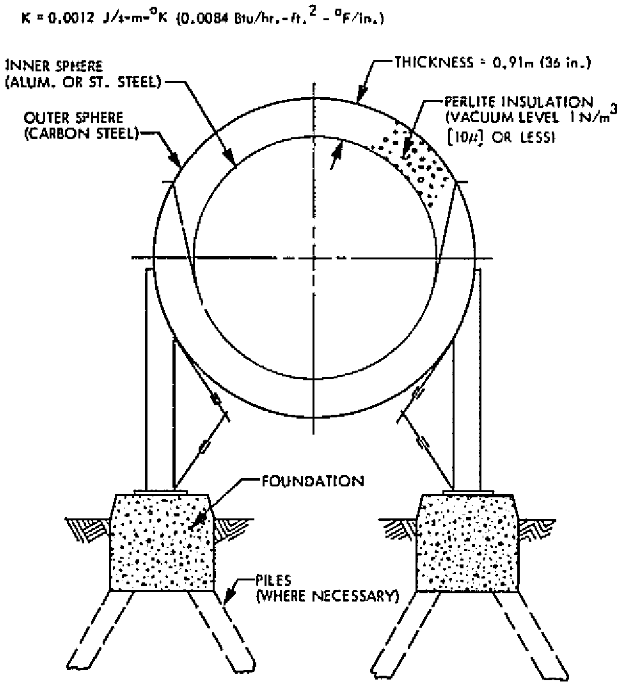
Proposed Quantity of LH_2 Stored	Estimated Cost of Construction		Purged Jacket Storage for LOX and LN_2 (Latshaw)	Purged Jacket Storage for LNG (Legatos)
	Quantity of LH_2 Stored (1968$) (Hallet, 1968)	Quantity of LH_2 Stored (1975$)		
$3.86 \times 10^3 m^3$ $(1.02 \times 10^6$ gal)	$174/$m^3$ ($0.66/gal)	$238/$m^3$ ($0.90/gal)	($291-330/$m^3$ $1.10 to $1.25 per gal)	$100/$m^3$ ($0.38/gal)
$11.6 \times 10^3 m^3$ $(3.06 \times 10^6$ gal)	$103/$m^3$ ($0.39/gal)	$140/$m^3$ ($0.53/gal)		
$23.2 \times 10^3 m^3$ $(6.12 \times 10^6$ gal)	$85/$m^3$ ($0.32/gal)	$116/$m^3$ ($0.44/gal)		
$46.8 \times 10^3 m^3$ $(12.2 \times 10^6$ gal)	$77/$m^3$ ($0.29/gal)	$103/$m^3$ ($0.39/gal)		

(3) the development of large scale lighter weight vapor barriers useable at LH_2 temperature

(4) exploration of a double wall tank design which could employ boil-off gas from the bulk propellant to intercept some of the ambient heat leak

2. Evacuated Perlite. This storage system, shown in Fig. G-5, represents the "best practice" state of the art for LH_2 vessels. Prestressed concrete vessels have little application here unless the concrete can be sealed against the vacuum. This is not "state of the art" at present so this storage technique is generally restricted to metal tank fabrication. The three largest metal vessel fabricators[3] have constructed units that are in field operation today. Among the examples are two 3218m^3 (850,000-gal) spheres (by CBI) located at Cape Kennedy; a 3786m^3 (100,000-gal) cylinder (by Pittsburgh Des Moines) in Mississippi; and several large dewars (by Graver) at the U.S. Government test area in Jackass Flats, Nevada.

The construction used for these tanks varies slightly between companies. Either aluminum or stainless is used for the inner liquid container, carbon steel for the outer vacuum jacket, and vacuum levels between 1 and 7 N/m^3 (10 and 50μ) in the insulation annulus. As can be seen in Fig. G-5, the insulation thickness as well as the effective thermal conductivity are reduced considerably compared to the purged perlite storage technique. Evacuated storage, however, is more limited from a size standpoint than the purged system. The outer shell of the vessel must carry an additional load because of the vacuum in the annulus. This extra loading generally dictates the maximum size of construction. Also, these tanks are subject to the other limitations pointed out in the Purged Perlite section. An "off-the-top-of-the head" upper limit diameter figure, for spherical dewars, is approximately 15m (50 ft) (Latshaw). This computes to a stored volume of approximately 2612 m^3 (690,000 gal). For storage units larger than this rough number, heavily reinforced cylindrical tanks would have to be considered.



(FROM HALLET, 1968)

Fig. G-5. Double-Wall Evacuated Perlite Storage System

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[3] Chicago Bridge and Iron Co., Pittsburgh Des Moines Steel Co., and Graver Tank and Manufacturing Co.

Note that this storage technique is dependent on the vacuum integrity of both inner and outer vessel walls. In the case of small leaks through the outer wall, this storage scheme is still safe since its effectiveness would tend to degrade more slowly because the perlite insulation would still remain. The storage vessel could then be drained and repairs accomplished. However, it seems to this author that stringent safety measures would have to be imposed to prevent any high-energy impact loading on the outer shell, which would jeopardize the vacuum annulus. Since most of the tanks now using this insulation system are for aerospace applications, the subject of their complete external protection has most probably not been explored to the degree necessary for large-scale commercial application.

Cost data for the double-metal wall evacuated perlite insulation system was estimated in 1968 by Hallet, and has been scaled up to 1975 dollars. These numbers are shown in Table G-4. Also shown are rough estimates for (a) the 3218 m^3 (850,000-gal) containers built by CBI for LH_2 storage and (b) the cost for LN_2 and LOX storage vessels per Pittsburgh Des Moines Co.

Technology work which would lead to improvement of this storage technique can be summarized generally as:

- a study to determine construction limitations for large scale spherical vacuum jacketed cryogenic containers
- determination of techniques for nondestructive leak-testing of large vessels in the field
- contracting for a study to determine the potential use of prestressed concrete employed as a load-bearing wall for vacuum-jacketed vessels
- experimental evaluation of insulation materials other than perlite for their thermal barrier effectiveness, degradation characteristics in case of air leakage, difficulty in refurbishment of the insulation after air contamination, any aging characteristics due to "settling", and dependency of insulation performance as a function of the quality control exercised during installation.

3. Evacuated Multilayer Insulation (MLI) Blankets. This insulated storage scheme is pictured ideally in Fig. G-6 as a large in situ storage system for LH_2. In actual practice, however, it (a) represents the "best practice" state of the art for transportable LH_2 tanks (e.g. up to 132 m^3 (35,000-gal) railroad dewars) and (b) heat shielding for space vehicle fuel tanks. As in the previous section, prestressed concrete vessels have even less application here because the vacuum level required for this insulation is much lower than in the evacuated perlite case. Further this author could find no evidence of work done by the major storage vessel manufacturers with regard to using this insulation scheme in a large-scale marketable product.

It is felt that, using this insulation system, storage units could be built which, size-wise, would be somewhere between the maximum "purged perlite" and "evacuated perlite" cases. The annular vacuum jacket for the MLI can be reduced considerably (to approximately a 0.61m (2-ft) minimum to allow personnel access between the tank walls) and hence would allow construction of tanks larger than the evacuated perlite case. However, the outer shell of the vessel must still carry the atmospheric pressure load so fabrications as large as the "purged perlite" case are doubtful.

An MLI insulation system has recently been actively pursued with regard to aerospace applications (Contract NAS3-15848, Barclay, et all). The program objective was to develop an evacuated MLI system which combined maximum thermal performance with minimum weight. The experimental work employed a tank approximately 2.3m (7.5 ft) in diameter. A test program to evaluate the thermal performance of the system

Table G-4. Cost of Evacuated Perlite Insulated Double-Wall Vessels

Proposed Quantity of LH_2 Stored	Estimated Cost of Construction		3217 m^3 LH_2 850,000 Gal. LH_2 Unit by CBI (Martz)	Vacuum Jacket Vessel Storage for LN_2 and LOX (Latshaw)
	Quantity of LH_2 Stored (1968\$) (Hallet, 1968)	Quantity of LH_2 Stored (1975\$)		
3.86×10^3 m^3 (1.02×10^6 gal)	\$193/m^3 (\$0.73/gal)	\$262/m^3 (\$0.99/gal)	\$1009/m^3 (\$3.82/gal)	528/m^3 (≈\$2.00/gal)
11.6×10^3 m^3 (3.06×10^6 gal)	\$172/m^3 (\$0.65/gal)	\$232/m^3 (\$0.88/gal)		
23.2×10^3 m^3 (6.12×10^6 gal)	\$161/m^3 (\$0.61/gal)	\$219/m^3 (\$0.83/gal)		
46.8×10^3 m^3 (12.2×10^6 gal)	\$156/m^3 (\$0.59/gal)	\$211/m^3 (\$0.80/gal)		

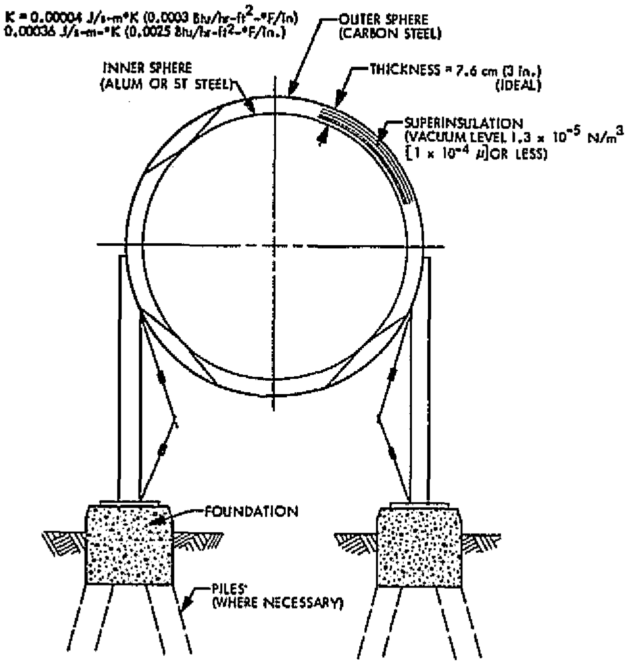

Fig. G-6. Double-Wall Evacuated Super-Insulation Storage System

was planned but did not commence because of the vacuum jacket failure during vacuum annulus preconditioning. The program results, however, showed that lightweight, high vacuum jackets are within the scope of present-day design and fabrication technology. No further experimental work is anticipated on this contract effort. It should be pointed out that the work accomplished could serve as a sound basis for further contracted study directed at large-scale ground-type storage systems.

It should be noted that this storage technique is the <u>most</u> dependent on the vacuum integrity of both inner and outer vessel walls. In the case of leaks through the walls, the insulation effectiveness would deteriorate rapidly causing high propellant evaporation rates. Large vent capability would be a necessary part of the construction specifications. In addition, the requirement to prevent any high-energy impact loading on the outer shell, which would jeopardize the vacuum annulus, is also present.

From a thermal insulation effectiveness standpoint, the MLI system is by far the best; however, severe design and construction problems still remain to be resolved before large scale <u>in situ</u> commercial storage applications can become a reality.

Cost data for this insulation system were not available from any of the major storage vessel manufacturers.

Technology work which should be pursued in further development of this storage technique can be summarized as:

(1) a follow-on effort, using Contract NAS3-15848 as a base, to study large-scale storage tank application of this system and obtain realistic pricing information

(2) determination of techniques for non-destructive leak testing of large vessels in the field

(3) contracting for a study to determine the potential use of prestressed concrete employed as a load-bearing wall for vacuum jacketed vessels.

C. <u>Double-Wall Tanks (One Flexible Wall)</u>

1. <u>Evacuated Hollow Glass Spheres</u>. An insulation study contract has recently been let from Lewis Research Center (LeRC) with the objective of providing necessary technology advancements required to demonstrate the practicality and design characteristics of a microsphere insulation/flexible metal vacuum jacket system for LH_2 and LOX tank application. This technique is directed at making the insulation system capable of withstanding atmospheric loads and making the protective outer jacket lightweight and flexible so that it transfers the load to the insulation system and ultimately to the inner tank.[4]

Assuming that this experimental work demonstrates the practicality of the insulation scheme, the results could be applied to large scale LH_2 or LNG storage tankage. Figure G-7 is such a system. The outer storage vessel wall is constructed of prestressed concrete. The inner vessel wall is a flexible membrane which is liquid and vapor tight. It would be sealed to the outer concrete wall and thereby form an enclosed volume which would contain aluminized glass microspheres in a carbon dioxide atmosphere. As the cryogenic liquid is loaded into the inner tank the pressure in the insulation annulus is reduced by cryopumping (i.e. the carbon dioxide liquifies and/or freezes). The weight of the cryogenic in the inner vessel is then directly transferred through

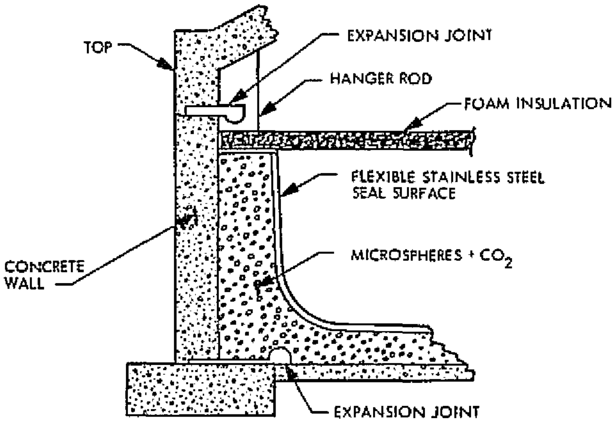

Fig. G-7. LNG Storage Tank (a Concept Using Microsphere Insulation)

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[4] Further details available under Contract NAS3-17817 directed from LeRC; J. R. Barber, program monitor.

the microspheres to the outer load bearing wall of the structure.

This storage technique promises to be more rugged and at least as practical as the evacuated perlite system, with the added benefit of having an insulation packing of much greater durability. This effort should be brought to the attention of the major storage vessel fabricators in order to obtain from them a commercial evaluation of possible construction difficulties and costs involved if this insulation system were employed in large-scale products.

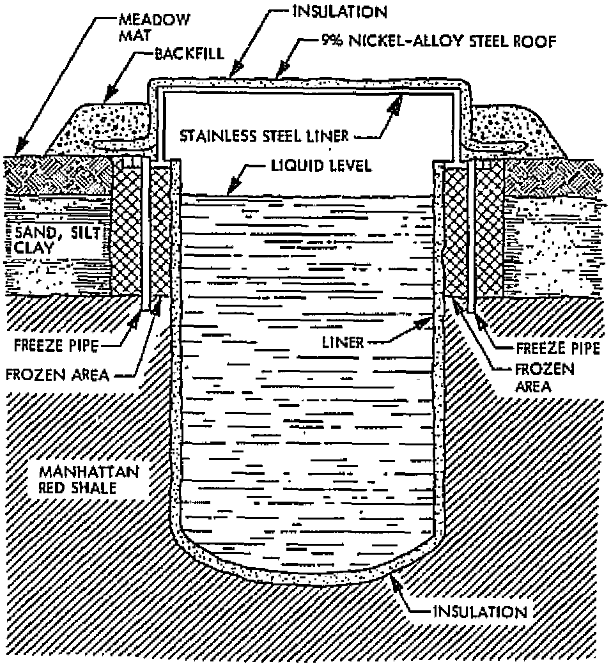
II. UNDERGROUND STORAGE

A. Frozen In-Ground Storage

Mined-Cavern Storage

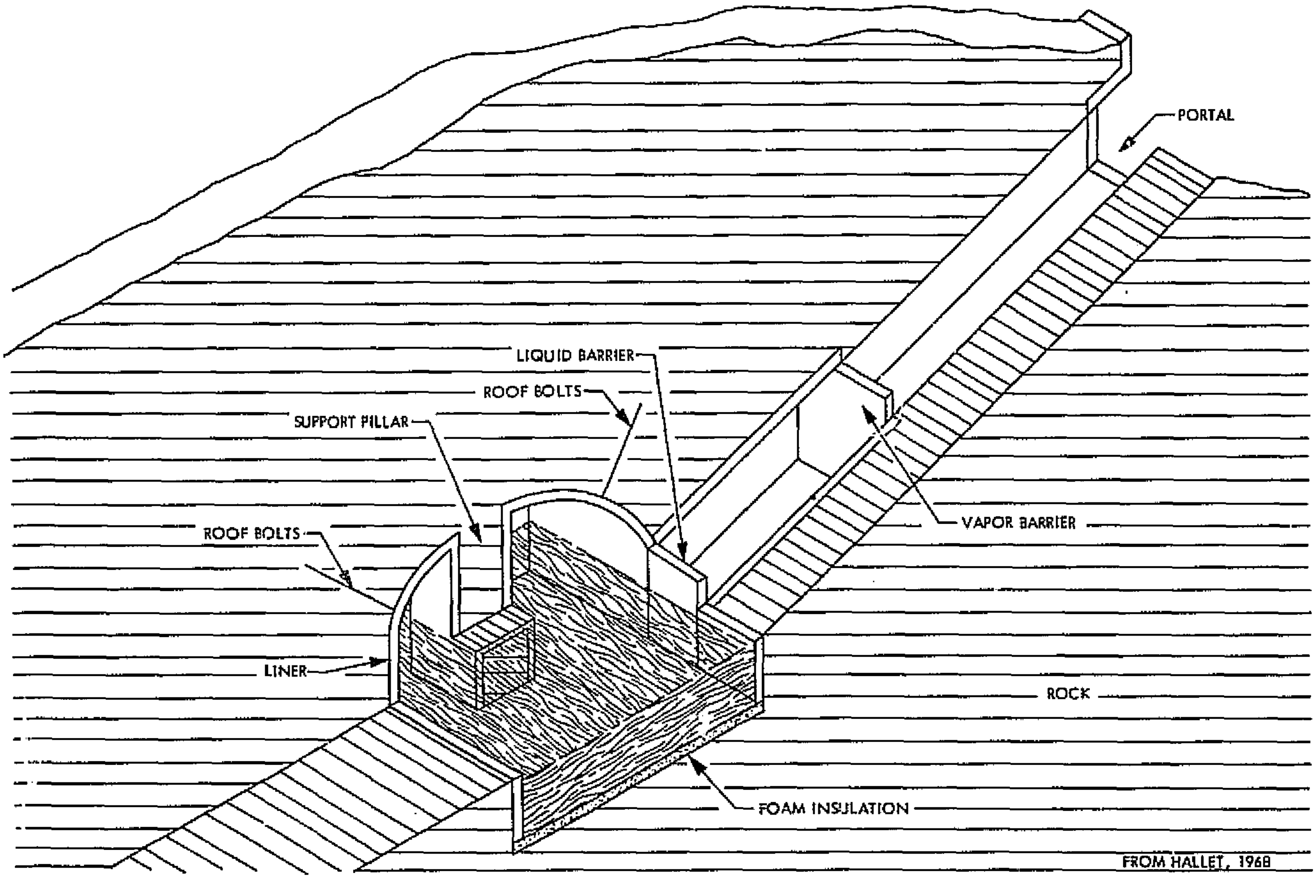
Both of these techniques, pictured schematically in Figs. G-8 and -9, may be treated simultaneously. Several below-ground storage installations for LNG have been attempted in recent years with generally poor results.

In 1963 Preload Technology Corp. designed and constructed a prestressed concrete wall for Transcontinental Gas Pipeline Corp. at Carlstadt, New Jersey. The wall, 36m (117-ft) in diameter and 5m (17-ft) high, was to provide the transitional element between frozen ground and the roof system



(FROM HALLET, 1968)

Fig. G-8. Frozen In-Ground Storage



FROM HALLET, 1968

Fig. G-9. Mined Cavern Storage

of a 35.8 x 10^3 m^3 (300,000-barrel) in-ground storage container. This facility was abandoned when boil-off rates considerably exceeded design expectations (Latshaw and Legatos).

Another underground storage unit was tried in Hopkinton, Mass. The walls of the cavity were solid granite. This construction, along with other in-ground storage units on the eastern seaboard, was abandoned in favor of above-ground storage because of high heat leaks.

In light of this past experience with the shallow cryogenic LNG, it seems highly unlikely that any effort should be made in these categories for a deep cryogenic such as LH_2.

B. Prestressed Concrete Storage Systems

Concrete storage vessels were discussed in the section "Double Wall Tanks, Purged Perlite." Figures G-10 and -11, taken from Hallet, are schematic representations of possible externally and internally insulated storage vessels. Large size tanks can be constructed underground at an increased cost. Considerations must be made for extra excavation, soil treatment, extra heating for the soil around the sidewalls of the vessel, etc. A rough cost estimate, for LNG storage, of approximately \$166/m^3 (\$0.63/gal) was obtained from Preload Technology. No estimates were available for LH_2 storage systems.

Approaches should be made to the metal storage tank manufacturers in order to obtain from them a commercial evaluation of construction difficulties and costs involved if their units were employed underground.

OTHER AREAS AND TOPICS FOR FUTURE WORK

1. Addition of "Illuminant" to make H_2 flame visible (makes for safer disposal operations and for operations within private residences)
2. Techniques for handling slush with hydrogen pressurant
3. Honeycomb antislosh baffles (for trucks, railroad cars, boats)
4. Ullage liquid-vapor screen separator
5. Establish better specifications for transfer equipment (i.e., thermal performance, structural integrity, functional requirements, and safety standards)
6. Development of low heat-leak insulation, piping and support devices to minimize pressure rise and boil-off
7. Investigate new manufacturing techniques to permit mass production and reduced cost of vessels
8. Evaluate existing methods to determine suitability of existing control devices, contents measuring, metering, pumps, disposal, and recovery methods

CITED REFERENCES

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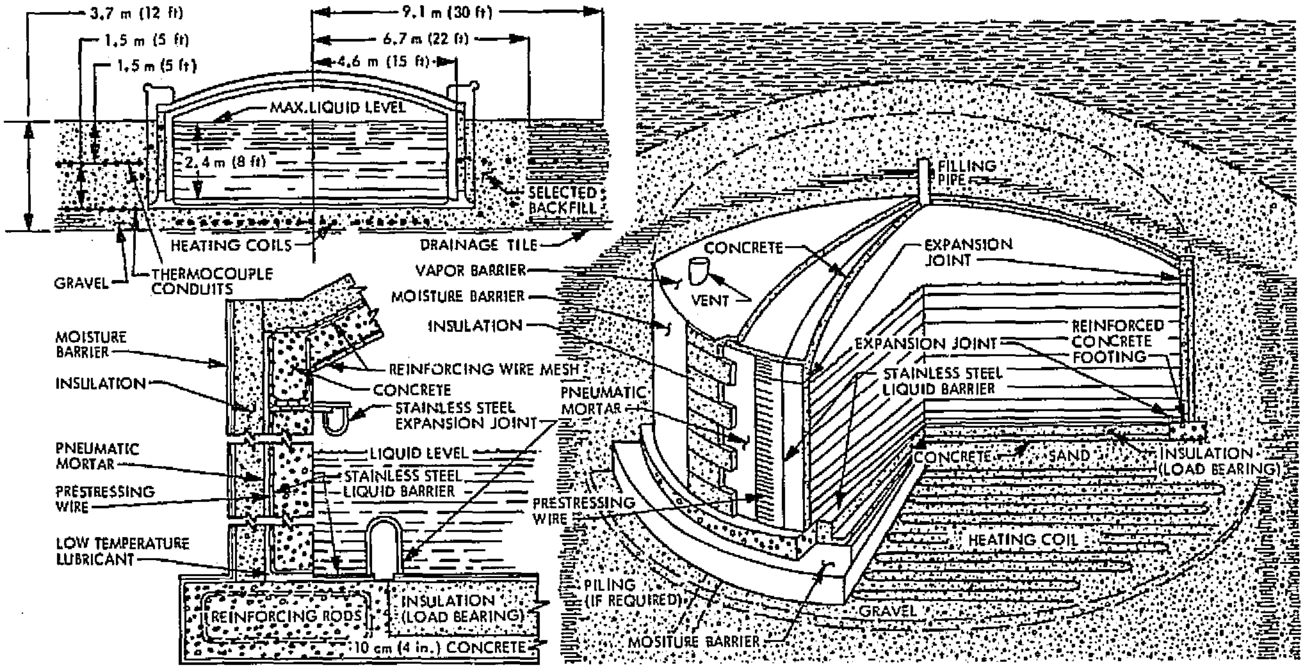

(FROM HALLET, 1968)

Fig. G-10. Externally Insulated Prestressed Concrete Tanks

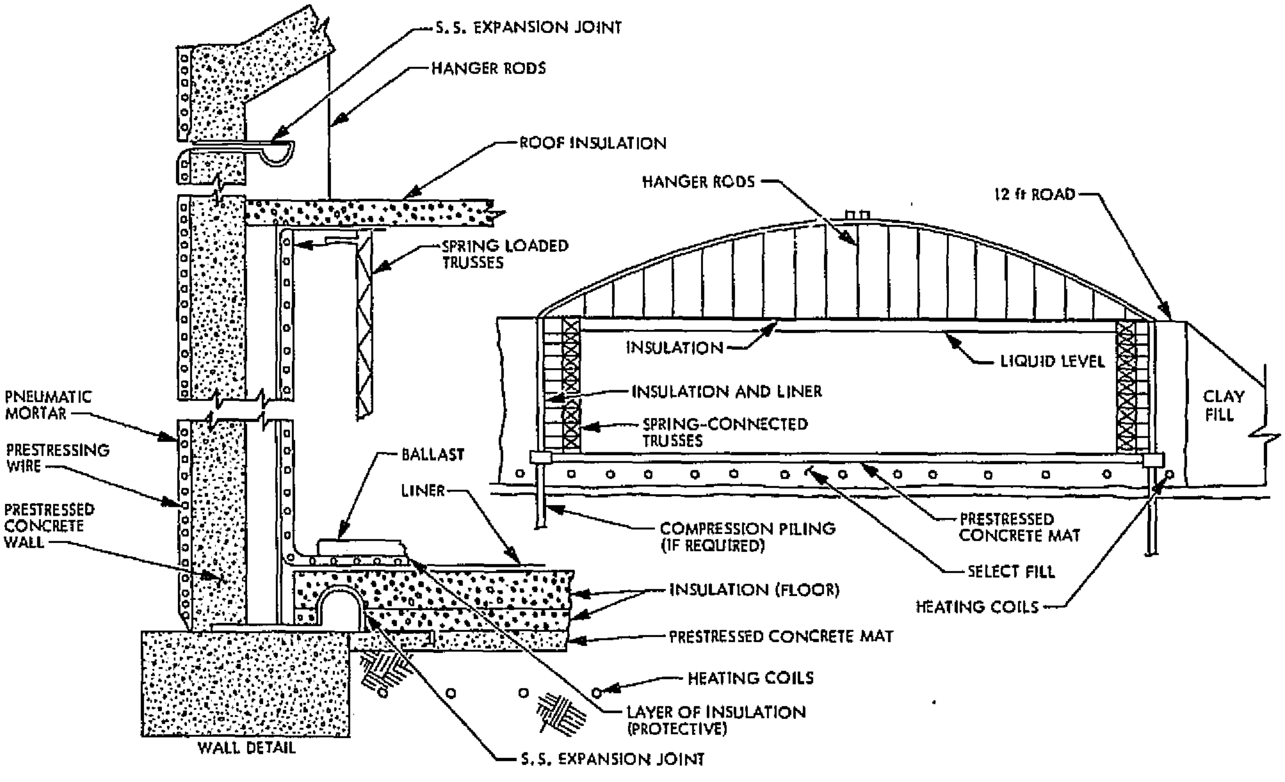

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Fig. G-11. Internally Insulated Prestressed Concrete Tanks

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APPENDIX H

MATERIALS CONSIDERATIONS

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I. INTRODUCTION

The purpose of this materials subtask is to identify potential materials problems that may be encountered within the three components of a hydrogen energy system—production, transmission/storage, and utilization. Many of the current and future hydrogen production processes involve chemical or thermochemical reactions that occur at elevated temperatures and pressures in a variety of aggressive environments. Such conditions may severely degrade the mechanical properties of structural alloys, influence system reliability, and increase maintenance costs. Since the specific operating conditions of many proposed hydrogen production processes have not yet been defined, this study program will focus on general material compatibility problems that will be encountered during hydrogen production, such as: hydrogen embrittlement, corrosion, oxidation, and erosion (Fig. H-1).

Regardless of which hydrogen production processes eventually prove economically feasible, transmission and storage of hydrogen will always be required in a hydrogen energy system to link hydrogen production with utilization. Potential problems of hydrogen embrittlement will be considered in some detail. The types of hydrogen embrittlement and their occurrence throughout a hydrogen energy system will be identified.

Specific materials research and development programs necessary to support a hydrogen energy system will be identified and prioritized. An awareness of a probable shortage in strategic materials will be maintained in these research and development recommendations.

II. GENERAL MATERIAL PROBLEMS

A. Interfacing with Process Heat

1. Nuclear. Waste heat or steam generated in boiling or pressurized water reactors is of limited value as process heat for thermochemical reactions because the temperature is only a few hundred degrees Kelvin (Celsius). With present designs of high-temperatures of 1023-1123°K (750-850°C) can be reached. In advanced designs, a temperature of 1273°K (1000°C) in the primary coolant may be realized. Temperature reached in breeder and fusion reactors will be as high, or higher.

The primary coolants considered for advanced reactor systems include helium and carbon dioxide gases, liquid lithium and sodium, and fused salts. Depending on the type of reactor and the coolant used, there will be large or small amounts of radioactive fission products in the coolant. The radioactive material may be either suspended solids, gases, or elements dissolved in liquid coolants. Of particular

PRODUCTION

HYDROGEN SOURCE

GAS
OIL
COAL
WATER

PROCESS HEAT

COAL
NUCLEAR
SOLAR
GEOTHERMAL

PRODUCTION TECHNIQUE

STEAM REFORMING
PARTIAL OXIDATION
THERMOCHEM. SPLIT
ELECTROLYSIS
COAL GASIFICATION
DIRECT WATER SPLIT

MATERIALS PROBLEMS

HYDROGEN EMBRITTLEMENT
TRITIUM PERMEATION
CORROSION
- ACIDS
- HALIDES
- BRINE
- LIQUID METALS
- HEAT TRANSFER FLUIDS AND SALTS

OXIDATION
- CARBURIZATION
- DECARBURIZATION
- SULFIDATION
- NITRIDATION

EROSION
- COAL SLURRIES
- HEAT TRANSFER SLURRIES

TRANSMISSION/STORAGE (GAS, LIQUID OR HYDRIDE) HYDROGEN EMBRITTLEMENT

UTILIZATION (GAS, LIQUID OR HYDRIDE) HYDROGEN EMBRITTLEMENT

Fig. H-1. Potential Materials Problems in Hydrogen Energy System concern is tritium gas because it has a high permeation rate through many structural materials and it may also act as an embrittling agent. The permeation problem in fusion reactor technology is more severe than in other types of reactors; work is in progress at Argonne National Laboratory and other laboratories to measure permeation rates and to develop permeation barriers.

Another problem area is the availability of materials with adequate high-temperature strength and corrosion resistance for the temperatures now projected for advanced systems. It may be necessary to develop new superalloys for these applications.

Because of the risk of materials failures in primary coolant systems, the coolant hardware will be contained within the reactor pressure vessel, and a heat exchanger for removing process heat will be built in. Even with a built-in heat exchanger, there is some concern about tritium permeating into the working fluid system. If it were possible to use the primary coolant directly for process heat instead of using a second working fluid, there would be substantial benefits in overall cost and efficiency.

2. Solar. Solar energy as a source of process heat has merit only if a special collector system is designed to reach high temperatures. In one proposed design of the central receiver type, a large array of mirrors reflects the solar energy into an insulated cavity at the top of a centrally located tower. The energy is absorbed in a heat transfer fluid such as Hitec.[1] An exit temperature of approximately 773°K (500°C) is being considered for generation of electrical power, which is somewhat higher than the recommended maximum operating temperature 723°K (450°C) for Hitec exposed to air. The practical upper limit in this solar energy application will depend upon the rates of salt decomposition. Mild steels have been used successfully for containing Hitec, but stainless steels or other alloys will probably be utilized in the high temperature portions of the system.

If a similar solar collection system is coupled with a thermochemical hydrogen production process, higher exit temperatures will probably be desirable 873-1273°K (600-1000°C). Gases, liquid metals or molten salts might be used as the heat transfer fluid. It is also conceivable that a slurry or solution containing one of the process reactants could be used as the heat transfer fluid. More work is needed to evaluate fluid characteristics and to qualify a structural material for containment. Preliminary studies at Sandia-Livermore indicate that high solar energy collection efficiency can be attained in this temperature range if the materials problems can be solved.

It has been demonstrated that much higher temperatures approximately 4173°K (3900°C) can be obtained in solar furnaces. They have been used for growing crystals of metals with high melting points and extracting moisture from rocks. It is conceivable that such solar furnaces could be used for direct thermal cracking of water, but the material problems are formidable.

3. Geothermal. In most of the geothermal processes in use or under development, the temperature obtainable in process steam or other fluids is 573°K (300°C) or less. An example is the Lawrence Livermore Laboratory program in which hot brine solutions will be used for electrical power generation in the Imperial Valley in California. The corrosion problem in handling the hot brine is very serious; the success of the program depends more on the solution to the material problem than any other factor.

B. Hydrogen Production

1. Thermochemical. Many of the thermochemical cycles being studied at various laboratories involve handling noxious reagents at high temperature and high pressures, particularly salts, acids, and liquid metals. To the best of our knowledge, none of the laboratories in the U. S. investigating thermochemical cycles have supporting programs on containment materials. For the most part, the reactions are being studied in glass and platinum laboratory apparatus. MgO and vitreous carbon crucibles work well for selenides. At the Institute of Gas Technology, hot acid and salt solutions are contained in alumina and mullite without difficulty. At Sandia-Livermore, a glass ceramic has been used for hot HCl solutions. None of the programs in the US has reached the stage where materials for scaling up a process have been selected.

The pioneering work on thermochemical cycles was carried out at the Euratom Joint Nuclear Research Laboratory at Ispra, Italy. During the past few years that laboratory has undertaken a rather extensive materials compatibility program to support its development work. Initial screening tests are done by exposing small specimens to corrosive media in quartz capsules. Some of the tests are conducted at high pressure by balancing the pressure built up in the capsules with an externally applied pressure. For candidate materials that exhibit good corrosion resistance in capsule tests, additional studies are made by pumping the corrosive media over the specimens in a recirculating test loop. In the future, metallic materials that have proved to have good corrosion resistance will be subjected to stress corrosion tests.

The test program at Ispra is designed to evaluate materials under conditions which correspond exactly to thermochemical process conditions. For their Mark I cycle, suitable materials have been found for service in $HgBr_2$, MgBr, and $CaBr_2$. Depending on temperature, teflon, vitreous carbon, and high-nickel superalloys have attractive properties. Coatings are being investigated in an attempt to find cheaper materials. Compatibility of alloys with liquid Hg has been studied for space nuclear power systems, and the results should apply quite well to the Mark I and other mercury cycles. Also

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[1] Dupont trade name for a mixture of nitrate and nitrite salts.

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receiving considerable attention in the materials program at Ispra are cycles which use $FeCl_2$ and HCl.

This discussion has been directed mainly to corrosion by hot acids and salt solutions. Another consideration is hydrogen compatibility of structural materials, which is not being investigated in any of the development programs and may not even be recognized as a potential problem at some laboratories.

Examples of some of the reactions under study at various laboratories in which hydrogen is one of the products are:

(1) $3FeCl_2 + 4H_2O = Fe_3O_4 + 6HCl + H_2$
723-1023°K (450-750°C)

(2) $Hg + 2HBr = HgBr_2 + H_2$
523°K (250°C)

(3) $2NH_4I = 2NH_3 + I_2 + H_2$
773-973°K (500-700°C)

(4) $6MnCl_2 + 8H_2O = 2Mn_3O_4 + 12HCl + 2H_2$
973°K (700°C)

(5) $Cu + 4HBr = H_2CuBr_4 + H_2$
373°K (100°C)

Note that in all of these reactions, hydrogen is present in combination with a halide. While our knowledge of materials behavior in pure hydrogen has progressed significantly in recent years, the possible synergistic effect of hydrogen and a halide is an unexplored subject which deserves attention.

If one examines a list of the reactions under study and the materials being used to contain them, it may seem that ceramic materials have more to offer than metals and alloys for scaling up thermochemical processes. However, there are at least two reasons why metals and alloys should be used for at least part of the hardware: (1) ceramic vessels and pumbing are difficult to fabricate; and (2) heat exchangers must be used if the processes are to be efficient, and only metals and alloys have thermal conductivities that are high enough for heat exchanger hardware.

2. Electrolysis. The principle need in electrolysis technology is modernization of facilities to obtain higher efficiencies. At the same time, it is suggested that the cell operating temperature be increased from approximately 363-473°K (90 to 200°C). There would then be a need to replace asbestos separators, gasketing, and insulating materials.. Improvements in electrode design could eliminate the need for new materials, particularly if a flow-through electrode were available. Relatively little research and development is in progress in these areas. Brookhaven National Laboratory is adapting Lurgi electrolyzers to produce hydrogen at a pressure of 3.2 MN/m^2 (32 atm).

An area in which considerable progress has been made is the development of solid electrolyte materials. The General Electric Co. has developed a solid polymer electrolyte that is being evaluated for hydrogen production. They are also investigating an electrochemical process for coupling the $CO-CO_2$ reaction to water splitting at a temperature of 1073°K (800°C). Ceramic membranes with mixed ionic and electronic conductivity are being developed for this process. No containment materials work in support of this program has been started.

A few laboratories are studying hybrid thermochemical-electrochemical processes for hydrogen production. The key step is electrolysis of a halide or sulfate solution which will decompose at a lower voltage than in the electrolysis of pure water. Since the electrolysis will be carried out at a relatively low temperature corrosion should not be a serious problem.

3. Coal Gasification. Many coal gasification processes require excess hydrogen for some reactions to maximize the methane yield. This hydrogen can be made by reacting steam with residual char. It is also possible to maximize hydrogen production during coal gasification by reacting all the carbon in coal in the water-shift chemical reaction. Potential material problems include erosion from coal particles, oxidation, and sulfidation at elevated temperatures.

Other processes which should be mentioned briefly are thermal, photo-chemical, and radiolytic decomposition of water. Calculations and preliminary experiments have shown that these thermochemical processes are probably not competitive with thermochemical cycles and electrolysis. The main reason is that the rates and efficiences of the processes are too low. Direct thermal decomposition would also require the use of expensive or perhaps strategic materials because thermal decomposition occurs only at very high temperatures.

II. HYDROGEN EMBRITTLEMENT OF STRUCTURAL ALLOYS

A. Types of Embrittlement

Potential hydrogen embrittlement problems exist in all three components of a hydrogen energy system — production, transmission/storage, and utilization.

Hydrogen embrittlement of metals is an old, a frequently encountered, and often misunderstood phenomenon. Metals processing, chemical, and petro-chemical industries have experienced various types of hydrogen problems for years. More recently, however, the aerospace industry has experienced new and unexpected hydrogen embrittlement problems. There are many sources of hydrogen, several types of embrittlement, and various theories for explaining the observed effects. Hydrogen embrittlement is classified into three types:

(1) Hydrogen reaction embrittlement

(2) Internal reversible hydrogen embrittlement

(3) Hydrogen environment embrittlement

1. Hydrogen Reaction Embrittlement. Although the source of hydrogen may be either atomic or molecular, this type of embrittlement is quite distinct from the other two types. Once hydrogen is absorbed, it may react to form a new phase near the surface of the metal or diffuse substantial distances within the metal before it reacts. Hydrogen can react with itself, with the metal, or with a foreign element in the metal. The chemical reactions that comprise this type of embrittlement, or attack, are well known and are encountered frequently in the petrochemical industry. The new phases formed by these reactions are usually quite stable and embrittlement is not reversible during low-temperature aging treatments.

Hydrogen can react with the metal or with an alloying element to form a hydride (MH_x). Hydride phase formation can be either spontaneous or strain-induced. Atomic hydrogen can react with itself within the metal to form molecular hydrogen (H_2). This problem is frequently encountered after steel processing and welding and has been termed flaking or "fish-eyes." Hydrogen can also react with a foreign element in the metal to form a gas. "Hydrogen attack" is the reaction with carbon in low-alloy steels to form methane (CH_4) bubbles (Fig. H-2). Another example is the reaction of hydrogen with oxygen in copper to form steam (H_2O) resulting in blistering and a porous metal component.

2. Internal Reversible Hydrogen Embrittlement. Internal reversible hydrogen embrittlement has also been termed slow strain rate embrittlement and delayed failure. This is the classical type of hydrogen embrittlement that has been studied quite extensively. Widespread attention has been focused on the problem resulting from electroplating — particularly of cadmium on high-strength steel components. Other sources of hydrogen are processing treatments, such as melting and pickling. More recently, the embrittling effects of many stress-corrosion processes have been attributed to corrosion-produced hydrogen. Hydrogen that is absorbed from any source is diffusable within the metal lattice. To be fully reversible, embrittlement must occur without the hydrogen undergoing any type of chemical reaction after it has been absorbed within the lattice.

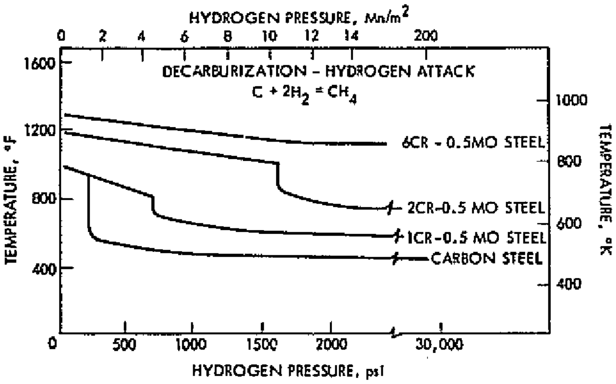

Fig. H-2. Nelson Diagram Describing the Safe Operating Limits for Steels in Hydrogen and Hydrogen-Containing Environments (Wilson, G. A., Hydrocarbon Process 45, No. 10, pp. 201-204, 1966)

Internal reversible hydrogen embrittlement can occur after a very small average concentration of hydrogen has been absorbed from the environment. However, local concentrations of hydrogen are substantially greater than average bulk values. For steels, embrittlement is usually most severe at room temperature during either delayed failure (static fatigue) or slow strain rate tension testing. This time-dependent nature (incubation period) of embrittlement suggests that diffusion of hydrogen within the lattice controls this type of embrittlement. Cracks initiate internally, usually below the root of a notch at the region of maximum triaxiality. Embrittlement in steel is reversible (ductility can be restored) by relieving the applied stress and aging at low temperatures provided microscopic cracks have not yet been initiated. Internal reversible hydrogen embrittlement has also been observed in a wide variety of other materials including nickel-base alloys and austenitic stainless steels provided they are severely charged with hydrogen (Fig. H-3).

3. Hydrogen Environment Embrittlement. Hydrogen environment embrittlement was recognized as a serious problem in the mid-1960s when the National Aeronautics and Space Administration (NASA) and its contractors experienced failures of ground-based hydrogen storage tanks (Fig. H-4). These tanks were rated for hydrogen at pressures of 35 to 70 MN/m^2 (5000 to 10,000 psi). Because of these failures and the anticipated use of hydrogen in advanced rocket and gas-turbine engines and auxiliary power units, NASA has initiated both in-house and contractual research. The thrust of the contractual effort generally has been to define the relative susceptibility of structural alloys to hydrogen environment embrittlement. A substantial amount of research has been concerned with the mechanism of the embrittlement process. There is marked disagreement as to whether hydrogen environment embrittlement is a form of internal reversible hydrogen embrittlement or is truly a distinct type of embrittlement.

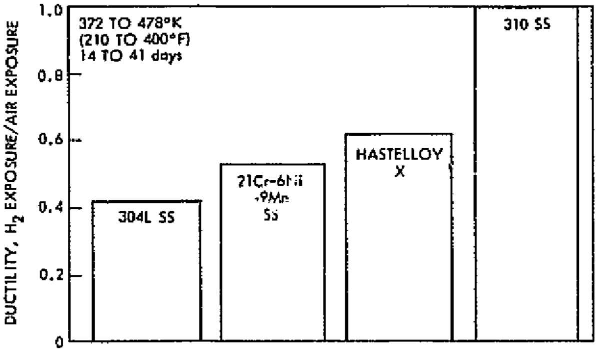

Fig. H-3. Effect of Exposure in 70 MN/m^2 (10,000 psi) Hydrogen on the Room Temperature Ductility of Austenitic Stainless Steels and a Nickel-Base Superalloy, Hastelloy X. (Louthan, M.R., et al, Mater. Sci. Eng., 10, 1972).

GROUND STORAGE TANKS				
1964-65	AEROJET	5 TANKS 35 MN/m^2 (5000 psi)	1146a STEEL	NOZZLE LEAKS AT WELDS
1965	AEROJET	3 TANKS 35 (5000)	A517-F	CRACKS UP TO 1.3 m (50 In.)
1966	NASA	3 21 (3000)	A517-F	INNER SHELL CRACKED AND LEAKED
1967	AEROJET	1 25 (3600)	A517-F	CRACKS UP TO 1.5 m (60 In.)
----	SUD AVIATION	1 117 (17 000)	MARAGING	EXPLOSION
BOURDON TUBES IN PRESSURE GAUGES				
1964-67	NASA	403 AND 431 STAINLESS STEELS INCONEL X		RUPTURE, FIRE AND INJURY

Fig. H-4. Hydrogen Storage System Failures

The characteristics of the types of hydrogen embrittlement are summarized in Fig. H-5. Hydrogen environment embrittlement has been observed over a wide range of gas pressures, temperatures, and in a variety of mechanical tests. Embrittlement appears to be most severe near room temperature. Gas purity and test strain rate can play significant roles in determining the degree of embrittlement. The transfer step of surface adsorption has been shown to be the overall rate controlling step during hydrogen environment embrittlement. However, if adsorption is bypassed, the rate controlling step for hydrogen environment embrittlement is either absorption or subsequent lattice diffusion. Analyses of substantial increases in the hydrogen content of embrittled alloys tend to support the necessity for lattice diffusion since it is unlikely that such large quantities of hydrogen can be absorbed within the first atomic layer below the surface. Another important characteristic of hydrogen environment embrittlement that has not been conclusively resolved is the location of crack initiation — at the surface or internally. These characteristics can be compared with those observed for internal reversible hydrogen embrittlement and for hydrogen reaction embrittlement which are also listed in Fig. H-5.

Hydrogen environment embrittlement has been observed in a wide variety of materials. The high strength structural alloys such as steels and nickel-base alloys are particularly susceptible. Metals and alloys subject to all types of hydrogen embrittlement are listed in Fig. H-6. Those affected by hydrogen environment embrittlement and internal reversible hydrogen embrittlement are listed in the approximate order of decreasing susceptibility at room temperature. The metals affected by hydrogen reaction embrittlement are also listed in Fig. H-6, and the types of reactions are called out.

B. Embrittlement Problems During Hydrogen Production

Hydrogen production processes, as well as other advanced energy conversion systems such as coal gasification, involve hydrogen as a product of one of the reaction steps, as a coolant or heat transfer medium, etc. In all of these cases, containment of hydrogen at various temperatures up to 2273°K (2000°C) and pressures up to 7 MN/m^2 (1000 psi) is an important design consideration. Additionally, the goals of these advanced energy conversion and generation systems are to: (1) increase service temperatures which equate to increased thermal efficiency; (2) increase reliability which equates to increased availability; (3) reduce failure which equate to reduced personnel hazard and reduced outage; and (4) reduce capital requirements. Such goals tend to further enhance and bring into focus a myriad of materials problems associated with hydrogen containment.

Fortunately, the requirements for hydrogen containment at high temperatures and pressures have existed for a number of years in the ammonia and petroleum hydrorefining industries. Much technology has been developed which at the least partially may be applicable to the anticipated requirements for hydrogen production. However, there are strong indications that the Nelson curves (Fig. H-2) used to design against elevated temperature hydrogen attack are inadequate. The Nelson curves are constructed from plant failures and data on satisfactory operating regions, accumulated over many years of experience. These curves delineate the safe and unsafe hydrogen pressure-temperature regimes for carbon and alloy steel in a purely empirical way. Each successive revision of these curves seems to widen the operating limits under which hydrogen attack is observed by lowering the allowable temperature or pressure for safe usage of a given steel.

It is both a strength and a weakness of the Nelson curve approach that it is based solely upon accumulated practical experience. The hydrogen gas environments are those used in the petrochemical industry and are far from pure. No attempt has been made previously to define the constituents of the environments and thus these observations may well reflect aspects of the gas mixture other than hydrogen.

The objective of a recently initiated, joint NASA-Ames and Electric Power Research Institute (EPRI) program is to establish the technology necessary to select or design economical and reliable pressure vessel steels for use in the aggressive, high-temperature, hydrogen-rich environments of coal gasifiers. This joint effort of NASA and EPRI consists of a four-component program comprising separate objectives:

(1) To establish the current state of the art of high temperature pressure vessel technology

CHARACTERISTICS	TYPES OF EMBRITTLEMENT		
	HYDROGEN ENVIRONMENT EMBRITTLEMENT	INTERNAL REVERSIBLE HYDROGEN EMBRITTLEMENT	HYDROGEN REACTION EMBRITTLEMENT
USUAL SOURCE OF HYDROGEN	GASEOUS (H_2)	PROCESSING ELECTROLYSIS CORROSION } (H)	GASEOUS OR ATOMIC HYDROGEN FROM ANY SOURCE
TYPICAL CONDITIONS	10^{-6} TO 10^{8} N m^{2} GAS PRESSURE MOST SEVERE NEAR ROOM TEMPERATURE OBSERVED 173°-973°K (-100° TO 700°C) GAS PURITY IS IMPORTANT STRAIN RATE IS IMPORTANT	0.1 TO 10 ppm AVERAGE H CONTENT MOST SEVERE NEAR ROOM TEMPERATURE OBSERVED 173° TO 373° K (-100° TO 100°C) STRAIN RATE IS IMPORTANT	HEAT TREATMENT OR SERVICE IN HYDROGEN, USUALLY AT ELEVATED TEMPERATURES
TEST METHODS	NOTCHED TENSILE UNNOTCHED TENSILE CREEP RUPTURE FATIGUE (LOW, HIGH CYCLE) FRACTURE TOUGHNESS DISC PRESSURE TEST	NOTCHED DELAYED FAILURE SLOW STRAIN RATE TENSILE BEND TESTS C-RINGS TORQUED BOLTS	CAN BE OBSERVED VISUALLY OR METALLOGRAPHICALLY
CRACK INITIATION	(SURFACE OR INTERNAL INITIATION)[a]	INTERNAL CRACK INITIATION -INCUBATION (REVERSIBLE) -SLOW, DISCONTINUOUS GROWTH -FAST FRACTURE	USUALLY INTERNAL INITIATION FROM BUBBLES OR FLAKES
RATE CONTROLLING STEP	ABSORPTION TRANSFER STEP (ABSORPTION OR LATTICE DIFFUSION)[a] EMBRITTLING STEP	LATTICE DIFFUSION TO INTERNAL STRESS RAISERS	CHEMICAL REACTION TO FORM HYDRIDES OR GAS BUBBLES

[a] UNRESOLVED

Fig. H-5. Characteristics of the Types of Hydrogen Embrittlement (Gray, H.R., ASTM STP-543, 1974)

(2) To expand our current understanding of the responsible kinetic and mechanistic aspects of the problem

(3) To develop by analytical means the life prediction and failure criteria for gasifier pressure vessels

(4) To develop improved low-cost steel alloys for gasifier service.

EPRI will use its monetary resources and unique connection with the operating power companies to accomplish objectives (1), (3), and (4). NASA will apply its significant background and talents in dealing with similar environment/material interactions to accomplish objective (2) through a combined in-house and contractual program. Specifically, studies will be conducted on carbon and low alloy steels in contact with pure hydrogen and hydrogen-rich environments containing mixtures of other relevant constituents. The kinetic processes involved in the transport of hydrogen from the environment through the steel and its interaction with the steel will be investigated as a function of temperature, pressure, applied stress, the presence of other gaseous species, modifications of the alloy composition and microstructure of the steel, and chemical modifications of the environment. The mechanistic processes of attack will be defined by changes in the mechanical properties of steels at room temperature after exposure and at elevated temperatures during exposure to hydrogen-rich gaseous environments as a function of time, temperature, pressure, and applied stress. The results of these kinetic and mechanistic studies will be combined in an effort to understand and predict the rate and severity of degradation by hydrogen rich gaseous environments.

The results of this program will be of significant benefit not only to coal gasification processes but also to hydrogen production processes.

C. Hydrogen Embrittlement During Transmission/Storage/Utilization

Hydrogen is envisioned to be transported in gaseous or liquid form and to be stored in either of these two forms or possibly as a solid hydride phase. Presently, we are capable of designing transport and storage facilities for hydrogen or hydrogen-containing environments which will be reasonably free from environmental degradation over their lifetimes. In general, however, these designs will have important limitations and must involve either relatively expensive alloy systems containing alloy elements such as chromium and nickel which may eventually be considered scarce, or involve the inefficient use of large quantities of less expensive materials. The problem is one of cost. The cost of acceptably safe systems will be too high unless we learn how to make the best, most effective use of materials in keeping with reasonable levels of safety.

1. Liquid Hydrogen. The transport and storage of hydrogen in the liquid phase presents different problems than will be discussed concerning hydrogen in the gas-phase. At cryogenic temperatures encountered in liquid hydrogen

HYDROGEN ENVIRONMENT EMBRITTLEMENT[a]	INTERNAL REVERSIBLE HYDROGEN EMBRITTLEMENT[a]	HYDROGEN REACTION EMBRITTLEMENT
HIGH STRENGTH STEELS 18Ni MARAGING 410, 440C, 430F H-11, 4140, 1042 (Q&T) Fe-9Ni-4Co, 17-7PH NICKEL AND NICKEL ALLOYS ELECTROFORMED Ni NICKEL 200, 270, 301 INCONEL 625, 700, 706, 718, X RENE 41, HASTELLOY X UDIMET 700, WASPALOY MAR M-200DS, IN 100 LOW STRENGTH STEELS ARMCO IRON, CK22, CK45, 1020 1042 NOR., HY-80, HY-100 A-302, A-515, A-517 TITANIUM ALLOYS Ti-6Al-4V, Ti-5Al-2.5Sn MOLYBDENUM-TZM COBALT ALLOYS HS-188, L-605, S-816 METASTABLE STAINLESS STEELS 304L, 305, 310, 309S K-MONEL Be-Cu ALLOY 25 PURE TITANIUM STABLE STAINLESS STEELS 316, 321, 347, A-286 ARMCO 21-6-9, 22-13-5 COPPER ALLOYS, OFHC Cu MAGNESIUM ALLOY HM21A ALUMINUM ALLOYS 1100, 2219, 6061, 7039, 7075	HIGH STRENGTH STEELS 4340, 4140, H-11 17-4PH, AM 355 18Ni MARAGING E8740, 17-7PH EXP. Fe-Ni-Cr ALLOYS EXP. Fe-Cu ALLOYS Ti, Zr, V, Nb, Ta Cr, Mo, W, Co, Ni Pt, Cu, Au, Al, Mg AND/OR SOME OF THEIR ALLOYS METASTABLE STAINLESS STEELS 304L, 310 K-MONEL HIGH STRENGTH NICKEL ALLOYS INCONEL 718 RENE 41, HASTELLOY X WASPALOY STABLE AUSTENITIC STEELS 316, A-286, U-212, 21-6-9	1. HYDRIDES (MH_X) (a) H REACTS WITH MATRIX Ti, Zr, Hf, V, Nb, Ta Mn, Ni, Pd, U, Pu, Th RARE EARTHS ALKALIES ALKALINE EARTHS (b) H REACTS WITH ELEMENT IN MATRIX MgZr, MgTh ALLOYS 2. HIGH PRESSURE GAS BUBBLES (a) H REACTS WITH ITSELF (H_2) STEELS, OFHC Cu Ni, Al, Mg, Be (b) H REACTS WITH FOREIGN ELEMENT IN MATRIX CH_4 - - LOW ALLOY STEELS, Ni ALLOYS H_2O - - WELDED STEELS, Cu, Ni, Ag NH_3 - - MOLYBDENUM

[a] LISTED IN APPROXIMATE ORDER OF DECREASING SUSCEPTIBILITY AT ROOM TEMPERATURE

Fig. H-6. Metals and Alloys Embrittled by Hydrogen (Gray, H.R.: ASTM STP-543, 1974)

systems, most reaction processes, including the dissociation of molecular hydrogen, are very slow and the movement of hydrogen from the environment into the metal becomes difficult. Most of the material problems encountered by NASA in its Apollo and Skylab programs were not directly associated with the hydrogen used in their propellant systems. For example, corrosion of stainless steel nuts, piping, and bellows occurred because of improper material choices, inadequate galvanic corrosion protection, or insufficient protective coatings. Other problems can be encountered, however, if the system is mistreated by thermal cycling where hydrogen is allowed to enter the metal at high temperatures. Under such conditions, a second phase, either gaseous or solid (hydride), may form and result in hydrogen reaction embrittlement which could severely degrade the reliability of the transport or storage system. Stable austenitic stainless steels or aluminum alloys should find continued application in liquid hydrogen transport or storage systems.

One uncertainty remains in using an austenitic stainless steel for long-term service at low temperatures. There is a tendency for martensite to form to a greater or lesser degree depending on steel composition. Some martensite will form immediately on cooling in Type 304L, but not in 310 or 316. Isothermal martensite formation over long periods of time has never been studied in these steels to the best of our knowledge. Rate of formation data and the tolerance level for martensite should be determined before the best choice of materials can be made.

2. Hydride Storage. The materials problems associated with hydrogen storage in the form of hydride again differ greatly from those encountered in gaseous or liquid hydrogen storage systems. Here, high temperatures, high pressures, and thermal cycling are encountered.

As an example, consider the reservoir built by Brookhaven National Laboratory for using iron titanium hydride ($FeTiH_{1.6}$) as a medium for storing off-peak electrical energy. The pressure vessel was made from a section of type-316 stainless steel pipe, 30 cm in diameter and 0.6-cm wall thickness. The vessel must contain hydrogen at 3 MN/m^2 (500 psi) pressure at ambient temperature. The highest temperature the vessel reaches in the hydride-dehydride cycle is approximately 333°K (60°C). This probably is not high enough to cause hydrogen reaction embrittlement (blistering from methane or hydrogen gas in voids).

However, potential problems may occur when hydride compounds which dissociate at a higher temperature are substituted for $FeTiH_{1.6}$. For example, if TiH_2 or MgH_2 were used, the maximum operating temperatures would be approximately 873° and 673°K (600° and 400°C), respectively. At these temperatures, hydrogen embrittlement could be a problem with either a stainless or a low-alloy steel.

3. Gaseous Hydrogen. Most of our present gaseous hydrogen transmission system in the aerospace and petrochemical industries involves either relatively short pipeline systems or the use of mobile tanks. Most local hydrogen transmission systems operate at 3 MN/m^2 (450 psi) or less with the exception of some systems in the petrochemical industry operating at 7 MN/m^2 (1000 psi). They are constructed of relatively small diameter pipe of some austenitic stainless steel and are not of sufficient length to require in-line compressors.

In addition to the relatively short pipeline systems mentioned above for "captive" hydrogen, there are at least five pipelines selling "merchant" hydrogen in the world. A summary of available data on these lines is tabulated in Fig. H-7. All of these pipelines, except the one at Los Alamos, have apparently been operating without any problems attributable to hydrogen embrittlement. However, the Los Alamos pipeline cracked, leaked, and was finally abandoned. Failure was attributed to poor galvanic corrosion protection, poor weld quality, and use of a steel susceptible to hydrogen embrittlement. None of these pipelines has any in-line compressor stations.

A limited amount of laboratory data also suggests that hydrogen environment embrittlement may be a potential problem with typical pipeline and pressure vessel steels (Figs. H-8 and H-9).

LOCATION	PIPELINE STEEL	AGE, YR	DIAMETER	LENGTH	HYDROGEN		COMMENTS
AIR PRODUCTS-TEXAS	CONVERTED NAT. GAS	6	0.1m (4 in.)	8 km (5 mi)	"PURE"	6 MN/m^2 (800 psi)	NO PROBLEMS
AIR PRODUCTS-TEXAS	NEW-SCHEDULE 40 STEEL	3	0.2m (8)	19 (12)	"PURE"	1 (200)	NO PROBLEMS
GERMANY	SEAMLESS 1015 STEEL	UP TO 35	0.15-0.3 (6-12)	209 (130)	"DIRTY"	2 (260)	NO PROBLEMS
NASA-KSC-FLORIDA	316 STAINLESS STEEL	10	0.05 (2)	2 (1)	"ULTRAPURE"	42 (6000)	NO PROBLEMS
LINDE	------	-	-	2-3 (1-2)	------		------
SOUTH AFRICA	------	-	-	80 (50)	------		------
LOS ALAMOS	5Cr-Mo STEEL	8	0.03 (1)	6 (4)	"PURE"	14 (2000)	LEAKED 3 yr CRACKED 4 yr ABANDONED

Fig. H-7. Hydrogen Pipeline Experience

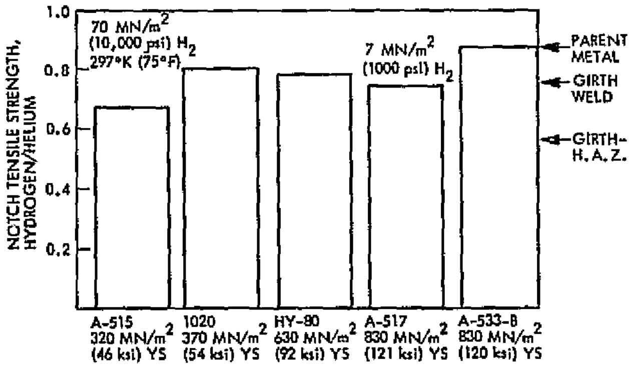

Fig. H-8. Effect of Hydrogen on Notch Tensile Strength of Pipeline and Pressure Vessel Steels (Chandler, W.T.: Presented at I.E.C.E. CONF., 1974)

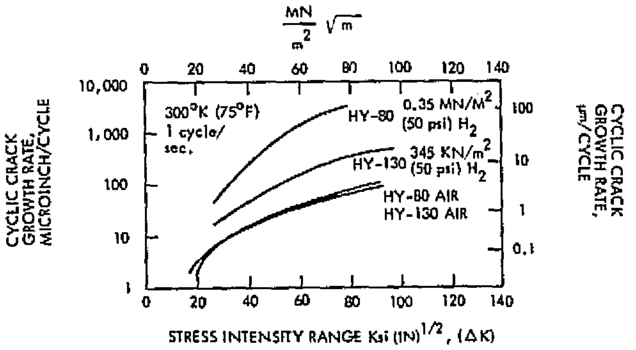

Fig. H-9. Cyclic Crack Growth of Pressure Vessel Steels in Hydrogen and Air (Clark, W.G., in Hydrogen in Metals, 1973, pp. 149-162)

These data indicate that: (1) low strength steels are embrittled; (2) weldments are particularly susceptible; and (3) embrittlement occurs at hydrogen pressures as low as 0.3 to 7 MN/m^2 (50 to 1000 psi).

III. CONCLUDING REMARKS

The primary consideration in a hydrogen transportation or storage system is one of cost. Economic considerations include operating costs, capital investment, and available resources. Additionally, to some extent, there is also a trade-off with respect to safety. One point of view is that public acceptance of current rates of failures in public transportation and gas pipeline systems can be extrapolated to extended hydrogen usage and thus no new, stringent requirements would be necessary. The second, and probably more likely point of view, is that the public will demand low failure rates for hydrogen systems, much the same as those required presently for nuclear reactor systems. Such a requirement for a low failure rate means that it is simply inappropriate to assume that much of the current experience can be readily extended to the new engineering circumstances encountered in hydrogen systems. If the latter position prevails, much research will be required to prove any new system.

Some consideration has been given to the possibility of using our present natural gas distribution system as an extended one for gaseous hydrogen. Major differences exist between methane, the primary gaseous constituent of natural gas and hydrogen which appear to make this economically unfeasible. The heat of combustion of hydrogen is 12.1/MJ/m^3 (325 Btu/ft^3) compared with 37.8 MJ/m^3 (1013 Btu/ft^3) for methane. Additionally, the compressibility of hydrogen at 296°K (23°C) and 10 MN/m^2 (100 atm) is 1.06 compared with 0.855 for methane. The energy throughput for hydrogen becomes near a factor of one-fourth compared with natural gas. The economics of the situation demand the operation of these pipelines at their maximum operating pressures.

Our present natural gas distribution system within the USA involves some more than 1500 Mm (900,000 mi) of pipeline of which more than 400 Mm (250,000 mi) are mains. These pipelines are made primarily of low carbon steel (e.g., 1015 or 1020) of varying age, manufacture, diameter and thickness, and fabrication practice operating at pressures near 7 Mn/m^2 (1000 psi). The stress level in these pipelines is set by a design code of 72% of the pipe steel tensile yield strength. To operate such a pipeline at 72% of its tensile strength with hydrogen would, in our opinion, be unthinkable. Especially considering the safety hazard associated with hydrogen compared with methane. The flammability limit for hydrogen ranges from a mixture of about 4 to 92% with flamespeeds through this range exceeding 0.3 m/s (1 ft/s) and reaching a maximum of 3 m/s (9 ft/s) while methane ranges from about 8 to 15% with a maximum flamespeed of 0.3 m/s (1 ft/s). It appears most unwise to contemplate pumping hydrogen through our natural gas system without a full-scale field validation even if, someday, it does become economically feasible.

Current methods of minimizing hydrogen environment embrittlement of transmission and storage systems are by the correct selection of materials, sound welds, design to minimize stress concentrations, the use of inhibitors, and the use of coatings. The variable of materials selection for new, extended gaseous hydrogen pipelines appears economically unfeasible. Economics of transport suggest pipelines of up to 1.2 m in inside diameter operating at pressures approaching 14 MN/m^2 (2000 psi). If a steel could be developed or be made safe from hydrogen environmental embrittlement of 72% of its yield strength, a 450 MN/m^2 (65 ksi) steel pipeline would require a wall thickness of approximately 3 cm. The amount of material required for such a pipeline becomes very large and thus inexpensive materials must be used. We will no longer have the option to use austenitic stainless steel rather than a ferritic steel for hydrogen service.

IV. RECOMMENDED RESEARCH AND DEVELOPMENT PROGRAMS

It is suggested that high priority research is needed to better understand how hydrogen gets from the environment to a point in the metal where the process of degradation can occur. The eventual goal should be to control these transport processes. Emphasis should be placed on practical environments using situations expected to be encountered in real systems. The role of specific inhibitors on the movement of hydrogen into the metal should be explored in great detail. Inhibitors can take the form of additives to the environment or to the metal itself, and protective coatings of all sorts including diffusion coatings. If any one of the reaction steps involved in the movement of hydrogen from the environment to the metal can be hindered or eliminated, inexpensive materials could then be used efficiently and safely for hydrogen transport and storage.

Priority research should also be undertaken to understand the influence of cyclic loading on the environmental degradation of materials used not only in the pipeline itself but also in compressor pumps, valves, etc. In-line compressors will be an absolute necessity in any extended transport system. Here complexing problems of adiabatic heating and cyclic loading must be contended with.

Specific research and development programs are suggested below and are listed in approximate order of decreasing priority:

(1) Evaluation of welded pipeline steel under simulated service conditions

(2) Evaluation of candidate compressor alloys under simulated service conditions

(3) Compatibility of materials in corrosive environments associated with most promising hydrogen production processes (as soon as production processes are reasonably well defined)

(4) Improved welding and nondestructive inspection technologies

(5) Determine feasibility of composite pipelines (thin metal liner with fiberglass overwrap)

(6) Improved catalysts, separator, and cell frame materials for high temperature electrolysis

(7) Improved cryogenic insulation materials

(8) Seal materials to minimize hydrogen leakage

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APPENDIX I

HYDROGEN, SOCIO-ENVIRONMENTAL IMPACT

A Report Prepared for
Jet Propulsion Laboratory
Pasadena, California
under
Contract 954155

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SECTION I. THE CONCEPT AND RATIONALE FOR ASSESSMENT OF HYDROGEN TECHNOLOGY

The search for and application of new technology is no longer self-justifying in the eyes of many. The use of new technology is often perceived as a threat to society. Yet many of our society's ends and goals require technological innovations, if they are to be achieved.

This paradox is discussed by Francois Hetman in the standard book on technology assessment:

> " . . . technology has always been a particularly dynamic part of the social structure belonging to a larger cultural framework in which man thrives as a human being. There is and always has been a continuous dialogue concerning society, its needs and aspirations, and the technical means potentially contained in technology for satisfying these needs and fulfilling those aspirations. The nature of technology cannot be understood without understanding the nature of this dialogue. Indeed, the place of technology in the scope of human knowledge is determined by the nature of the dialogue concerning the aspirations of society and the potentials of technology.
>
> This dialogue has been broken and it would be of no use to try to resume it in terms which have become largely irrelevant. A new form of dialogue must be invented to take account of human potentialities rather than of the frontiers of scientific technology"[1] (Emphasis added.)

It is not too surprising that Hetman says the dialogue has failed.

The consequences of widespread use of chlorinated hydrocarbon insecticides were not adequately examined or made known. The impact on central cities of the automobile and the U.S. institutions set up to encourage its use were not anticipated. The effects of substituting synthetics for natural, biodegradable materials were not considered.

On the other hand, alternative propulsion technologies permitting economical, low-polluting automobiles were neglected for decades. In-situ processing of coal and oil shale has been given scant research and development. Societal ends and technological means have not been consistently related in recent years.

Suspicion and political reaction against innovators and innovations which lack full and credible justification have resulted. Supersonic transport aircraft and the trans-Alaska pipeline have suffered costly delays and their merit is still in doubt. The Congress often reflects societal scepticism when it considers federal research and development programs. Lacking Hetman's dialogue, decisions on the development of technology are often made in the adversarial environment of legislatures and courts, without adequate information.

Technology assessment[2] is one response to the need to reestablish the dialogue between the various parties-at-interest who relate society's ends and means. The phrase, technology assessment, first mentioned in Congressional proceedings nine years ago, is now well defined and institutionalized in both government and industry.

Technology assessment is usefully defined as ". . . the systematic study of effects on society that may occur when a technology is introduced, extended, or modified, with special emphasis on the impacts that are unintended, indirect, and delayed. . . . Technology assessment is a policy generation and analysis or decision-oriented tool. Its aims, techniques, and methods are best conceived as yielding systematic inputs into the larger political economic decision process."[3]

This concept of technology assessment, the effort to rebuild the dialogue, was first formally institutionalized in the National Environmental Policy Act of 1969 (Sections 101 and 102).[4] The Act requires interdisciplinary planning and decision analysis, and environmental impact

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[1] Francois Hetman, Society and the Assessment of Technology. Paris: Organization for Economic Cooperation and Development, 1973, p. 43.

[2] A comprehensive bibliography in this field has been prepared by The Futures Group and is available upon request (Wayne I. Boucher, with Sarah Beckett, Mark Anderson, and Linda Rodger, A Bibliography of Technical Assessment, The Futures Group, 124 Hebron Ave., Glastonbury, Connecticut, Mar. 1975).

[3] Joseph Coates, "The Identification and Selection of Candidates and Priorities for Technology Assessment." Technology Assessment, Volume II, Number 2, February 1974, p. 77.

[4] 42 U.S.C. 4321-4327.

statements on significant federal actions. Subsequently, the Congress has established its own Office of Technology Assessment, and a number of agencies in the Executive branch of government have undertaken technology assessments. The National Science Foundation and the Office of Management and Budget (following up on work done earlier by the Office of Science and Technology) are actively involved. An increasing number of mission-orietned agencies are now sponsoring formal technology assessment projects, including the Department of the Army and the Environmental Protection Agency. Canada and several states in the U.S. are using some degree of assessment. Japan is using assessment as a governmental tool to select technologies needed to foster industrial development.

Typical assessments recently undertaken or in process in the U.S. include:

- Weather modification.
- Site-of-use solar generation of electricity.
- Geothermal energy resource development.
- Drug bioequivalency.
- Earthquake prediction.
- Integrated hog farming.
- Terrestial solar energy resource development.
- Oil drilling on the continental shelf off the eastern United States.
- Biological substitutes for chemical pesticides.
- The cashless, checkless society.

The cost of these assessments ranges from $115,000 for the drug study to $525,000 for the continental shelf oil drilling project.

The concern with assessment of energy technology is understandable. Given the current concerns about new fuel sources and energy systems, it also suggests questions about the development of hydrogen technology:

Q. What can be said about the environment in which hydrogen technology will be developed and applied?

A. It is complex, as with most major innovations.

Q. What can be said about the significance of the impacts of developed and applied hydrogen technology?

A. They will probably be substantial, they might be very great; this is uncertain.

Q. Is the state-of-the art of technology assessment such that it can reduce the uncertainty?

A. A qualified yes.

Q. How might an assessment of hydrogen technology be carried out?

A. After dealing with the questions above, the remainder of this report describes an appropriate concept and methodology of assessment.

Hydrogen: The Environment for its Future Development and Use

As may be seen from the following diagram, hydrogen usage at the present time is largely limited to its use as a chemical. Its potential uses range widely:

1. A new fuel--for generation of electricity from fuel cells.
2. A substitute fuel--for combustion processes which presently burn gasoline, other petroleum fractions, natural gas or coal.
3. A medium of energy transmission and storage--after conversion from heat energy, electrical energy, solar energy or other energy forms, hydrogen in liquid or gaseous state can be stored in tanks or underground and may be transported from point to point by pipelines, water-borne transport, or tank-carrying vehicles.
4. A process input--a direct input to chemical processing or to new processes such as direct reduction of iron ore.

The introduction and utilization of hydrogen in each of these potential areas will depend upon five major factors: societal needs; societal and environmental concerns; governmental findings, policies, and regulatory factors; economic considerations; and the capability for purely technological innovation. All of these are the stimuli and barriers to the introduction and use of hydrogen in greater quantities.

At the present time, the stimulus stems from the societal needs. The barriers result not only

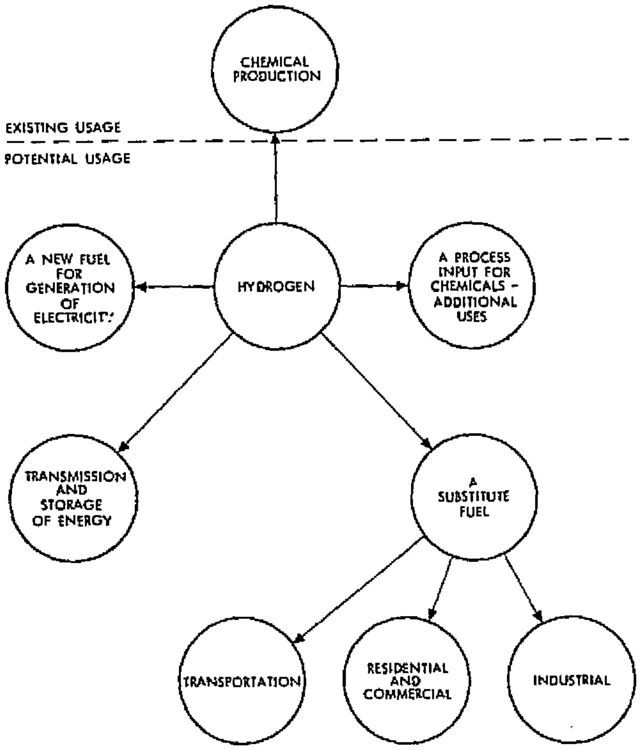

Diagram of hydrogen usage

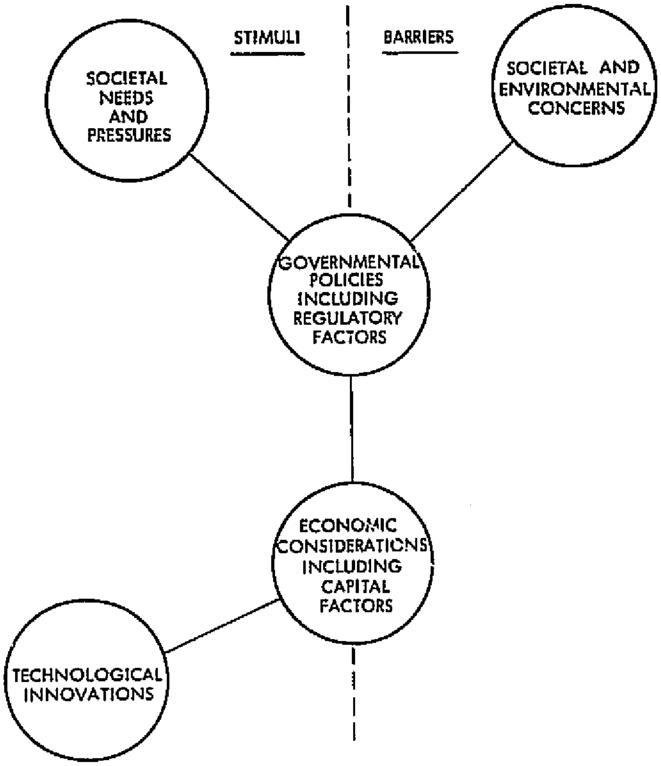

Diagram of factor relations

from societal and environmental concerns but also from the lack of the necessary technological innovations which would make the economics more attractive.[1]

Why is There a Need for a Technology Assessment of Hydrogen Technology?

The underlying reason for assessment is the possibility that the societal and environmental impacts of widespread usage of hydrogen might be profound. It is crucial that these impacts be evaluated in advance and coordinated within an overall policy, including energy and quality of life components.

Too often, we have seen the result of technology and wished we had had the foresight to have planned in advance rather than be faced with the problems of restoration and recovery or the cost of lost opportunity.

If the potential impact of a technology is minimal, then we can be forgiven our failure to prepare for the impact. In the case of hydrogen, the potential impact from changes in systems and institutions makes such an approach harder to accept.

In general, technology assessment of hydrogen research and development should:

- Relate hydrogen technology development to national goals and problems.
- Offer guidance for research and development programming.
- Suggest institutional arrangements for developing the needed capabilities to best use the new technology.
- Identify pacing factors that will affect development and use of hydrogen technology.

More specifically, each major area of innovation--new fuel, substitute fuel, storage and transmission medium, processing input--probably requires a substantially separate assessment. Different functions are involved, different market and institutional relationships are affected. There would be overlap, but consequences, pacing factors, and policy responses might be quite different in these major areas of use.

The State of the Art in Technology Assessment

Assessments of new technologies are being done. Those done so far involve a variety of tools and methodologies. They also reflect different weaknesses, both in data and methodology.

Data shortages show up even in economic information. In the energy field, there are no good studies of comparative capital and operating costs of alternative energy systems. In existing studies, costs are not adequately expressed in comparable terms or in constant dollars. Social indicators--qualified measures of social states and trends--are sometimes not sought, or are not available. This lack of data often leads to poor identification and evaluation of relevant present and future societal states and needs.

Methodologically, there are few realistic evaluations of the uncertainty inherent in using different data and assumptions, and of resulting forecasts. Mechanistic, data-limited techniques are sometimes used. In many of the assessments, technological forecasting is emphasized at the expense of forecasting social needs, of evaluating identified impacts, and of analyzing policy responses to the impacts. As a result, likely modifications of technology and constraints on its introduction are neglected.

The restoration of the dialogue between technology and its users in society requires equalizing the emphasis in assessment. This is not to say there is too much emphasis on technological forecasting; it says that more emphasis is needed on identification of societal constraints and responses.

D. The Derivation of the Recommended Methodology

One of the most important aspects of any technology assessment is anticipation of the innovation process involved in applying a new technology, as well as in identifying the consequences of that application. (Innovation can be defined as ". . . that process by which a new idea is successfully translated into economic impact within the society. . . Thus, an idea, or invention is a necessary but not sufficient prerequisite for innovation. Only after an invention is put into sufficient use to have an economic effect is it to be termed an innovation."[2]) Properly, the assessment addresses the entire innovation process. Conversely, the success of the innovation process depends on the accommodations and modifications of the

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[1] Other factors affect the economic attractiveness of hydrogen, e.g., the price of foreign petroleum.

[2] Robert A. Charpie, Technological Innovation and Economic Growth," Applied Science and Technological Progress, a report to the House Committee on Science and Astronautics, Congress of the United States, Washington, GPO, 1967.

technology made by the innovators to actual or anticipated consequences (including stimuli for the use of, and barriers to the use of the technology.)

A successful technology assessment will facilitate the societal accommodations to the new technology. It will also identify societal constraints or limits which must be dealt with or accommodated to if a technology is to come into use.[1] This is the way that assessment may restore Hetman's dialogue concerning society and technology.

The technology assessment methodology to be recommended here is synthesized from several sources. It draws on work done in the study of the innovation process. It depends heavily on the logic flow of a recent technology assessment report on geothermal energy[2] by The Futures Group. It uses a Denver Research Institute policy analysis methodology, both (1) to orient the assessment, and (2) to include anticipated changes in society and in national policy as summaries of impacts. A successful synthesis of all these approaches is the desired output. The three components of this synthesis are described as follows.

The innovation process. The innovation process is conceived as a relatively sequential process as far as the research and development of new technology is concerned. However, this process is also an iterative one in that each stage in the technology sequence is affected by many factors external to the research and development effort. This process is depicted in Figure 1.[3] It represents technological innovation in the private sector; that is the marketplace where innovations traditionally are brought to our domestic society.

Pacing factors affecting the development of the technology are shown surrounding the circle--the circle contains a depiction of the research and development sequence itself. Some of the factors in the original model are largely internal to the individual firm; these are largely excluded for this purpose. The external pacing factors must be considered in a technology assessment because they affect and are affected by development of the technology--in this case, a hydrogen technology. Thus technology assessment at the outset involves forecasting the evolution of both the technology and the pacing factors through the time period in which the innovation is expected to take place.

Logic flow for assessment. The technology assessment logic flow is considered by the writers (and others interviewed during this project) to be the best depiction of the technology assessment process hitherto available.[4] It is an iterative process with feedback from anticipated impacts back to the forecasts and scenarios for their revision. It actually uses a number of analytical tools described in Section II, Technology Assessment Procedure, later in this report. See Figure 2.

Policy analysis. The policy analysis methodology is based on that first described in DRI's Environmental Policy Analysis.[5] This model is depicted in Figure 3. For technology assessment purposes the hierarchy of threats and objectives

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[1] Societal limits are here considered to be social, economic, political, cultural, environmental and other prospective problems which, either in themselves or in public policy response to them, may preclude a particular application of a technology.

The accommodation versus conflict possibility is further addressed by Daniel Bell, who first defines society and then specifies the problems.

> "Analytically, society can be divided into three parts: the social structure, the polity, and the culture. The social structure comprises the economy, technology, and the occupational system. The polity regulates the distribution of power and adjudicates the conflicting claims and demands of individuals and groups. The culture is the realm of expressive symbolism and meanings. . . . changes in social structure pose "management" problems for the political system. In a society which becomes increasingly conscious of its fate, and seeks to control its own fortunes, the political order necessarily becomes paramount Since the post-industrial society increases the importance of the technical component of knowledge, it forces the hierophants of the new society--the scientists, engineers, and technocrats--either to compete with politicians or become their allies. The relationship between the social structure and the political order thus becomes one of the chief problems of power in a post-industrial society." Bell, The Coming of Post-Industrial Society. New York: Basic Books, 1973, pp. 12-13.

[2] The Futures Group and Bechtel Corporation, Draft of A Technology Assessment of Geothermal Resource Development. Glastonbury, Connecticut: The Futures Group, October 1974.

[3] Robbins, Burke, and Milliken, Federal Incentives for Innovation, Part II: The Innovation Process in the Private and Public Sectors. Denver: University of Denver Research Institute, 1973, p. 49. This model was adapted by Colleen A. Burke and John S. Gilmore from Eldon Sweezy's (The Institute for Public Administration, Washington, D.C.) 14-Stage Model of Technological Development.

[4] Theodore J. Gordon, A Discussion of Some Methods of Technology Assessment, presented to the Technology Assessment and Forecasting Symposium of the American Chemical Society's National Meeting, Los Angeles, California, April 1, 1974.

[5] Gilmore, Bortz, Duff, et al., Environmental Policy Analysis: Public Policy Intervention in Inter-Industry Flows of Goods and Services to Reduce Pollution. Denver: University of Denver Research Institute, 1971.

(the entry point of the Policy Analysis phase) will be instead a hierarchy of opportunities and threats and objectives. Such a hierarchy (greatly simplified) is as follows:

HYPOTHETICAL AND SIMPLIFIED HIERARCHY OF GOALS, THREATS, OPPORTUNITIES, AND OBJECTIVES

Grand Goal: ". . . man and nature live in productive harmony. . ." NEPA, 101 (2).

Threat: Energy shortage.

Opportunity: New sources within national policy constraints.

Constrained Objective: Furnish 116 × 10^{18}J (110 Quads/yr) by 1985, while maintaining competition; staying within air and water quality standards and radioactivity dosage and hazard limits; with 90 percent domestic production; and with interests of consumers and of Western states protected; and with inflation rate less than 6 percent.

The Industry Analysis phase on the left of Figure 3 would be substantially elaborated by forecasts of technological development and the state of society, and projected forward in time into the assessment forecast periods. Pollutant output would be only one consideration, along with social and economic impacts.

For assessment, less emphasis would be put on implementation programs for policies: more would be put on the feedback from policies to forecasts (see above).

The synthesis. The three components--the innovation process, the assessment logic flow, and the policy analysis methodology--will be synthesized. The logic flow in its original form will be modified for the purposes of this report by adding emphasis to the forecasting of the entire innovative process, and also by adding emphasis to the policy analysis of the prospective governmental responses to the innovation process.

The Recommended Technology Assessment Methodology

The logic flow synthesizing these models for hydrogen technology assessment follows in Figure 4. This process starts with a definition of the present state of society, as it may affect the innovative process--the development of hydrogen technology. This is expressed in a hierarchy specifying goals and objectives. (The underlined terms are those on the synthesized logic flow of the recommended methodology [Figure 4].)

The hierarchy is based on relevant national policies (where they are expressed) or inferred from national and societal strivings (where they are not formally expressed). It emphasizes matters affecting the innovation variables.

The desired end product is an operational or constrained objective indicating what is desired relative to the prospective innovation. It states the societal ends towards which the technology might offer means of achievement. The constrained objective also notes the limitations imposed by policy or by institutions in the present context.

Also described in the present context are the innovation variables, the state-of-the-art, and the other pacing factors which will affect the rate at which hydrogen technology is developed and used. These will change time and again, however. All of these factors are also presented and analyzed in the future context.

From the changing factors, scenarios of the future of the technology are forecast, along with possible timing of the technology's development, based on forecasted changes in the state-of-the-art and the other variables and factors.

Policies modifying the technology or related problems are nominated and described as they might change the forecast. These also reflect the scenarios, the descriptions of alternative futures depicting the evolution of hydrogen technology and the world in which it is developing. These reflect the variables and pacing factors, and must also allow for major discontinuities in the state-of-the-art or in other variables and factors.

The interest groups affected by and affecting the evolution of hydrogen technology for a major use must be identified.

Impact description relates the scenarios and the interest groups including institutions and the physical environment to describe specific impacts. Then the impacts are assessed by their effects on the major interest groups, in terms of helping, harming, or otherwise changing.

From these varying assessments and from review of the policies and positions of the interest groups, policy conflicts and constraints on innovation will be identifed. Possible resolution of such conflicts and the effects of the constraints will be noted, and examined as possible policy or institutional actions and changes. These changes and actions are then fed back into the other policy steps. They are also fed back into the hierarchy to suggest the impacts at the societal level, and to review their significance in scenario preparation.

This feedback system of technology assessment is a likely approach to restoring Hetman's dialogue.

Hydrogen Development and Assessment Procedure

The remainder of this report will describe the assessment procedure outlined above and discuss the development of hydrogen technology.

TECHNOLOGY ASSESSMENT PROCEDURE

The concept and the logic flow of a hydrogen technology assessment were described in Section I, The Concept and Rationale for Assessment of Hydrogen Technology. This section will suggest a more specific procedure for such an assessment.

This recommended procedure covers two phases, each a year long. A continuing review process will be needed after that, as with any forecast.

Phase I. Information Gathering Analysis

The first phase should define the context of the study and its boundaries, e.g., 10-year and 25-year forecast periods probably should be selected. After data gathering, a preliminary assessment should be carried out across the breadth of hydrogen technology uses identified in Section III, The Environment for the Future Development and Use of Hydrogen. The prospectively most significant uses of hydrogen technology should be identified and prioritized for in-depth assessment.

Phase I should consist of the following tasks:

- Determine the societal and policy context for development of hydrogen technology.
- Assemble and relate estimates of present future energy supply, demand, and cost data.
- Examine trends in energy use.
- Examine trends in hydrogen-consuming industries (actual and potential).
- Describe the general context for development and use of hydrogen technology.
- Forecast the development of hydrogen technology.
- Describe and forecast the states of society.
- Develop scenarios of hydrogen technology development.
- Estimate, preliminarily, impacts of hydrogen technology development, societal and policy responses, and other pacing factors for development.
- Design in detail the second phase work plan.

1. The Energy Policy Context. Information should be gathered on formal and inferred public policy and institutional requirements. Parties-at-interest to hydrogen's prospective roles in energy development should be identified. Conflicting policies and objectives concerning energy use in the United States and concerning other societal objectives which may affect the use of energy should be noted.

The eventual product of analysis of this information should be a hierarchy of goals, threats, opportunities, and objectives, describing with increasing specificity the objectives which hydrogen technology may help to meet or which might require modification if hydrogen technology is to be developed.

Policy comparison matrices should be prepared for each of several national policy areas, e.g., energy, environmental protection, economic stability. One axis of the matrix should list change factors in societal relationships which have led to energy legislation, including threats and opportunities. It should also list inferred justifications for legislation which should be derived from examination of the relevant legislation and regulation. The other axis should list the selected energy policy-related legislation and significant regulations. Each cell should note the cognizance that the legislation or regulation takes of the change factors, threats and opportunities, or inferred objectives. The purpose of this is to array present public policy, presumably representing formalized societal response, which forms part of the context for developing new energy technology. An example of such a matrix is presented as Figure 5.

In an iterative process which should last at least throughout the first phase, a check list for parties-at-interest or interest groups should be designed. Tentatively, the categories include:

1. Parties internal to the affected industry: e.g., owners, stockholders, management, employees and their unions.
2. Suppliers and customers of an affected industry: e.g., vendors of materials and services including financing, insurance and advertising, intermediate and final consumers. An analysis of input/output tables facilitates this listing.
3. Competitors of an affected industry: e.g., firms or industries threatened by either direct competition or substitution for their outputs resulting from developing of hydrogen technology. Their suppliers and customers may also be involved.
4. Government: e.g., at federal, state, and local levels, and in different roles. Includes government as legislator, executor, adjudicator, tax collector, regulator, and keeper of economic stability, social welfare, and national security.
5. Affected bystanders: e.g., constituencies, institutions, and ecosystems. Involved with natural resources, wildlife, recreation potential, aesthetic affects, and the persons involved with these including investors, employees, residents and neighbors, and other property owners.

Examination of responses to environmental impact statements relevant to development of various energy technologies should identify numerous parties-at-interest--both persons and institutions--and may generate additional categories.

Another check list should be designed for conflicting policies/objectives. It will be based on three questions:

1. What are the relevant policies or objectives of government agencies (at all levels) which will affect or constrain objective setting and implementation of energy policies and other public policies affecting the use of hydrogen technology?
2. What are the goals of identifiable social or cultural or locational groups (the concern of the Rocky Mountain states over rapid coal development as an example) which lead them to perceive problems differently, to set different priorities for solving problems, or to respond differently to particular objectives affecting the development of hydrogen technology?
3. What are the different institutions, including the variety of life styles and ways of doing things, which are significant or pervasive enough to program people and events in specific directions, regardless of whether or not they are embodied in public policy?[1] Such an institutionalized factor may significantly affect the prospects for an innovation.

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[1] For example, our tradition of product maximization by an individual firm leads to the externalization of costs--sometimes at the expense of other parties-at-interest or of the environment.

Then, statements specifying conflicting goals and policies can be prepared. An example relating the prospective implementation in a specific setting of environmental protection policy to sometimes conflicting economic and social policy and goals is shown in Figure 6.[1]

From this information a hierarchy of goals, threats, opportunities, and objectives should be tentatively prepared and refined through the course of the project. A brief example was offered in Section I, and in Figure 4. An actual hierarchy should have additional levels specifying policies (both formal and inferred) and layers of objectives which grow increasingly specific as constraints and as time limits for achievement may be added into them. It should emphasize the presumed state of the innovation variables described in Section I.

Energy supply, demand and cost data. The several potential uses of hydrogen suggest that it might be used in several different market structures.[2] Without valid economic data, it will be almost impossible to estimate where, when, or how much hydrogen usage will fit into these market structures. Such data is presently available in fragmented or noncomparable form.

The existing studies and forecasts of energy supply, demand should be collected and reconciled. These should be related to different uses of energy, and should be expressed in comparable units. Energy supply figures involve both fuel reserves and resources and generation or conversion capacity. Energy demand figures are relatively easily reconciled since they are usually expressed in GJ (million Btu), x 10^{18}J quadrillion Btus (Quads), 907 10^6 kg (million tons) of oil equivalent, or megawatt capacity and 3.6 GJ (megawatt hr).

Cost figures are harder to reconcile because they are so often expressed in current dollars rather than constant dollars. They tend to be particularly weak on the components involving fuel costs and capital costs, both of which have been very volatile. Construction costs for energy conversion plants have been increasing at unprecedented rates in the early and mid-1970's. The cost and price relationships of different fuels and different energy systems should be sufficiently reduced to common units of measurement so that the economic considerations in substituting one fuel or one system for another can be reasonably estimated. Confidence levels, on at least a judgmental basis, should be assigned to the varying estimates.

Trends in energy use. Quantities of fuels and energy from different systems being used over time should be plotted and the trends calculated. Price elasticities should be studied and the sensitivity of energy use to cost changes should be analyzed. These economic relationships should be forecast tentatively through both periods, and compared with available forecasts.

Trends in hydrogen-consuming industry. Existing, nonenergy uses of hydrogen should be inventoried. Trends in such consumption should be examined and projected through the forecast periods. The potential of substitution of hydrogen for existing hydrocarbon feedstocks to chemical processing should be evaluated.

Forecasts of the development of the use of different fuels and development of various energy systems, e.g., from government agencies, the Electric Power Research Institute, and the National Petroleum Council should be collected and related to each other. Various technology assessments completed or in process concerning fuels and energy systems should be reviewed. From these, technological obstacles to the development and use of these fuels and energy systems should be identified to the extent possible. Additional information on such technological obstacles should be generated by interviews with knowledgeable persons in industrial firms, research organizations and universities, and energy-related governmental agencies. It may be desirable for personnel from the agency sponsoring this assessment to participate with the assessment contractor personnel in this, as in other technological forecasting aspects of this project.

Similar inquiry should be made into technological obstacles to additional uses of hydrogen as a chemical processing feedstock.

The general context for hydrogen development. This task should embody information generated in previous tasks to describe, textually and graphically, prospective developments in the energy and energy-consuming industries and the relevant portions of the chemical processing industries which might utilize hydrogen. The description should be based in the present and should involve prospective development throughout the forecast period.

The description of this context should be based on a relevance tree[3] of technologies for the production of electric power and heat using various energy forms and systems, and also for the potentially hydrogen-related chemical processing activity. These relevance trees should be similar to those used in the geothermal resource technology assessment,[4] examples of which are presented in Figure 7. These demonstrate a four-level relevance tree examining the context of fusion power generation. Such a relevance tree should be supplemented by a similar undertaking for the

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[1] Gilmore, Bortz, Duff, et al., op cit., p. 15.

[2] The main elements of market structure are: concentration, product differentiation, barriers to entry of new firms, growth rate of market demand, price elasticity of market demand, and ratio of fixed to variable costs in the short run. Richard Caves, American Industry: Structure, Conduct, Performance, Englewood Cliffs, N.J., Prentice-Hall, 1964, p. 16.

[3] "A relevance tree is a hierarchical structure; at each level in the structure, mutually exclusive elements are displayed which, in the aggregate, completely define the next higher level." The Futures Group and Bechtel Corporation, op. cit., p. 131.

[4] Ibid, p. 361.

hydrogen-related chemical processing activity. The general context section in the technology assessment of resource development[1] offers a good model of such a statement as far as energy development is concerned, albeit can be strengthened as far as the policy aspects are concerned. However, in its present form it offers an excellent guide for the context statement.

The data gathered in the previous tasks, and their analysis, furnish the information base for the assessment activity subsumed under "Present Context" on Figure 4.

Forecasts of hydrogen technology development. These forecasts should be undertaken for both forecast periods. They should be based on a technical relevance tree depicting the elements of hydrogen technology. The purpose of this is to help assure all important subsystems and components are considered. This technical relevance tree is presently conceived as a six-level tree and should be drawn in response to the following relevance interrogations:

Level One:	What are the sources and uses of hydrogen under consideration?
Level Two:	What are the outputs of these sources and uses?
Level Three:	What major technologies are associated with the development of the capabilities for these sources and uses?
Level Four:	What applied technological areas are involved in these major technologies?
Level Five:	What systems, processes, or methods are involved in these applied technological areas?
Level Six:	What major components comprise these systems and processes, or what specific techniques are used in these methods? [2]

Interviews with knowledgeable people concerning the appropriate technologies should then be carried on to help identify the future course of the hydrogen-related technologies found significant in the technical relevance tree. The interviews should seek opinions on the seriousness of particular impediments[3] and judgments as to when the impediments might be removed and the inputs of capital, manpower, policy changes, or material resources which would be required to effect the removal of the impediments. Here, as mentioned before, it should be desirable to have scientific and engineering personnel from the agency sponsoring this assessment as participants in the interviewing concerning the development of hydrogen-related technologies.

From this inquiry, and in conjunction with sponsoring agency scientific and engineering personnel or other technical consultants, forecasts of the evolution of hydrogen technology through the forecast periods should be prepared. These should be technological forecasts assuming that necessary inputs should be available and that no external factors such as the innovation variables described earlier will interfere. They should be presented in two cases: one through normal evolution of the market system, and second, through a substantial governmental effort to accelerate the development of hydrogen technology.

If major impediments to achieving successful development of the technology are found, the extent and direction of the assessment effort should be re-evaluated. The criteria for the re-evaluation should be related to the objectives cited on page K-3.

The state of society estimates and forecasts. This statement should relate the policy aspects and constraints in the hierarchy of goals, threats, opportunities and objectives to existing social and economic relationships which may be forecast into the future and which might thus indicate how the components of such a hierarchy would change. For instance, changes in per capita annual consumption of energy might substantially change anticipated requirements for energy by 1985; so might shifts in existing fertility rates or other population variables. Changes in the extent of federal intervention in state activities could be subjectively forecast along such variables as federal intervention in planning, significant federal preemption of state powers in planning and energy siting, the growth trend of federal to state transfer payments (including revenue sharing), the actions of precursor states whose legislation is commonly followed by other states in the same region, urbanization trends, investor confidence trends as manifested by price-earnings ratios of equities, and so forth.

To the extent possible the hierarchy should be related to Bell's model of social structure, polity and culture[4], and prospective changes in these as they relate to the innovation variables described in Section I should be examined. Based on this, changes in the state of society during the forecast period under various specific assumptions would be postulated. Emphasis should be on changes in policies relevant to the hierarchy, specifically as they may affect any of the inputs required for development of hydrogen technology past the prospective impediments.

Scenario development. This should be a two-stage task. First, the state-of-society forecasts, and the related forecasted hierarchies should be integrated with the technological forecasts to lay out two or more scenarios, possible time-phased patterns of the development of hydrogen technology.

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[1] Ibid, p. 26ff.

[2] Ibid, p. 131.

[3] An impediment is defined as any technical condition or deficiency which will materially impede the development of hydrogen technology in the United States to its fullest potential within the next 25 years.

[4] Daniel Bell, op cit.

Major state-of-society variables, policy variables, and any other identified innovation variables could then be altered for testing (at least subjectively) of the sensitivity of the forecasts to variation in the various factors. After one or two iterations of sensitivity testing and examination of the interdependency of these variables, a cross-impact matrix[1] analysis of the relationship of the more important variables may be attempted. Lacking very large resources, cross-impact analysis is generally done with a limited number of variables and on a rather subjective basis. It may well be a useful tool, however, for relating state-of-society forecasts to prospective policy changes.

Satisfactory scenarios specifying both assumptions on change and the sequence of change leading into statements of alternative futures embodying the partial or complete development of hydrogen technology can then be prepared. The scenarios are useful for preliminary identification of prospective impacts[2] of the development of the technology on various interest groups and institutions, and for first-order speculation about the responses to those impacts. Besides the strictly analytical purpose, the scenarios in reasonably brief form, are useful for interviewing to gain information from knowledgeable people for iterative reforecasting of both changes in the technology and in the state of society.

The scenarios, however, are a crude tool even with the assistance of such techniques as trend impact analysis, a forecasting method that permits extrapolations of historical trends to be modified in view of expectations about future events which could influence the trends.[3] In the second phase of the hydrogen technology assessment, an interactive computer model should be sought. It is believed that such a model would permit easier generation of a variety of scenarios, would permit easier examination of their sensitivity to specific variables, would permit more variables to be handled, and could serve as the basis for a simulation game which might have substantial value in the policy analysis phase of the assessment where alternative policies and actions can be examined in a gaming situation involving representatives of the actual interest groups or parties-at-interest to the development of the technology.

First phase subjective impact estimates and identification of responses and pacing factors. Impacts of the development of hydrogen technology and their polarity (are they good or are they bad?) for the major interest groups should be estimated. These estimates should be based on the scenarios and the perceptions of the concerns and values of the different parties-at-interest and interest groups (reinforced by interviewing with representatives of these).

Examples, assessed as among the most important, from a list of 89 significant impacts in the geothermal resource technology assessment[4] include:

- Increased geothermal research and development on environmental matters.
- Improved inflation prospects, compared to a "nongeothermal world."
- Decreased rate of depletion of oil and gas.
- Increased possibility of seismic activity and land subsidence near geothermal installations.
- Creation of new opportunities for crime, e.g., sabotage of wells.
- Relocation of population and use of agricultural and recreational land to accommodate geothermal installations.

From the estimated impacts, prospective societal and policy responses should then be identified. These should be examined for their effect on policy--as expressed in the hierarchy--and for their possible modification of the scenarios on the development of hydrogen technology.

Detailed design of the second phase. The work thus far will presumably have suggested widely diffused areas of usage for hydrogen technology. The areas will have differing degrees of need and significance. The technological development in the areas may have varying rates of advance. These should all be analyzed to set priorities for in-depth technology assessment of the various areas of use; the priorities should be set with the participants of the sponsoring organization.

Based on the priorities, the degree of overlap among areas, and the resources available, one or more in-depth or comprehensive assessments should be designed for completion in the second phase. The design should reflect the recommended logic flow shown in Figure 4.

Phase II. Refinement and Completion of a Hydrogen Technology Assessment

"Inevitably, those doing technology assessment these days are amateurs. Therefore, it should be recognized from the start that a second and a third crack will be needed for a satisfactory

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[1] A technique of cross-impact analysis is at least theoretically available and permits some ordered examination of the relationship between change in one variable and resulting change in another. An input-output matrix of economy can offer a quantitized version of a similar matrix; however, that level of effort is rarely available for this sort of analysis.

[2] Impacts are here defined as changes from the present state of things, or changes from the way things are presently evolving. Impacts are neither "good" nor "bad" in this definition.

[3] This technique was developed by the Futures Group which also developed a computer program facilitating it. It was briefly described in T. J. Gordon's "A Discussion of Some Methods of Technology Assessment," op. cit.

[4] Futures Group and Bechtel Corporation, op. cit., p. 281.

assessment."[1] The speaker was Joseph F. Coates, Staff Director of Congress' Office of Technology Assessment and formerly in charge of the National Science Foundation's technology assessment program. By reason of his present job he has high standards for technology assessments; by reason of his experience, his judgment can be considered sound.

The remainder of this section responds to the Coates doctrine and offers the present view of what the second phase--the second crack--at the hydrogen technology assessment should be, in accord with the logic flow of Figure 4. As mentioned above, the final task of the first phase is to design the second phase work. It is anticipated that the following activities should be carried out in that year-long effort.

Redefine the forecasts of technological development including identification of research and development needs. The relationship of hydrogen technology to existing and prospective energy systems and to chemical processing should be reexamined. This should be done with the participation of scientific and engineering staff of the sponsoring agency, or with consultants. This should involve a re-review of technical judgments and additional inquiry on the likelihood of policy and other innovation factors affecting the sequence of technological development. Based on this, further inquiry should be made of knowledgeable people in the various technological fields to revise the technological relevance tree and to better attach timing estimates (and probability estimates of achievement) to the removal of impediments to the development and use of the technology.

A side benefit of this task is expected to be a set of informed comments and possibly consensus on R & D priorities on advancing hydrogen technology.

Development of an interactive or dynamic model for scenario construction. The model should be designed based on the revised forecast of technological development and the forecasts of response by the social structure, the polity, and the culture. Ideally, the model might be refined to respond to both the announcement effects of responses, e. g. , changes in policy, and to the actual implementation of policy changes. In any case, the model should be amenable to manipulation by introducing alternative policy responses into it, each alternative set of policies being represented by a revised hierarchy.

Systems dynamics, as proposed and demonstrated by Jay W. Forrester, offers an approach to such modeling. The Futures Group has adapted this concept to also encompass the event-handling techniques of cross-impact analysis. If this technique is appropriate to the requirements already defined, it might well be worth incorporating into this methodology. It is called Probablistic Systems Dynamics.[2]

Policy analysis and decision-making simulation. A model should be developed which is adequate for decision-making simulation by a panel of representatives of the major parties-at-interest or interest groups, specifically including government and industry officials. The simulation should be designed to identify responses to events and policies, to note the pacing of events as response and counter-response occur, and to clarify the varying perceptions of impacts, e.g., good or bad?, how good?, how bad?, developed in the assessment.

The simulation should relate alternative futures to differing states of society and to the outcomes of various uses of hydrogen technology. Based on strategic gaming experience, it would supplement the assessment team's cost effectiveness-oriented evaluation of policies and actions relative to the hierarchy's objectives. Both techniques should support the logic flow functions of generating proposed policy modifications for government and action recommendations for firms, institutions, and other parties-at-interest or interest groups.

The Outputs of the Assessment

There should be four major outputs of the entire two-phase project:

(1) The project report. This should report the substance and the methodology of a hydrogen technology assessment. As defined in Section I, The Concept and Rationale for Assessment of Hydrogen Technology, this should describe the ". . . effects on society that may occur when a technology is introduced, extended, or modified, with special emphasis on the impacts that are unintended, indirect, and delayed . . . ." It should also offer guidance for the programming of hydrogen research and development.

(2) The decision-making simulation. This should permit effective identification and assessment of impacts, and evaluation of policies and actions to deal with those impacts in a variety of situations. It should facilitate continuing review of the assessment, and might furnish a substantial base for extending the assessment to cover other uses of hydrogen.

(3) Participative dissemination of the assessment. Involvement of government and industry officials in the decision-making simulation should arouse their interest in hydrogen technology and in policies and actions affecting it. Their involvement should also improve the quality of the assessment. Participation should help restore the principle of Hetman's dialogue, relating technological means to societal ends.

(4) Other options. The need for other assessment action concerning hydrogen technology is uncertain now. The assessment report should recommend (a) appropriate extension of the assessment to other hydrogen uses or areas, (b) review and revision of the assessment as there is change

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[1] Joseph F. Coates, "Conference on Technology and Growth," Ottawa, February 5, 1975.

[2] T. J. Gordon, "A Discussion of Some Methods of Technology Assessment," op. cit.

in anticipations on the technology, the state of society and the innovation variables, national policies, other factors, or assessment methodology, (c) revision or interpretation of the report for specific audiences.

These continuing outputs, if obtained, offer enhanced prospects for timely introduction of hydrogen technology by:

- Relating hydrogen technology development to national goals and problems, justifying investment in the development effort.
- Offering guidance for research and development programming.
- Suggesting institutional arrangements for developing the capabilities to best use new hydrogen technology.
- Identifying pacing factors affecting the development and use of hydrogen technology.

The assessment will help integrate the developing technology with societal needs. Such an effort at well-managed innovation here may also contribute to the entire process for making national energy policy.

SECTION III. THE ENVIRONMENT FOR THE FUTURE DEVELOPMENT AND USE OF HYDROGEN

As is shown in the diagram, the introduction and development of any new technology can be influenced by five major factors. These factors can act to stimulate or as barriers to the introduction.

For example, a recognized societal need will act as a stimulus to the development and introduction of a technology. A similar stimulus may result from the existence of a suitable technology itself. In contrast, societal and environmental concerns may act as barriers to the introduction.

Governmental policies and economic considerations may act either as stimuli or barriers. Legislative or regulatory action may encourage the development of technology by providing a favorable R&D or market environment or may hinder it by favoring alternative systems or technologies. If the economic considerations are attractive then these may be a stimulus to the technology's use. However, under the free enterprise concept of market development, unfavorable economics will prevent the development and introduction of a technology.

Where do we stand with regard to the development and increased utilization of hydrogen technology in the economy . . . in terms of each of these potential stimuli and barriers?

I. Societal Needs - A Stimulus

The underlying societal pressures for the development of new energy sources can be seen in virtually any article describing the future energy needs and potential sources of supply. As D. P. Gregory pointed out in his article, "The Hydrogen Economy:"

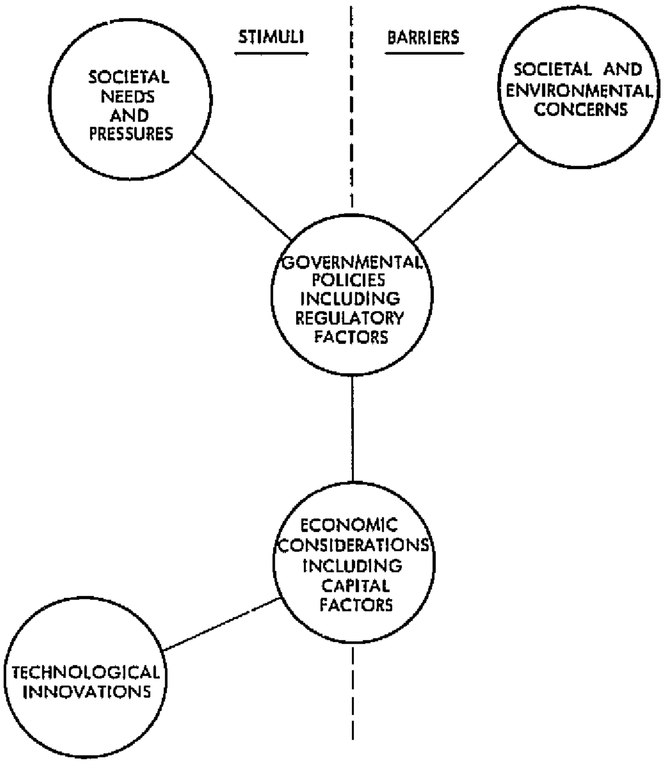

Diagram of factor relations

> The basic dilemma represented by what has been termed the "World Energy Crisis" can be simply stated: At the very time that the world economy in general and the economies of the industrialized countries in particular are becoming increasingly dependent on the consumption of energy, there is a growing realization that the main sources of this energy - the earth's non-renewable fossil-fuel reserves - will inevitably be exhausted.[1]

This realization, coupled with the increasing awareness of the vulnerability of American industry resulting from its dependence on foreign sources of fuel, has led to a growing awareness of the problems facing the U.S. economy . . . and to a growing effort to develop solutions to this problem. There is, therefore, a societal stimulus to the development and utilization of new sources of fuel and new energy systems, irrespective of whether they are based on hydrogen or other energy sources.

To a large extent, however, this societal stimulus stems from the government and energy experts who voice their concern. The mass population, while concerned about increasing fuel bills, etc., has not yet reached a level of concern at which they would demand new energy systems. The situation has not, as yet, reached the dissatisfaction level necessary for widespread action. The 1973 gasoline shortage produced annoyance and vocal outcries but little concerted demand for remedial action. Increased fuel bills and fuel

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[1] Derek P. Gregory, "The Hydrogen Economy." Scientific American, January 1973, Volume 228, No. 1., p. 13.

shortage still appear to be within "acceptable" levels.

Each of the new fuel sources and energy systems has its vocal advocates and researchers. Yet it is impossible, at this time, to state that "the time has come" for any specific technology or energy production system. We presently have a situation in which there is a recognized societal need, but not a critical societal pressure for action.

II. Technical Innovation--A Stimulus

Where does hydrogen technology, which might meet societal needs, stand in terms of being available? To what extent will it act as a widespread stimulus to the usage of hydrogen? To what extent is there a "push" for hydrogen usage?

To put these questions in perspective, we must look at the current state-of-the-art with regard to:

(i) Raw material feedstocks,

(ii) Energy sources,

(iii) Manufacturing processes,

(iv) Transmission of hydrogen, and

(v) Storage of hydrogen.[1]

Table I subjectively estimates the magnitude of the barriers to the manufacture of hydrogen, i.e., the raw material feedstock, energy sources, and the manufacturing process.

(i) Raw Material Feedstocks

Let us look at each of these areas in turn beginning with the potential sources of hydrogen.

(a) Hydrocarbons/fossil fuels.

(b) Water.

(a) Hydrocarbons/Fossil Fuels

The existing hydrogen production processes utilize petroleum or natural gas as the feedstock. The supply of such hydrocarbons is limited and it is forecast that the reserves will be exhausted in a relatively short time. It seems unlikely, therefore, that there will be further extensive development of processes based on petroleum or natural gas feedstocks.

The next step involves the use of the extensive coal deposits which are seen as the alternative to reliance on foreign fuel sources. Coal represents a nonrenewable, potentially polluting, environmentally threatening source of energy. As such, it is often portrayed as an intermediate source of energy to be utilized in the years prior to the development of a "cleaner" technology.[2]

While coal has the advantages of a C-H bond which is relatively easy to break (at least in comparison to the O-H bond), it suffers from the fact the hydrogen content of most coal is less than 10 percent. Thus, the use of coal is not so much as a hydrogen feedstock, but as a source of energy to assist in "splitting" the alternative feedstock, water.

In summary, therefore, the use of coal seems unlikely to be a major stimulus to the production of hydrogen for other than essential uses.

(b) Water

Water is, unlike the fossil fuels, a renewable and potentially nonpolluting and environmentally nonthreatening and nondamaging source of hydrogen. It has, therefore, tremendous appeal.

The problems facing the utilization of water to produce hydrogen are relatively minor. With the exception of certain parts of the country, water is present if it can be obtained at relatively low cost and, if pure water is required, the purification technology is available.

While water may pose no barriers to the production, it is unlikely to provide a major stimulus, since the problems associated with its use stem from the technology and energy costs.

(ii) Energy Sources

The existing energy sources, i.e., fossil fuel combustion and nuclear fission, are available for the production of hydrogen. The usage of the former to produce heat or electricity for the "splitting" of water does not appear an optimal use of this resource. Nuclear fission, however, is an existing source of electricity which will undoubtedly see increased usage in the years to come (assuming environmental protection constraints and economic factors aren't overwhelming barriers). However, the cost of electricity will determine the cost of the hydrogen and there is little evidence which suggests that there will be any great stimulus (for hydrogen usage) from the generation of electricity from nuclear sources. It is possible, however, that hydrogen will be used for the transmission and storage of energy (see below).

The yet-to-be-developed sources of energy, i.e., solar,[3] wind,[3] geothermal,[4] oceanic thermal gradients,[5] and nuclear fusion[6] are in various stages of development. The first three have been demonstrated in limited situations and it seems probable that each of these energy sources will find utilization in specific circumstances during the remaining years of this century.[7] However, considerable work needs to be done on each of these processes before widespread application can be

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[1] For supporting material on the state-of-the-art, see Attachment.

[2] Hydrogen and Other Synthetic Fuels, p. 52.

[3] R. Aiken, "Solar and Wind Power as Alternatives to Fossil Fuels." Science Forum, Vol. 6, No. 5, pp. 7-11, October 1973.

[4] R. A. Bowen and E. A. Groh, "Geothermal-Earths Primordial Energy." Technological Review, Vol. 73, 42-8, 1971.

[5] Office of Coal Research, A Hydrogen Energy Carrier, Volume II, p. 30.

[6] Ibid., p. 20.

[7] R. Aiken, op. cit.

Table 1. Magnitude of Barriers to Utilization--the Manufacture of Hydrogen: Tentative Characterizations

	Barriers		
	Requires Technological Development	Societal and Environmental	Economic
(i) Raw Material Feedstocks			
- Petroleum/natural gas		▱	▱
- Coal		●	▱
- Water		o	o
(ii) Energy Sources (Electricity)			
- Solar	●	o	●
- Wind	●	o	▱
- Fossil fuels		●	●
- Nuclear--fission		▱	▱
- Nuclear-fusion	●	o	▱
- Oceanic thermal gradient	●		N
- Geothermal	●		▱
Energy Sources (heat)			
- Solar	●		●
- Fossil fuels		●	●
- Nuclear--fusion	●		▱
(iii) Manufacturing Processes (fossil fuels)			
- Steam-methane reforming		o	o
- Partial oxidation		o	o
- Steam-oxygen process	o	▱	o
- CO_2 acceptor processor	o	▱	o
Manufacturing Processes (using water)			
- Electrolytic	●		o
- Thermochemical decomp.	●		o
- Direct thermal splitting	●		▱
- Photolysis	●		N
- Biophotolysis	●		N

Key

o Important barriers to usage exist but these should be reasonably easy to overcome.

▱ The barrier to usage will require extensive research and investigation.

● Overcoming the barrier to usage will require massive inputs to achieve resolution.

N Unknown.

expected. Furthermore, it is unclear if these sources of energy will be coupled to hydrolytic units for the production of hydrogen or whether they will merely supplement the existing electricity energy system.

Oceanic thermal gradients and nuclear fusion have only been developed conceptually and still appear to face major barriers to operational usage. Undoubtedly, nuclear fusion will be a most attractive energy source for nationwide usage since it is a non-polluting, renewable process. However, its availability is still far in the future.

In summary, there is still a gap between the available technology and energy sources and a real stimulus to the use of hydrogen. Until this technology is available and a cheap energy source can be obtained, there is unlikely to be any major "push" in the use of hydrogen.

(iii) Manufacturing Processes

Since neither the feedstock nor the energy source appear to provide a dramatic stimulus to hydrogen usage, it is not surprising that the manufacturing processes themseleves suggest little impetus.

First of all, we can look at the fossil fuel-based processes. Among these are those currently used for the commercial production of hydrogen, i. e., steam-methane reforming and partial oxidation. Although there are few barriers to widespread utilization of these processes, the fact that they utilize petroleum or natural gas as the feedstock would make further development seem unlikely. This leaves the coal-based coal-water processes, e. g., steam-oxygen process, the CO_2 (acceptor) process, etc.

Research is being conducted on hydrogen-producing processes and it appears likely that the necessary technology will be available in the next decade.[1] However, there are some real questions as to whether these processes (and an overall approach using coal/steam) will act as a stimulus to hydrogen usage across-the-board. Clearly, this technology (assuming cost comparability) will replace the existing petroleum and natural gas-based processes as a means of producing hydrogen for the chemical uses of hydrogen.

However, the hydrogen technology is very similar to that encountered in the production of methane from coal . . . and in the production of power gas (carbon monoxide and hydrogen) and it is far from clear that hydrogen will be the inevitable output of plants based on coal. It appears likely that such plants will be used to produce whichever product is needed for specific end uses.

Furthermore, as will be covered later, it seems that environmental concerns may well limit coal extraction so that its use may logically be for essential consumption only, rather than its availability serving as a pressure for widespread usage.

In summary, therefore, one would certainly anticipate the use of coal-steam technology for the production of hydrogen but it will not <u>necessarily</u> be a major stimulus factor for the widespread usage of hydrogen.

As far as the water-based processes are concerned, there are a number which can be used to produce hydrogen in a laboratory or on a small scale. There are the electrolytic processes and thermochemical decomposition (closed-cycle) processes. Both approaches have their supporters and could provide the necessary future technology. A study of the literature, however, suggests that these technologies are still far from commercially viable.[2] In the case of electrolytic processes, the current costs of electricity result in hydrogen nearly twice as expensive as that generated from coal.[3] The thermochemical decomposition processes still await the development of usable technology including high-temperature heat exchangers.[4]

Thus, at the present time, there would appear to be little likelihood of these processes acting as a major stimulus for widespread usage.

Other potential processes such as direct thermal splitting, photolysis, etc. all seem to be a long way from commercial usage.[5,6,7] Considerable research is being conducted in each of these areas and it would be unrealistic to suggest that one or the other may not become economically competitive or even advantageous. However, at the present time, none of the processes would appear to represent a major source of stimulation.

(iv) (v) <u>Transmission and Storage of Hydrogen</u>

The major stimulus to the widespread usage of hydrogen would probably come from the availability of the manufacturing process and the necessary energy and feedstock sources. However, it is important to look at both the capability for the transmission and storage of hydrogen not only because they support the usage of hydrogen, but because they are a potential "usage" of hydrogen.

Table 2 subjectively estimates the magnitude of barriers to utilization--in terms of transmission and storage.

From a technological viewpoint, neither the transmission or storage question appear insoluble--given the lead-time inherent in developing the manufacturing process.

Hydrogen can be transmitted either as a gas or cryogenically. There is experience with transmission of a gas and it is known to be feasible. There is the question of whether existing natural gas systems could be used (due to embrittlement, changeover costs, etc.)[8] but solution to these problems would follow specific transmission needs, i.e., the evaluation of whether to utilize an existing pipe or build a new one.

Cryogenically, we currently ship liquid hydrogen using tractor-trailers and tank cars with minimal problems. The use of tanker ships or barges will pose some technical problems, but these can probably be overcome. Pipeline transmission would appear to pose greater technological problems (whether or not in combination with electricity transmission) and would appear further

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[1] Office of Coal Research, op. cit., p. 30.

[2] Office of Coal Research, op. cit.

[3] E. M. Dickson, J. W. Ryan, and M. H. Smulyan, "A Technology Assessment of the Hydrogen Economy Concept," <u>THEME</u> 1974.

[4] J. Douglas Balcomb and Lawrence A. Booth, "High-Temperature Nuclear Reactors as an Energy Source for Hydrogen Production," <u>THEME</u> 1974.

[5] R. E. Chao and K. E. Cox, "An Analysis of Hydrogen Production via Closed-Cycle Schemes, <u>THEME</u> 1974.

[6] S. N. Paleocrassas, "Photolysis of Water as a Solar Energy Conversion Process: An Assessment," <u>THEME</u> 1974.

[7] W. R. Parrish et al, <u>Selected Topics on Hydrogen Fuel</u>, p. 19.

[8] Office of Coal Research, op. cit., p. 30.

Table 2. Estimated Magnitude of Barriers to Utilization-Transmission and Storage: Tentative Characterizations

	Barriers		
	Requires Technological Development	Social and Environmental	Economic
(iv) Transmission-Gaseous			
- Existing pipelines	□		
- New pipeline system		o	•
- Combined new/old system	□		o
- Dirigibles	□	o	o
Transmission-Cryogenic			
- Tank car/railroad		o	o
- Tanker ships/barges	o	o	□
- Pipeline		o	□
- Pipeline/electricity	o	o	•
(v) Storage-Gaseous			
- Tank		o	o
- Underground	□	□	
Storage-Liquid	o		o
Storage-Solid Hydride	•		□

Key:

o	Important barriers to usage exist but these should be reasonably easy to overcome.
□	The barrier to usage will require extensive research and investigation.
•	Overcoming the barrier to usage will require massive inputs to achieve resolution.
N	Unknown.

distant in the time spectrum--especially given the unattractive economics of these alternatives.

Hydrogen storage would seem to pose some real technical problems, although again not insuperable given the overall time horizon. The major problem may well be that of sealing up existing known technologies.

Storage in a gaseous form is a known technology in terms of tanks, but has yet to be proven for underground storage where environmental problems may prove paramount. Liquid hydrogen can be stored in volumes of up to a million gallons and larger tanks should be feasible where the necessary liquifaction facility is available. A key question will be the economics of maintaining the hydrogen in liquid form. Finally, hydride storage remains a possibility although it still awaits the development of large-scale systems.

In view of the relatively low pressures involved in the distribution system, it appears likely that the network currently in place would be usable for hydrogen distribution if there are not extensive embrittlement problems.

In summary, the transmission, storage and distribution problems seem relatively minor in comparison to a substantial basic need for a hydrogen system. It is not believed that they will greatly retard the "push" of hydrogen if the technology and energy source were to become available.

The interesting aspect of hydrogen transmission and storage is its possible usage as a means of distributing energy. It has been suggested by many individuals that "off-peak" (or other surplus) power will be used to produce hydrogen, which can be stored (or transmitted and stored) for use during times of high demand to augment the normal operation.[1, 2] If this were to occur (and other learned individuals have stated that the country's energy needs and the current rate of construction of nuclear plants make it highly unlikely) then a major development in the usage of hydrogen would be as an energy medium.

The obvious potential user of hydrogen for energy transmission and storage purposes are the energy (electricity) producers who do not have

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[1] Kenneth C. Hoffman, "Economics of Hydrogen Energy Systems." Hydrogen Energy Fundamentals, A Symposium Course, Miami, 1975.

[2] H. Lee Craig, Jr., "The Production of Hydrogen by Electrochemical Means." THEME, 1974.

alternative storage mechanisms available, e.g., pumped water storage facilities, or who need energy available (in a storable form) at a distant location for electricity production. This would appear to be basically an internal usage wherever the economics are attractive to the energy generator. There may well be additional uses at the end of the pipeline or near a storage facility, but these are likely to be incremental to the basic use.

III. Economic Considerations--a Stimulus or a Barrier

If the delivered cost of hydrogen at the user's location is below that of alternative sources of energy, assuming comparable environmental impacts, then there may exist a "pull" stimulus to the usage of hydrogen. The strength of the "pull" depends upon the extent to which hydrogen is the cheaper fuel. The other factor which a potential user takes into consideration is availability. Availability has a value for which the user may be prepared to pay an additional price. For example, a regular sure supply may be infinitely preferable to a cheaper, less certain source of supply.

As R. G. Murray comments, "Hydrogen serves in two modes, as a fuel and as a chemical."[1] Table 3 subjectively estimates the magnitude of the barriers in the end uses of hydrogen in each of these modes.

(i) Industrial - Chemical

There is little question but that the usage of hydrogen as a chemical will, in fact, show substantial increases.[2] Much of this increase will come from new uses of hydrogen in the chemical field.

Two points are important. First, this increase in hydrogen consumption can be satisfied without any major breakthrough in hydrogen technology. It can be coal-based usage. Second, these demands can, and probably will be met without a dramatic surge in usage of hydrogen for non-traditional end-uses.

(ii) Industrial - Fuel

There appear to be no insuperable barriers to the use of hydrogen as an industrial fuel. The extent to which it is so used will depend upon the

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[1] R. G. Murray, "Hydrogen as an Energy Carrier." THEME, 1974.

[2] Graham C. Taylor and Richard Doran, The Market for Metal Hydrides (Denver: University of Denver Research Institute, March 1973), p. 4.

Table 3. Estimated magnitude of barriers to utilization - end users: Tentative characterizations

	Barriers		
	Requires Technological Development	Societal and Environmental	Economic
(i) Industrial-Chemical			○
(ii) Industrial-Fuel			○
(iii) Electrical Power Generation	▱	○	▱
(iv) Residential and Commercial	●	▱	▱
(vi) Transportation			
- Aviation (commercial)	●	○	●
- Aviation (general)	●	▱	●
- Public (ground)	●	▱	●
- Commercial vehicles	▱	▱	▱
- Automobiles	▱	●	●
- Agricultural/ construction	●	▱	▱
- Recreational	●	●	●
- Oceanic	●	▱	▱
- Small power plants	●	●	▱

Key

○ Important barriers to usage exist but these should be reasonably easy to overcome.

▱ The barrier to usage will require extensive research and investigation.

● Overcoming the barrier to usage will require massive inputs to achieve resolution.

N Unknown.

delivered cost (and availability) relative to existing fuels, e.g., natural gas.

It is likely, therefore, that hydrogen as a fuel will be used in those circumstances where a hydrogen supply exists for chemical purposes and where the cost of hydrogen as a fuel may be considered as "incremental."

(iii) Electrical Power Generation

The use of hydrogen for electric power generation is a major potential stimulus for expanded utilization. At the present time, electrical power generation is based on coal (ca. 47%), natural gas (ca. 24%), hydropower (ca. 15%) and liquid hydrocarbons (ca. 13%).

The extent to which hydrogen will play an active role in this usage will depend largely upon the relative costs (in terms of delivered energy) and availability. Confusing the magnitude of this "pull" on the system (in terms of hydrogen consumption) is the fact that the utilities would probably be as willing to adopt alternative gaseous fuels, e.g., power gas, if the cost were comparable. The decision will undoubtedly be made on the basis of the relative economics at that time.

(iv) Residential and Commercial

Residential and commercial usage of hydrogen faces some technical problems although, in general, these appear to be soluble. However, these uses would be implemented only (a) as new installations or (b) as a widespread changeover in a region or area. Again, it appears to be a question of cost. Once the usage of hydrogen becomes competitive economically with existing fuels then it is conceivable that a "pull" stimulus would exist. However, this "pull" is unlikely to derive from either the household consumer or the equipment manufacturer. The former is unlikely to be concerned unless the savings are 20-40% and the latter will undoubtedly follow the existence of an energy supply.

The most likely "pull" would be the economic one generated by the utilities. If they can see the economic benefits, including those from a more reliable supply, of a changeover to hydrogen (even allowing for adaptation costs) then they may wish to implement it in specific geographic areas.

The major "pull" leading to a dramatic increase in the usage of hydrogen will come from a changeover from an existing fuel to hydrogen. For this, one must evaluate potential use of hydrogen in transportation or residential and commercial stiuations.

Transportation is an interesting and complex question from the viewpoint of hydrogen. At the present time, it is difficult to identify many situations where the cost of hydrogen (in any form) would approach the cost of the existing fuel. Yet, as we have seen in recent years, these cost relationships can change dramatically. Thus, it is not unrealistic to envisage hydrogen as an attractive fuel in some aspects of transportation . . . leading to, for a period of time, a dual system.

Dual systems are not unheard of. We currently have electric vehicles, regular gasoline vehicles and non-leaded gas vehicles. This situation exists largely because of environmental regulation. The cost relationships affected by such regulations are not yet fully known. It is conceivable, therefore, that a liquid-hydrogen metallic hydride, on a hydrogen-oxygen fuel cell vehicle could be added. Fairly obviously, however, the cost of adopting an alternative system would be a massive one--both in terms of the capital investment in the production facilities and the investment necessary in the service end of the business. Operating costs would also be increased due to safety, training, and control needs. With very few exceptions, it appears unlikely that there will be a major clamor from the manufacturers for such a changeover.

An exception to this generalization might be the airline companies which are accustomed to high costs associated with the introduction of new models of aircraft. The use of liquid hydrogen as a replacement for aviation fuel appears attractive in that it enables more efficient usage of the energy with greater potential payloads. While there are major problems to be solved in this usage, e.g., handling, availability overseas, etc., this does appear an attractive usage which could become a reality if the cost of aviation fuel increases dramatically. Reduced pollution problems might also be a consideration.

As far as other uses are concerned, it seems more likely that a move would be made to an intermediate position, e.g., the use of methanol as an extender of existing fuels, or a changeover to a greater usage of electricity in transportation vehicles through the development of more effective battery-storage systems.

In summary, the "pull" looks rather weak as of 1975. The magnitude of the future "pull" will be determined very largely by the economics, possibly in combination with regulatory action. Once the economics are comparable, then convenience will become important. It is true, however, that no corporation or user is going to rush into the usage of another fuel system requiring a major capital investment unless there are considerable economic advantages.

IV. Societal and Environmental Concerns

As mentioned above (see Section I) there exist societal pressures for the development of new fuel sources. Far more vocal are those interest groups concerned about the environmental impact of the development of such energy sources. These environmental concerns encompass such issues as:

- Impact of extensive coal mining.
- Dangers of nuclear waste.
- Impact of thermal pollution, etc.

In addition to these environmental concerns, there are growing societal concerns over:

- Disruptive exploitation of a state's resources.
- Impact of rapid subregional population growth on the quality of life, services provided, health, etc.

The extent to which these concerns will impact the development of hydrogen technology (and vice versa) is a key question which will require in-depth analysis. It is noticeable that environmental concern tends to wilt in the face of gasoline shortages and blackouts.

The "let the environmentalists freeze in the dark" attitude may prove to be the winning one. Yet, these are likely to be serious political issues with profound political impact.

One can foresee that the societal and environmental concerns have a variety of different effects:

- A "slowing down" effect in which the country will continue to rely on foreign fuel sources (at increasing prices) until nonpolluting, renewable energy technology becomes available.
- A "let it happen, we need the energy" effect in which there would be a rapid changeover to an intermediate technology based on coal.
- A "massive effort" effect to stimulate the development of the non-polluting, renewable energy technology thus by-passing the intermediate technology.

It is clear, however, that the societal and environmental concerns will have a dramatic impact--especially in terms of setting regional or area policies. Our ability to judge the nature of these impacts will depend upon the extent to which response by different interest groups to potential scenarios can be predicted.

V. Governmental Policies

The federal and state governments can have a major impact on the development and use of any technology. In the case of hydrogen this impact may prove to be crucial.

At the federal level, the impact is currently in terms of organizational structures, planning, objectives, and research and development effort. The emphasis is on the thinking and planning for the future. Yet there are also indirect impacts in terms of regulatory activities. For example: legislation on strip-mining, which will directly affect the environment in which alternative energy systems will have to be evaluated. Legislation has, and will continue to stimulate or retard certain energy sources or development.

However, the federal government may choose (possibly under pressure from world energy prices) to act more directly through the impositions of taxes to greatly reduce consumption of a particular fuel source. . . and since the economics are the key factor, directly stimulate the development of alternative fuel sources.

At the state level, it is more likely that the state governments will impose taxes on the extraction of raw materials, on the export of such raw materials (including for example, water), and upon the energy sources produced within the state. The objective of these taxes will be not only fiscal but also to use the income from non-renewable resources to counterbalance the societal and environmental impacts.

The states may also impose legislation considerably stricter than the federal ones to limit exploitation of the resources. Whether the federal government will accept such maneuvers is open to question.

Taxes and limitations to development will have the net effect of increasing the cost of existing energy sources thus making the development of alternative energy systems even more attractive.

There have been a number of attempts made at developing scenarios relating to the future development and utilization of hydrogen. These scenarios vary in terms of:

(a) The assessment of the present decision-making environment.

(b) The assumptions made with regard to future developments, and

(c) The detail supporting the assumptions.

In a complex system such as the one under consideration in the case of hydrogen, it is very easy to ignore certain key factors. The output is impressive but potentially fallacious. All it says is that the future will be as indicated--given those inputs. It is basically a static system.

There is, further, a tendency to pick on certain key assumptions as indicative of specific "types" of scenario. For example, the assumption that the federal government will take a particular course of action leads to a chain of events and associated level of utilization.

The problem with this approach is that, with the exception of providing materials for articles, it is unlikely to be of value. Any attempt to model an extremely complex system in terms of relatively simple parameters will undoubtedly result in relatively simplistic outputs.

This raises the question of the role of scenarios. The current scenarios--although they tend to avoid societal and environmental factors and impacts--do act as the basis for discussion. Is this sufficient? It would appear that the objective should be something more substantial than a basis for discussion. The objective, we believe, should be the development of an interactive model which can continually respond to various inputs, e.g., foreign oil prices, domestic taxes, etc. Then we are describing an operational model.

The scenarios which exist tend to reinforce many of the conclusions which are reached in the earlier parts of this section, i.e., they question the rapid utilization and adoption of hydrogen technology and tend to agree, in general terms, with the order of potential usage. As Dickson et al comment:

> "Ignoring the relative cost factor (which could only delay interest in hydrogen), the time scale when hydrogen implementation could reach a significant scale is so distant . . ."[1]

Whether one can, in fact, ignore (as this study or model did) the relative cost of energy in the form of hydrogen is possibly the most important question. It would seem to these authors that the relative economics of hydrogen utilization will be the determinants of its usage. For example, the "strong government forcing" scenario sees 100% penetration of the automobile market by the year 2000. In contrast, the "optimistic free choice" scenario sees this as not occurring prior to 2025 and the "plausible free choice" scenario sees a

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[1] Dickson, Ryan, and Smulyan, op. cit.

more distant utilization. Yet, a five dollar/gallon tax on gasoline would surely stimulate a more rapid changeover to another fuel, if not hydrogen.

It is simplistic to consider hydrogen as the sole new entrant into the energy scene. Methanol, ammonia, hydrazine as well as electricity may be the future fuel, leaving hydrogen for chemical usage alone.

A meaningful model must take into consideration all the alternatives. There is no single scenario or two or three most probable scenarios, there is a spectrum of scenarios. The "tune" played on the spectrum depends on the "strings" plucked by the various players. The most "probable" scenario of today may become the "least probable" tomorrow.

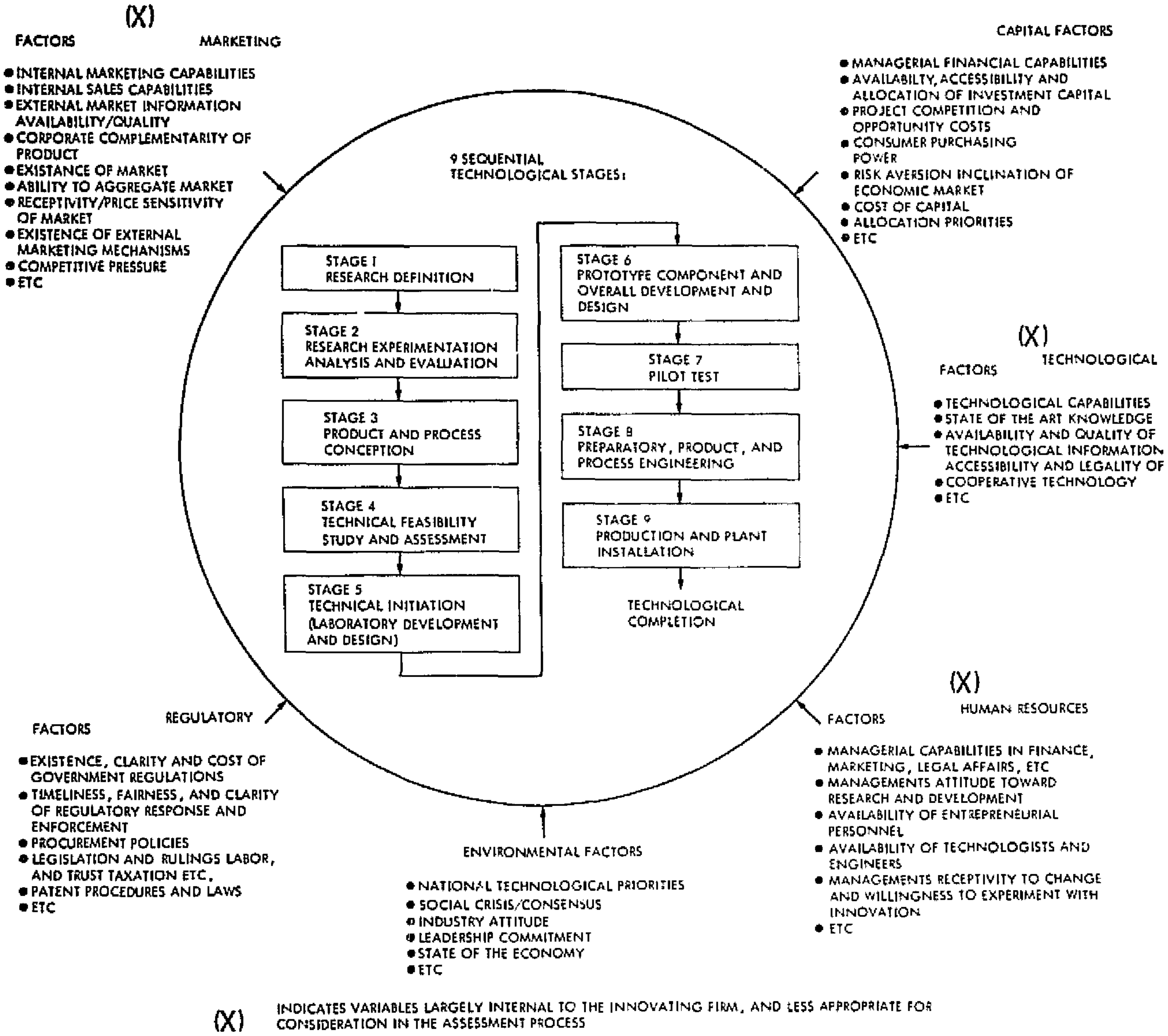


Figure 1. The sequential stages of the private sector innovation process leading to the first application of new technology and selected institutional and environmental factors

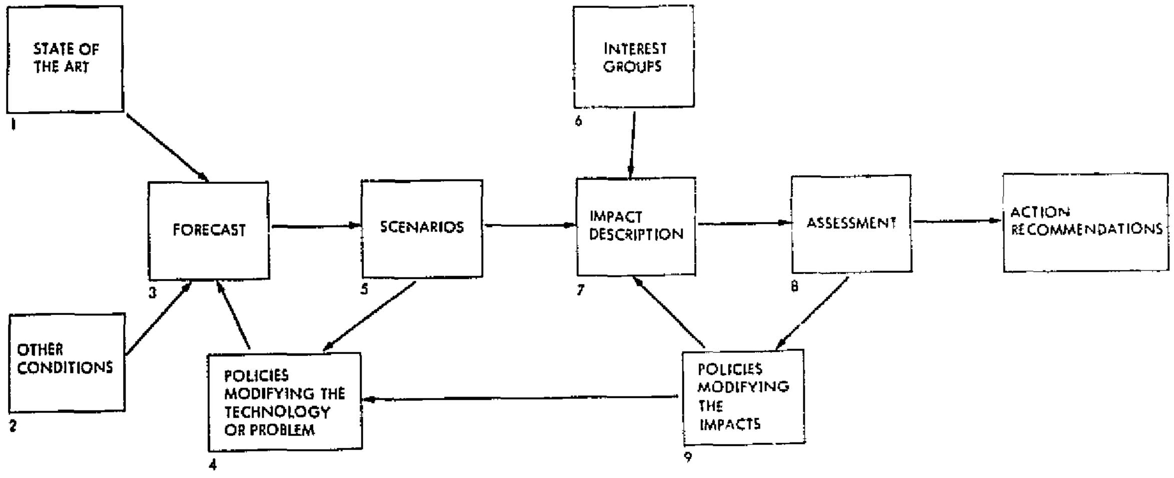


Figure 2. Technology assessment logic flow

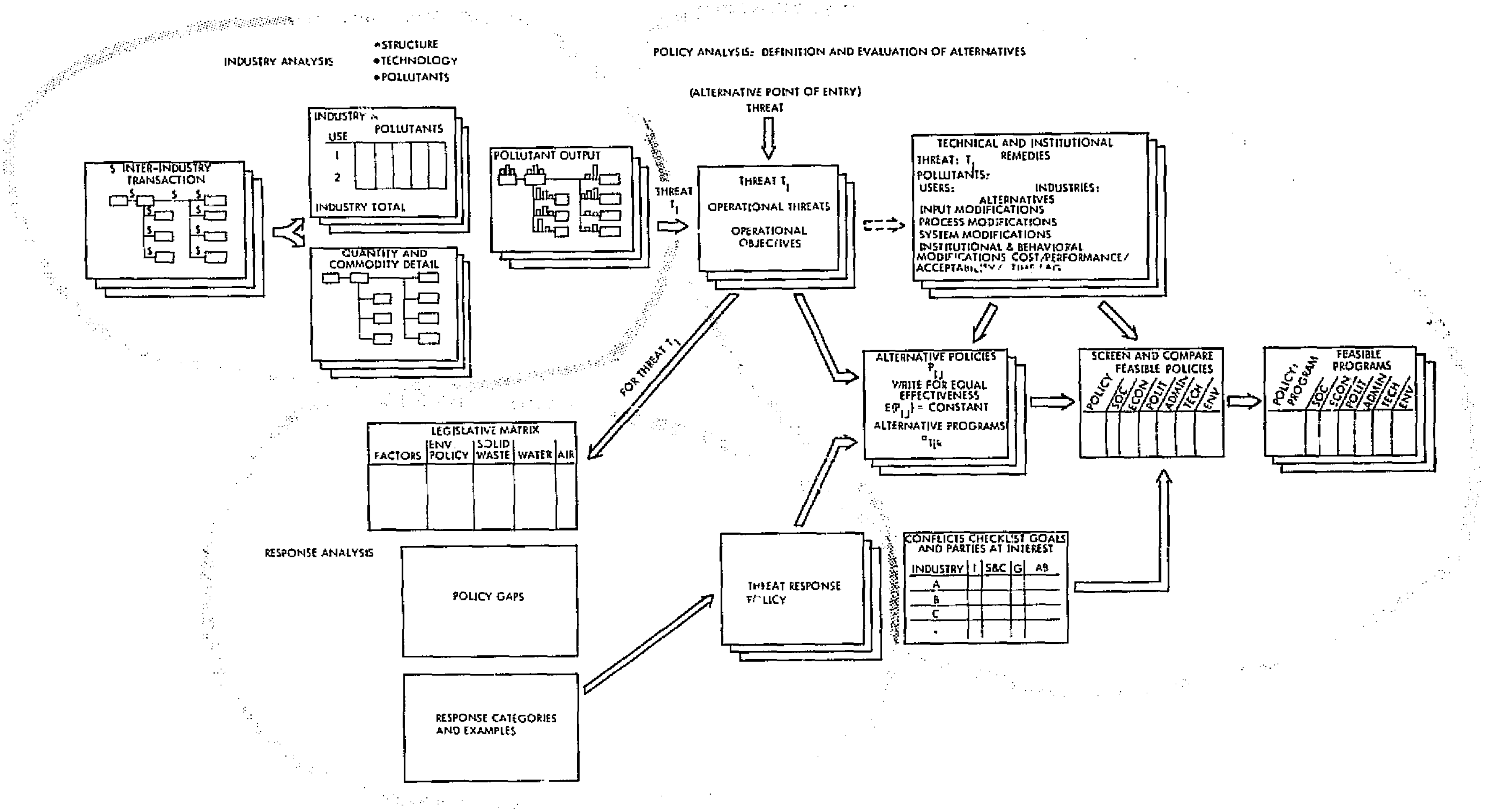
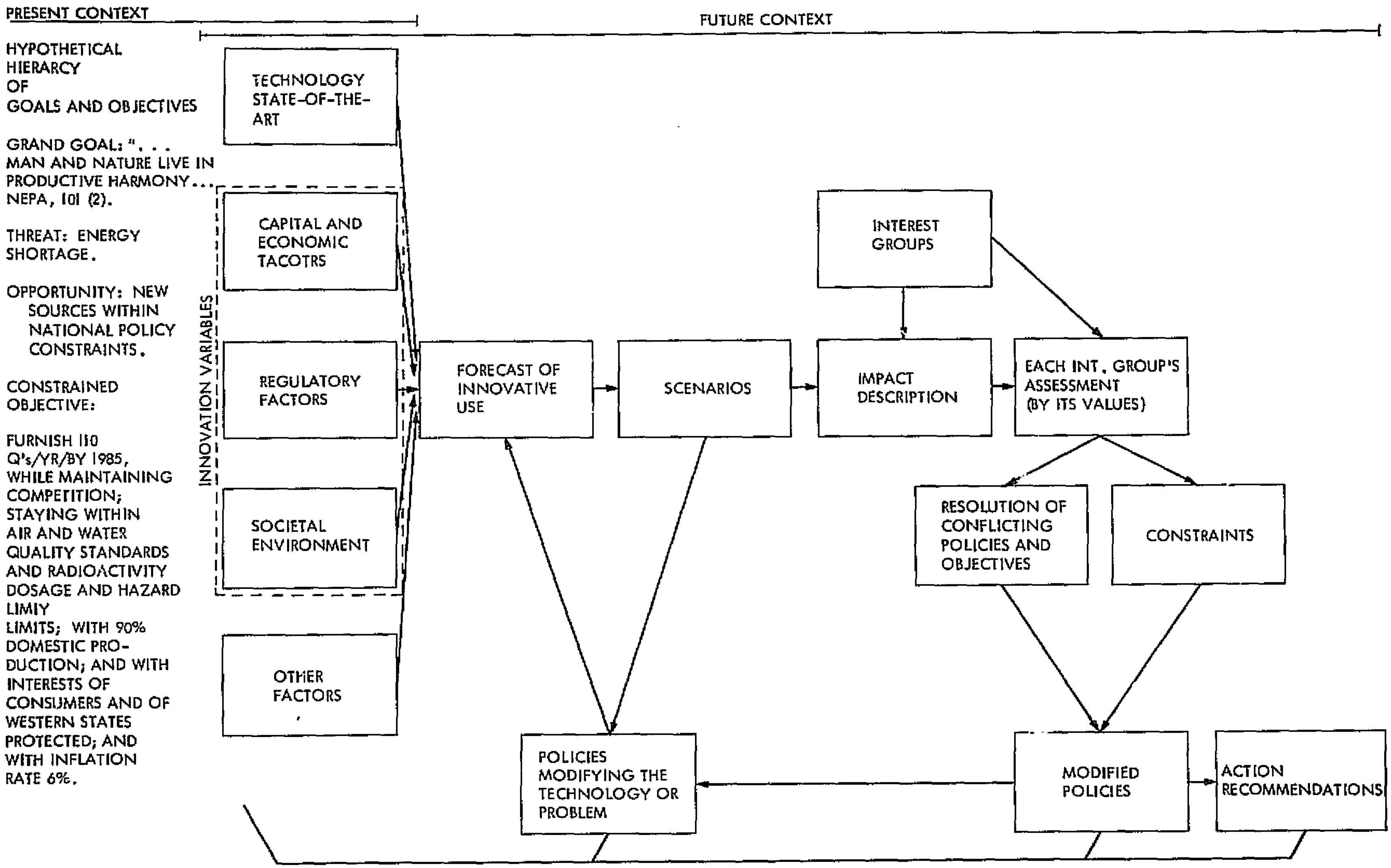


Figure 3. Sequence of procedures: Methodology for analyzing public policy intervention in inter-industry flows of goods and services to reduce pollution



HYPOTHETICAL
HIERARCY
OF
GOALS AND OBJECTIVES

GRAND GOAL: ". . . MAN AND NATURE LIVE IN PRODUCTIVE HARMONY... NEPA, 101 (2).

THREAT: ENERGY SHORTAGE.

OPPORTUNITY: NEW SOURCES WITHIN NATIONAL POLICY CONSTRAINTS.

CONSTRAINED OBJECTIVE:

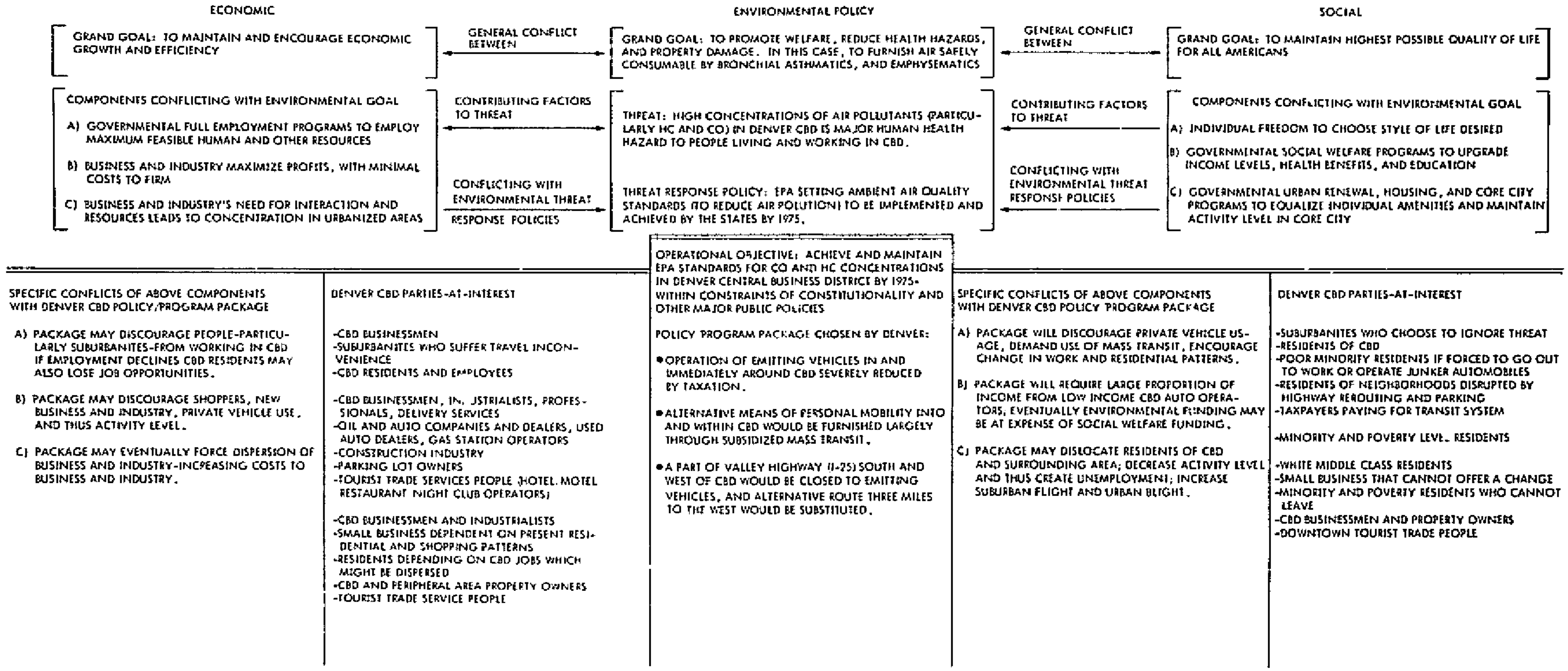
FURNISH 110 Q's/YR/BY 1985, WHILE MAINTAINING COMPETITION; STAYING WITHIN AIR AND WATER QUALITY STANDARDS AND RADIOACTIVITY DOSAGE AND HAZARD LIMIY LIMITS; WITH 90% DOMESTIC PRODUCTION; AND WITH INTERESTS OF CONSUMERS AND OF WESTERN STATES PROTECTED; AND WITH INFLATION RATE 6%.

Figure 4. Synthesized methodology for technology assessment

	ENVIRONMENTAL POLICY ACT	SOLID WASTE	AIR POLLUTION CONTROL	WATER POLLUTION CONTROL
CHANGE FACTORS:				
TECHNOLOGY CHANGE AND PROGRESS	ENCOURAGE PRODUCTIVE HARMONY BETWEEN MAN AND ENVIRONMENT	X	NEW SOURCE STANDARDS	
POPULATION GROWTH	ACHIEVE BALANCE BETWEEN POPULATION AND RESOURCE USE	X	X	
ECONOMIC GROWTH AND ACTIVITY: INDUSTRIAL EXPANSION	MAINTAIN HIGH LIVING STANDARDS: WIDE SHARING OF AMENITIES	X	LAND USE IN IMPLEMENTATION PLANS DEVELOP IMPROVED PROCESSES AND PLANT DESIGN	
URBANIZATION-MULTIPLE JURISDICTIONS	X		ENCOURAGE REGIONAL BASIN PROGRAMS	ENCOURAGE REGIONAL BASIN PROGRAMS
RESOURCE EXPLOITATION AND DEPRECIATION	ENCOURAGE MAXIMUM RECYCLING	ENCOURAGE RESOURCE RECOVERY SYSTEMS	X	NO OFFSHORE OR CONTIGUOUS COASTAL AREAS SPILLAGE FROM DRILLING OR VESSELS
TRANSPORTATION (INCREASING USE)		X	AUTO STANDARDS; TRANSPORTATION PLAN IN IMPLEMENTATION DEVELOPMENT OF LOW EMITTING VEHICLES, MORE EFFICIENT FUELS	CONTROL OF OIL FROM VESSELS CONTROL OF VESSEL SEWAGE
THREATS:				
HUMAN HEALTH HAZARDS	ASSURE SAFE, HEALTHFUL, ECONOMICALLY PRODUCTIVE ENVIRONMENT	PROMOTE RESEARCH TO ELIMINATE ADVERSE HEALTH EFFECTS	PROMOTE HEALTH AND WELFARE AND THE PRODUCTIVE CAPACITY	X
SCENIC BLIGHT	MAINTAIN PLEASING SURROUNDINGS	X		X
POLLUTION OF AIR, WATER, LAND	PROMOTE EFFORTS TO ELIMINATE DAMAGE TO ENVIRONMENT	ENCOURAGE RESOURCE RECOVERY	NATIONAL AIR QUALITY STANDARDS	ESTABLISH NATIONAL POLICY FOR PREVENTION AND CONTROL OF WATER POLLUTION
ENVIRONMENTAL DEGRADATION	RESTORE AND MAINTAIN ENVIRONMENT	ENCOURAGE SOLID WASTE MANAGEMENT SYSTEMS	NOISE ABATEMENT FROM AIRCRAFT, AUTOS	CONSIDER STREAM FLOW REGULATION: CONTROL IN RESERVOIR PLANNING (NON-REIMBURSEABLE)
WELFARE OF MAN DAMAGE TO FISH AND WILDLIFE PROPERTY DAMAGE	PRESERVE HERITAGE; SUPPORT DIVERSITY AND VARIETY OF INDIVIDUAL CHOICE	X	"HEALTH AND WELFARE" STANDARDS	HAZARDOUS SUBSTANCES CONTROL MINE WATER DEMONSTRATION PROJECT GREAT LAKES DEMONSTRATION FWQA CRITERIA PESTICIDE CONCERNS: ESTUARINE CONCERNS: PERMIT SYSTEM (1899 ACT) CONSERVE WATERS FOR PUBLIC WATER SUPPLY: (FISH, WILDLIFE AND AGRICULTURE
INFERRED OBJECTIVES:				
INFERRED AWARENESS OF BUREAUCRATIC SUBOPTIMIZATION	COORDINATION FUNCTION OF EPA (BY EXECUTIVE ORDER): 102 STATEMENTS:GOVERNMENT AGENCIES MUST CONFORM TO ENVIRONMENTAL POLICY	INTERGOVERNMENTAL PROBLEMS: FEDERAL AGENCIES MUST CONFORM (HIGHWAYS AND STRUCTURES)	MULTIPLE JURISDICTION PROBLEMS REGIONAL PLANNING EMPHASIS FEDERAL AGENCIES MUST CONFORM ENCOURAGE COOPERATIVE ACTIVITIES BY FEDERAL DEPARTMENTS, AGENCIES	ENCOURAGE COOPERATIVE PLANNING AND EFFORT; FEDERAL AGENCIES MUST CONFORM
INFERRED LACK OF INCENTIVE FOR PRIVATE R&D TO REDUCE POLLUTION		R&D PROGRAMS - INCENTIVES TO ACCELERATE RESOURCE RECOVERY	R&D PROGRAMS; TECHNICAL SERVICES AND FINANCIAL AID	R&D PROGRAM TECHNICAL SERVICES AND FINANCIAL AID: GRANTS FOR CONSTRUCTION PROVIDE ADEQUATE SUPPLY OF TRAINED PERSONNEL
INFERRED LACK OF WILLINGNESS AND RESOURCES IN STATE AND LOCAL PLAN AND ENFORCEMENT	FINANCIAL AND TECHNICAL ASSISTANCE	TECHNICAL SERVICES AND FINANCIAL AID; TRAINING PROGRAMS	FEDERAL PROVISION OF IMPLEMENTATION PLANS IF NEEDED- AND ENFORCEMENT FEDERAL MONEY FOR STATE AND LOCAL PLANNING AGENCIES/PROGRAMS	FEDERAL PARTICIPATION IN COMPREHENSIVE PLAN TO CONSERVE NAVIGABLE WATER SUPPLY; WILDLIFE: RECREATION: AGRICULTURE AND INDUSTRY USERS
INFERRED LACK OF KNOWLEDGE AND FAILURE TO ASSESS CONSEQUENCES	MAKE AVAILABLE INFORMATION USEFUL IN RESTORING ENVIRONMENT	SETTING OF GUIDELINES	CITIZENS SUITS: 102 STATEMENTS PUBLISHED EARLY ASSIGNMENT OF FEDERAL EMPLOYEES TO STATE AND LOCAL GOVERNMENTS: TRAINING PROGRAMS MANDATORY PATENT LICENSING COLLECT AND DISSEMINATE INFORMATION	SECRETARY MAY IMPOSE CRITERIA AND ENFORCEMENT ON STATE PROMOTE INTERSTATE COOPERATION AND UNIFORM LAWS DEMONSTRATION PROTEST SUBSIDIES TRAINING PROGRAMS SUPPORT TECHNICAL RESEARCH

NOTE: X = MENTIONED IN LEGISLATION

Figure 5. Matrix of environmental objectives and program responses in federal legislation (as of 1971)



ECONOMIC

GRAND GOAL: TO MAINTAIN AND ENCOURAGE ECONOMIC GROWTH AND EFFICIENCY

COMPONENTS CONFLICTING WITH ENVIRONMENTAL GOAL

- A) GOVERNMENTAL FULL EMPLOYMENT PROGRAMS TO EMPLOY MAXIMUM FEASIBLE HUMAN AND OTHER RESOURCES
- B) BUSINESS AND INDUSTRY MAXIMIZE PROFITS, WITH MINIMAL COSTS TO FIRM
- C) BUSINESS AND INDUSTRY'S NEED FOR INTERACTION AND RESOURCES LEADS TO CONCENTRATION IN URBANIZED AREAS

ENVIRONMENTAL POLICY

GRAND GOAL: TO PROMOTE WELFARE, REDUCE HEALTH HAZARDS, AND PROPERTY DAMAGE. IN THIS CASE, TO FURNISH AIR SAFELY CONSUMABLE BY BRONCHIAL ASTHMATICS, AND EMPHYSEMATICS

THREAT: HIGH CONCENTRATIONS OF AIR POLLUTANTS (PARTICULARLY HC AND CO) IN DENVER CBD IS MAJOR HUMAN HEALTH HAZARD TO PEOPLE LIVING AND WORKING IN CBD.

THREAT RESPONSE POLICY: EPA SETTING AMBIENT AIR QUALITY STANDARDS (TO REDUCE AIR POLUTION) TO BE IMPLEMENTED AND ACHIEVED BY THE STATES BY 1975.

SOCIAL

GRAND GOAL: TO MAINTAIN HIGHEST POSSIBLE QUALITY OF LIFE FOR ALL AMERICANS

COMPONENTS CONFLICTING WITH ENVIRONMENTAL GOAL

- A) INDIVIDUAL FREEDOM TO CHOOSE STYLE OF LIFE DESIRED
- B) GOVERNMENTAL SOCIAL WELFARE PROGRAMS TO UPGRADE INCOME LEVELS, HEALTH BENEFITS, AND EDUCATION
- C) GOVERNMENTAL URBAN RENEWAL, HOUSING, AND CORE CITY PROGRAMS TO EQUALIZE INDIVIDUAL AMENITIES AND MAINTAIN ACTIVITY LEVEL IN CORE CITY

SPECIFIC CONFLICTS OF ABOVE COMPONENTS WITH DENVER CBD POLICY/PROGRAM PACKAGE

- A) PACKAGE MAY DISCOURAGE PEOPLE-PARTICULARLY SUBURBANITES-FROM WORKING IN CBD IF EMPLOYMENT DECLINES CBD RESIDENTS MAY ALSO LOSE JOB OPPORTUNITIES.
- B) PACKAGE MAY DISCOURAGE SHOPPERS, NEW BUSINESS AND INDUSTRY, PRIVATE VEHICLE USE, AND THUS ACTIVITY LEVEL.
- C) PACKAGE MAY EVENTUALLY FORCE DISPERSION OF BUSINESS AND INDUSTRY-INCREASING COSTS TO BUSINESS AND INDUSTRY.

DENVER CBD PARTIES-AT-INTEREST

-CBD BUSINESSMEN
-SUBURBANITES WHO SUFFER TRAVEL INCONVENIENCE
-CBD RESIDENTS AND EMPLOYEES

-CBD BUSINESSMEN, INDUSTRIALISTS, PROFESSIONALS, DELIVERY SERVICES
-OIL AND AUTO COMPANIES AND DEALERS, USED AUTO DEALERS, GAS STATION OPERATORS
-CONSTRUCTION INDUSTRY
-PARKING LOT OWNERS
-TOURIST TRADE SERVICES PEOPLE (HOTEL. MOTEL RESTAURANT NIGHT CLUB OPERATORS)

-CBD BUSINESSMEN AND INDUSTRIALISTS
-SMALL BUSINESS DEPENDENT ON PRESENT RESIDENTIAL AND SHOPPING PATTERNS
-RESIDENTS DEPENDING ON CBD JOBS WHICH MIGHT BE DISPERSED
-CBD AND PERIPHERAL AREA PROPERTY OWNERS
-TOURIST TRADE SERVICE PEOPLE

OPERATIONAL OBJECTIVE: ACHIEVE AND MAINTAIN EPA STANDARDS FOR CO AND HC CONCENTRATIONS IN DENVER CENTRAL BUSINESS DISTRICT BY 1975- WITHIN CONSTRAINTS OF CONSTITUTIONALITY AND OTHER MAJOR PUBLIC POLICIES

POLICY PROGRAM PACKAGE CHOSEN BY DENVER:

- OPERATION OF EMITTING VEHICLES IN AND IMMEDIATELY AROUND CBD SEVERELY REDUCED BY TAXATION.
- ALTERNATIVE MEANS OF PERSONAL MOBILITY INTO AND WITHIN CBD WOULD BE FURNISHED LARGELY THROUGH SUBSIDIZED MASS TRANSIT.
- A PART OF VALLEY HIGHWAY (I-25) SOUTH AND WEST OF CBD WOULD BE CLOSED TO EMITTING VEHICLES, AND ALTERNATIVE ROUTE THREE MILES TO THE WEST WOULD BE SUBSTITUTED.

SPECIFIC CONFLICTS OF ABOVE COMPONENTS WITH DENVER CBD POLICY PROGRAM PACKAGE

- A) PACKAGE WILL DISCOURAGE PRIVATE VEHICLE USAGE, DEMAND USE OF MASS TRANSIT, ENCOURAGE CHANGE IN WORK AND RESIDENTIAL PATTERNS.
- B) PACKAGE WILL REQUIRE LARGE PROPORTION OF INCOME FROM LOW INCOME CBD AUTO OPERATORS, EVENTUALLY ENVIRONMENTAL FUNDING MAY BE AT EXPENSE OF SOCIAL WELFARE FUNDING.
- C) PACKAGE MAY DISLOCATE RESIDENTS OF CBD AND SURROUNDING AREA; DECREASE ACTIVITY LEVEL AND THUS CREATE UNEMPLOYMENT; INCREASE SUBURBAN FLIGHT AND URBAN BLIGHT.

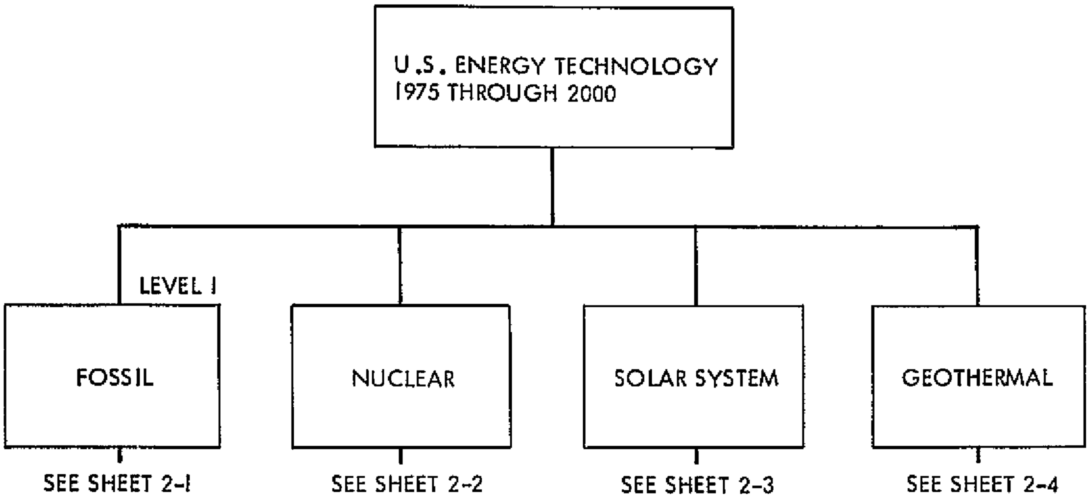
DENVER CBD PARTIES-AT-INTEREST

-SUBURBANITES WHO CHOOSE TO IGNORE THREAT
-RESIDENTS OF CBD
-POOR MINORITY RESIDENTS IF FORCED TO GO OUT TO WORK OR OPERATE JUNKER AUTOMOBILES
-RESIDENTS OF NEIGHBORHOODS DISRUPTED BY HIGHWAY REROUTING AND PARKING
-TAXPAYERS PAYING FOR TRANSIT SYSTEM

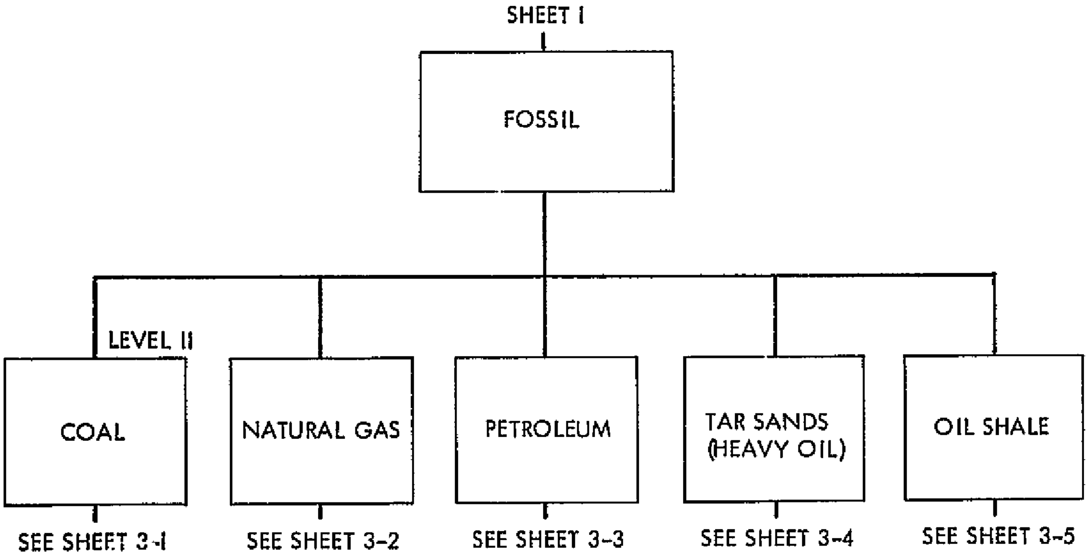
-MINORITY AND POVERTY LEVEL RESIDENTS

-WHITE MIDDLE CLASS RESIDENTS
-SMALL BUSINESS THAT CANNOT OFFER A CHANGE
-MINORITY AND POVERTY RESIDENTS WHO CANNOT LEAVE
-CBD BUSINESSMEN AND PROPERTY OWNERS
-DOWNTOWN TOURIST TRADE PEOPLE

Figure 6. Denver Central Business (CBD) conflicting policies and goals

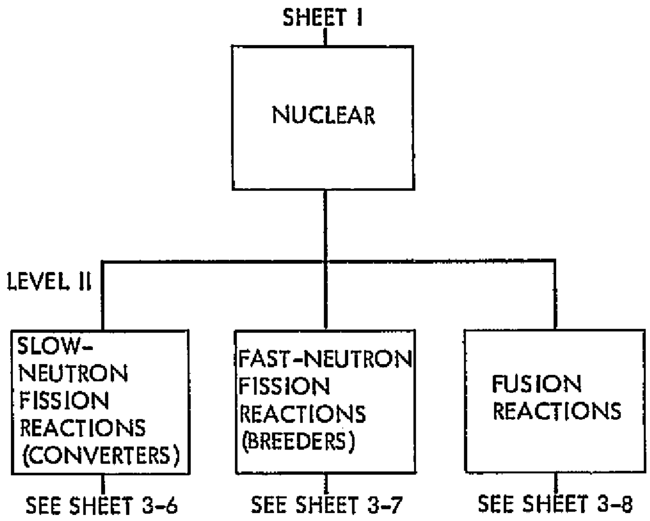


SHEET I

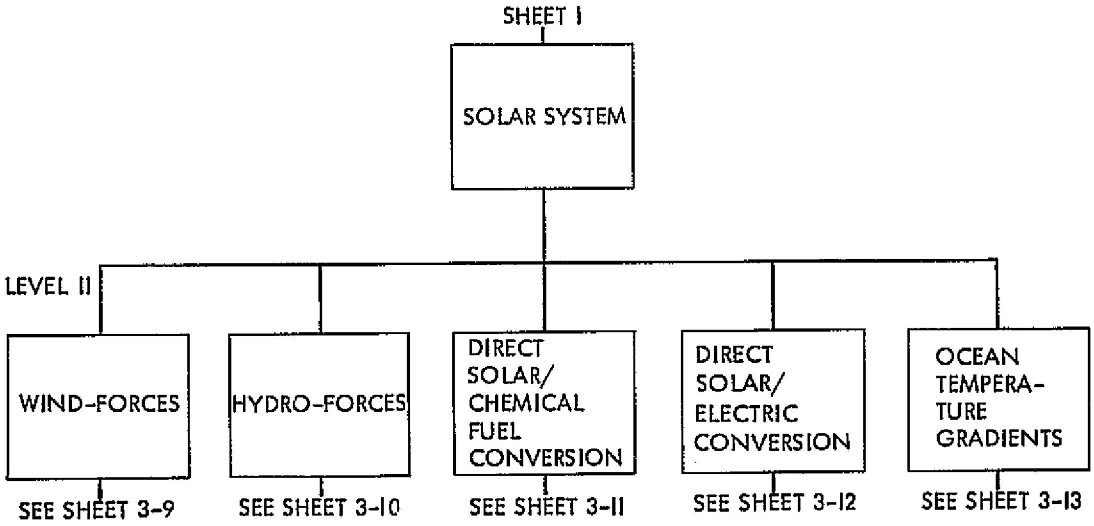


SHEET 2-I

Figure 7. The energy relevance tree

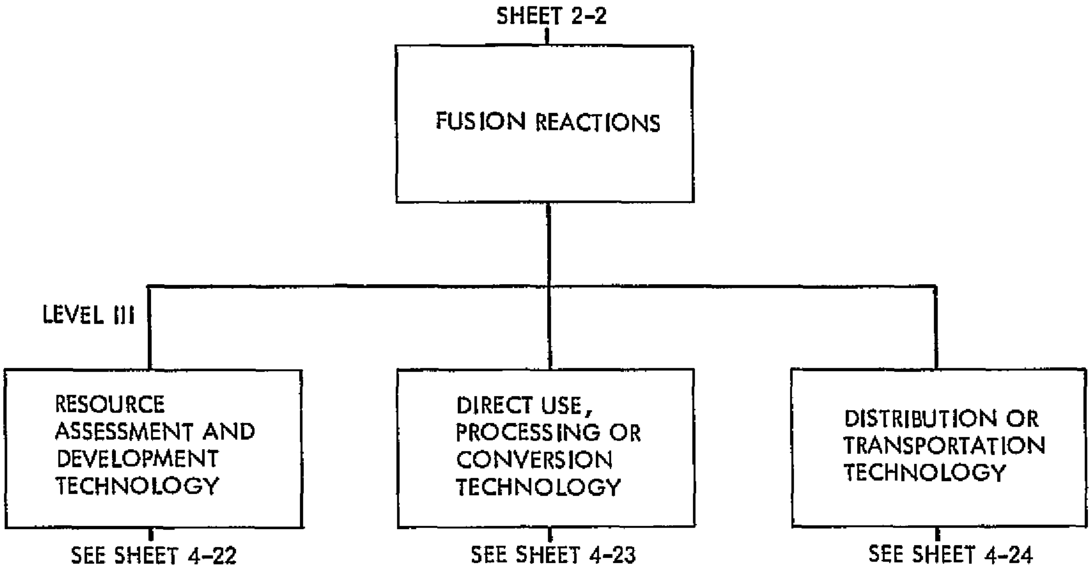


SHEET 2-2

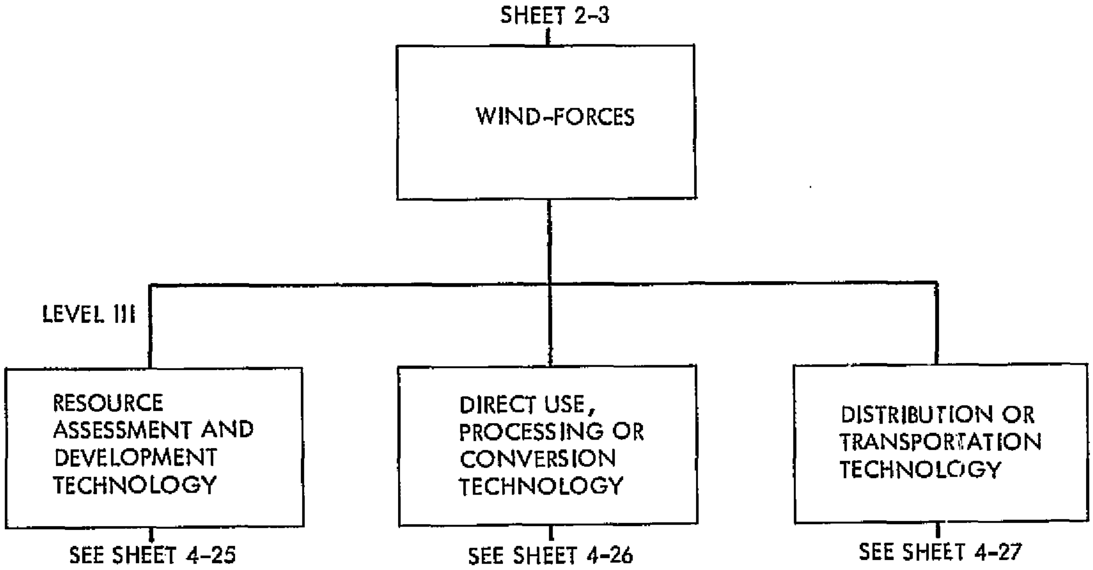


SHEET 2-3

Fig. 7 (contd)

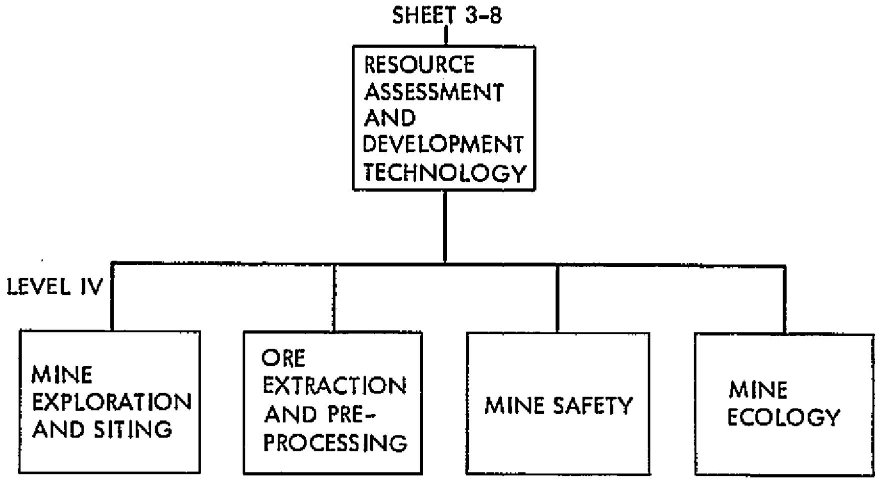


SHEET 3-8

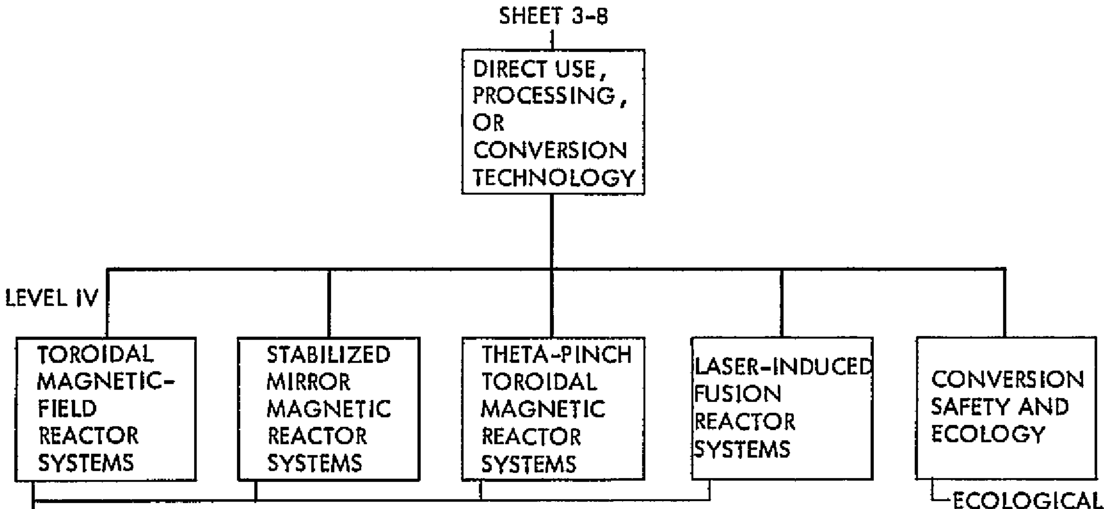


SHEET 3-9

Fig. 7 (contd)



SHEET 4-22



MAJOR TECHNOLOGICAL IMPROVEMENTS ARE REQUIRED IN THE BASIC UNDERSTANDING OF THE FUSION PROCESS, HIGH-TEMPERATURE MATERIALS, PLASMA CONTAINMENT AND CONTROL, AND LIQUID-METAL AND SUPERCONDUCTOR TECHNOLOGY, BEFORE A SUCCESSFUL REACTOR CAN BE VISUALIZED.

ECOLOGICAL AND SAFETY PROBLEMS CENTER AROUND TRITIUM MANAGEMENT IN THE FUSION PROCESS AND IN THE RADIOLOGICAL ACTIVATION OF THE FACILITY DUE TO NEUTRON BOMBARDMENT.

Fig. 7 (contd)

SHEET 4-23

ATTACHMENT

IMPACTS[1] OF ELEMENTS OF HYDROGEN SYSTEMS

A. MANUFACTURE OF HYDROGEN

1. Using Fossile Fuels as the Feedstock for Hydrogen

a. Steam-Methane reforming

Advantages

- Relatively high purity (97%) hydrogen.
- Doesn't require an oxygen plant, which is expensive (cf., the partial oxidation process).

Barriers to Use

- Uses hydrocarbons as a fuel to supply the process heat thus using up limited hydrocarbon reserves.
- Total sulfur content in the hydrocarbon feed must be reduced to less than 5 ppm.[1]

b. Partial oxidation of oil

Advantages

- Can process any hydrocarbon feedstock.[2]
- Relatively high purity (97%) hydrogen.
- No catalyst needed.[3]
- High thermal efficiency.[3]

Barriers to Use

- Need for and cost of oxygen plant (25% of the total capital cost)[3] limits use primarily to locations where the lighter hydrocarbons are either unavailable or uneconomical compared with oil.[3]

c. Partial oxidation of coal by steam and oxygen (coal gasification)

Advantages

- Produces a high purity (95 to 98%) hydrogen.[4]
- Pure CO_2 as a by-product.[4]
- CO_2 absorbents are regenerated.[4]
- Reduces dependence on foreign sources of gas and oil.
- Coal reserves are extensive.
- Process technology is fairly well understood[5] and the technology is known for power gas.

Barriers to Use

- Requires an oxygen supply.
- Uses up the coal resources — environmental problems.
- The basic process is less expensive than the one producing synthetic natural gas. Why go further?

Table 1. Identification of impact areas, major impact categories (from Francois Hetman, Society and the Assessment of Technology, Organization for Economic Cooperation and Development, Paris, 1973)

Categories	Types
Values	Personal Community National Other
Environment	Air Water Open Space Quiet (Noise) Olfactory Weather Sunlight
Demography	Total Major Segments Rates*
Economic	Production Income Employment Prices Trained Manpower Natural Resources Inventory
Social**	National Security Economic Growth Opportunity (Class Relations, Poverty) Health Education Safety (e.g., Crime) Transportation Leisure-Recreation Other Amenities
Institution	Political Legal Administrative Organization Custom-Tradition Religious

* Migration, population density, birth and death rates, etc.

** Goals and problems.

Impacts

Values

- Minimal.

Environment

- The manufacturing process itself will probably have minimal incremental impact if it is located within existing industrial parks and adequate pollution controls are installed.

- If, however, the plants are located at the feedstock or energy site, then the impact will be greater.

Demography

- Major impact if production is located at either the feedstock or energy source due to need for new and expanded towns, facilities, and services.

Economic

- Major investment required in the production facilities (especially if a source of oxygen is required).
- Limited employment increase.
- Cost of support services if new towns are built.

Social

- Minimal.

Institutional

- Minimal; impact on business would probably represent expansion by existing businesses.
- Major impact (in certain regions) on the political and administrative structures.

2. Using Water

a. Electrolytic

- Water electrolysis
- Advanced technology electrolytic processes.

Advantages

- Nonpolluting (exception in the sense that it produces oxygen).
- Can be located near load or near energy supply.
- Technology is available.

Barriers to Use

- Expensive using existing technology[6] (restricted to areas of the world such as Canada, Norway, Egypt, and India where there is a cheap abundance of hydroelectric power or no natural gas source[7]).
- Energy cost of electrolytic hydrogen will always be higher than that of electricity.[8]
- Technology is limited to 2153 A/m^2 (200 A/ft^2); need 10764 A/m^2 (1,000 A/ft^2) to get a high hydrogen output.
- While work is being done on the electrodes and the electrolytic solutions most experts seem to believe that there are major technical barriers to be overcome before a commercial process is developed.
- It is questionable if this process is intrinsically feasible due to its high dependence on the cost of electricity.

Impacts

Values

- Minimal.

Environment

- Impact of oxygen output.
- Transmission of electricity to the plant and hydrogen from the plant.
- By-products, e.g., dissolved salts discharge.

Demography

- Slight to moderate — depending upon location.

Economic

- Capital investment will be high.
- Minor employment increase.

Social

- Minimal.

Institutional

- May require new institutions or may see existing energy suppliers, e.g., utilities or coal/oil companies enter this field.

b. Thermochemical decomposition.

Advantages

- Water is the only expended material.
- Little or no work required in the chemical cycle; therefore no inefficiencies associated with the conversion of large quantities of heat into useful work such as electricity.[9]
- Heat temperatures required are available with present or foreseeable advances in technology.[9]
- No major technological breakthroughs are needed.[9]

Barriers to Use

- Still need to develop usable technologies, i.e., the need to develop a practical thermochemical hydrogen cycle that is compatible (in temperature) with current high-temperature reactor and materials technology.[10]
- Will not be developed until the price of coal increases to the point that hydrogen from coal costs more than thermochemical hydrogen.[10]
- Need to design high-temperature process heat exchangers.[10]
- Need to develop high reagent recovery — 99.9% — and maintain this recovery rate.[11]

Impacts

Values

- Minimal.

Environment

- Dangers of chemical leakages from plants.
- Danger of escape of high temperature gases.

Demography

- Slight to moderate -- depending upon location.

Economic

- Major capital investment.
- Limited employment needs.

Social

- Minimal.

Institutional

- May result in new institutions, e.g., the chemical companies may become involved.

c. Direct thermal splitting

Advantages

- Nonpolluting.
- High efficient use of energy.

Barriers to Use

- High temperature source not yet available.[12, 13]
- Membrane problems--heat and the diffusion of hydrogen.[14]
- High pumping costs at low pressures.

Impacts

Values

- Changes due to the acceptance of high temperature (probably nuclear fusion) technology.

Environment

- Dangers of leakage and explosion.

Demography

- Slight to moderate--depending upon location.

Economic

- Capital investment will be high.
- Employment increase will be limited.

Social

- Minimal

Institutional

- May see the federal government move into this area combining the nuclear plants with the splitting processes.

d. Photolysis

Advantages

- Potentially renewable energy source.

Barriers to Use

- Does not seem feasible at present.[15]
- Only ultraviolet has the energy necessary to decompose water directly. However, a very small amount of this light actually reaches the surface of the earth. If visible light is to be considered for the photolysis of water, it must involve a stepwise process, with a number of quanta contributing their energy for the decomposition reaction.[15]

Impacts

- Too far from development to evaluate.

e. Biophotolysis

Advantages

- Potential of relatively high conversion efficiency of sunlight to chemical energy, at least when compared to conventional solar heat-to-hydrogen systems.[16]

Barriers to Use

- Many problems must be solved before the process can be considered commercially viable.[17]

Impacts

- Too far from development to evaluate.

B. GENERATION OF ENERGY

1. Electricity

a. Solar

Advantages

- Energy source is readily available (in certain geographic areas).
- Nondepletable.
- Nonpolluting.

Barriers to Use

- Low power density (or low flux) of sunshine.
- Intermittent source (i.e., no direct sunlight at night or on cloudy days).
- Problems of collection.
- Problems of storage of energy (hydrogen production is one means of storage).

Impacts

Values

- Possible return to the Sun God.
- Reduces dependence on foreign energy sources.

Environment

- Theoretically limited. However, the collection system would undoubtedly have to cover a large geographic area.
- Impact of transmission lines (or hydrogen pipelines) from the generation points.

Demography

- May result in the construction of new towns at the generation point, and thus a shift in population.

Economic

- Major investment in the collection, generation, and transmission equipment.

Social

- Possible impact on national security due to exposed nature of collection system.

Institutional

- Question of ownership of resources.
- Will require new manufacturing institutions.

An alternative collection method has been proposed. W. J. D. Escher and J. A. Hanson suggest the location of solar collectors in the open sea.[18, 19]

Advantages

- Virtually unlimited area.
- Enormous thermal sink.
- Immediate source of feedstock water, cf., deserts.
- Available for ocean-borne transportation.

Barriers to Use

- Salt water, air corrositivity.
- Marine organism fouling.
- Design problems.

b. Wind

Advantages

- Renewable resource (caused by sun).
- Clean source.
- Nonpolluting.
- Technology is well established.

Barriers to Use

- Locational-wind turbines may need to be located at a considerable distance from the point of usage.[20]
- Variations in wind energy require a storage procedure (which role hydrogen might play).
- Economic--due to location.
- Unlikely to provide more than backup supply.[21]

Impacts

Values

- Minimal.

Environment

- Apart from despoiling the scenery in remote locations, the impact would be limited.

Demography

- Building and maintenance of these isolated generation plants will necessitate some demographic movements.

Economic

- Major capital investment in generation and transmission.

Social

- Minimal.

Institutional

- There are no major corporations in this area, thus new institutions, possibly the existing utilities or the energy companies will have to move in.

c. Fossil fuels

Advantages

- Known resources--often extensive.
- In most cases, the technology is available.

Barriers to Use

- Can be depleted.[22]
- Nonrenewable resources leading to society's desire to conserve resources.
- Most sources require considerable capital investment.
- Societal and environmental objections since use of these fuels have dramatic effects.

Impacts

Values

- Further extensive exploitation of fossil fuels would require a change in the way prople view the country's resources, the environment, etc.

Environment

- Major impact--especially if the source of energy were coal.

Demography

- Exploitation of coal, shale oil, tar sands would all result in major demographic disruptions.

Economic

- Widespread exploitation will require major capital investments.

Social

- Minimal.

Institutional

- In addition to existing institutions, new corporate entities are being formed to exploit such resources as western coal, shale oil, etc.

d. Nuclear

Advantages

- Technology is well developed.
- Costs are of the same order as coal and gas.

REPRODUCIBILITY OF THE
ORIGINAL PAGE IS POOR

Barriers to Use

- Availability of uranium (danger of cartel action).
- Environmental concerns.
- Safety concerns.[23]
- Problem of water disposal.[23]

Impacts

Values

- Widespread usage would require a change in attitudes towards usage.

Environment

- Problems associated with water usage and hot water discharges.
- Dangers from possible leakages.
- Concerns over the disposal of radioactive materials.

Demography

- May result in slight population shifts and associated demands if the plants are sited away from major population centers.

Economic

- A major investment in plant and equipment.

Social

- There is a major safety concern with the waste product disposal problems on certain types of reactor--and with the fundamental safety of certain reactor types.

Institutional

- Questionable as to whether the existing utilities have the financial resources to invest in the necessary capacity.

Nuclear Fusion

- Fusion (energy) is clean, practically inexhaustible, and adaptable to any area.[23]
- Still far short of a working reactor.[23]
- Would require deep water 76 m (250 ft + for thermal discharge.[24]

e. Oceanic thermal gradient

Advantages

- Renewable energy source.
- Environmental effects (by reinjecting discharge water at depths corresponding to its temperature[25]) are minimal.
- If plant is submerged, minimal aesthetic degradation, reduces safety problems to shipping (?), not susceptible to storms.[25]
- Some technology available-two demonstration plants (Cuba in 1929 and Ivory Coast in 1956).[25]

Barriers to Use

- The technology needs to be developed.
- Economic considerations do not, as yet, look too attractive.

Impacts

Values

- Would influence the general view of the oceans as a source of energy, raw materials.

Environment

- Although possible environmental impacts have been downplayed, it seems inevitable that the water purification and electrolysis will have negative effects.

Demography

- Minimal.

Economic

- Major capital investment in the equipment designed to tap the thermal gradient.

Social

- Minimal.

Institutional

- Would need new institutions. Again, the utilities or energy companies may enter this field.

f. Geothermal

Advantages

- Resources are known/identified (some close to major load centers).
- Renewable resource (?).
- Technology is well developed (in the case of dry steam--near San Francisco).

Barriers to Use

- Each geothermal well will have a rather limited energy capability.[26]
  - (a) Dry steam: impurities (corrosive)/ odors, etc.
  - (b) Hot water: lack of technology; fouling of heat exchangers.
  - (c) Hot rock: lack of technology; a water source for pumping into the underground source.[27]

Impacts

Values

- Minimal.

Environment

- The direct impact will be limited to specific areas of the country where it will affect scenic areas.

Demography

- Limited, due to the likely size of the individual projects.

Economic

- The investment is likely to be less critical than other energy sources since the individual wells will have limited energy capability.

Social

- Minimal.

Institutional

- Widespread development of geothermal resources would result in the need for expanded institutional capabilities.

2. Heat

a. Solar

Impacts

- The societal and environmental impacts would differ little from those of solar energy used for electricity. The main difference would result from the location of the hydrogen production. In the case of solar heat, it would have to be close to the collection point; whereas in the case of solar electricity, it could be located at a point distant from the collection point.

b. Nuclear

Impacts

- The impact of a nuclear fission or fusion plant would appear to be the same irrespective of whether the output is electricity or heat. The key factor will be the siting of the hydrogen production facility.

C. EXTRACTION AND SUPPLY OF RAW MATERIAL FEEDSTOCKS

1. Petroleum and Natural Gas

Advantages

- The technology for the usage of petroleum and natural gas as a feedstock is known and proven.

Barriers (to continuing use)

- The raw material sources are either rapidly being depleted or are increasingly expensive.

Impact (of continued use)

Values

- People will increasingly begin to value their automobile, standard of living, etc.

Environment

- Further extensive drilling for petroleum and natural gas to support additional hydrogen utilization would impose a major environmental burden.

Demography

- Limited.

Economic

- Additional investment would be required but it would be considerably less than for the alternative feedstocks.

Social

- Increased independence from foreign fuel sources.

Institutional

- Minimal unless the U.S. Government decides to play a major role in the petroleum and natural gas exploration.

2. Coal

Advantages

- The U.S. has abundant coal resources, much of which can be readily mined.

Barriers to Use

- Nonrenewable resource.
- Polluting resource.
- Negative environmental impacts associated with further widespread usage.

Impacts

Values

- Minimal.

Environment

- Extensive mining would have a major impact on the environment in a number of states.
- The supporting facilities, e.g., trains, slurry pipelines, etc., will also have negative impacts.

Demography

- There will be a continuing demographic shift to the coal producing states.

Economic

- Major investment in both the mining operations and in the towns for support services will be needed.

Social

- Reduced dependence on foreign energy sources.

Institutional

- The larger oil companies have already moved into coal through acquisition. Thus it is unlikely that the extensive extraction would have major institutional impacts.

3. Water

Barriers to Use

- Possible massive water needs could lead to water shortages.
- Problems associated with impurity removal.
- Corrosion of vessels due to dissolved materials.

Impacts

Values

- Greater awareness of the importance of water.

Environment

- Changes in the composition of lakes and seas.
- Impact of transmountain shipments.
- "Effluent" from plants using water as a feedstock.

Demography

- Minimal.

Economic

- Limited investment needed.

Social

- Water disputes.
- Impact of potential widespread shortages on usage of water, e.g., lawns, car washes, etc.

Institutional

- Minimal.

D. HYDROGEN TRANSMISSION

1. Gaseous

a. Using existing natural gas system

Advantages

- Extensive network nationwide. Thus a reduced capital investment.[28]
- For long distance transport of hydrogen in large quantities, gas pipelines laid underground are clearly least expensive.[29]

Barriers to Use

- Hydrogen embrittlement.[30, 31]
- Need for research on hydrogen embrittlement.[31]
- Changes in compressor capacity.[32, 33]

Impacts

Values

- Minimal.

Environment

- Minimal if cracking due to embrittlement doesn't occur. If it does, then the impact would depend upon fires, etc.

Demography

- Minimal.

Economic

- Relatively minor investment.

Social

- Minimal.

Institutional

- Minimal.

b. Establishment of a hydrogen pipeline system

Advantages

- Could be designed with technology which would avoid embrittlement problems.
- Geographic distribution would follow demand.

Barriers to Use

- More expensive than transporting natural gas.[34]
- Cost of building extensive pipelines.
- Problems over selection of materials.[35]

Impacts

Values

- Minimal.

Environment

- Limited if pipes installed underground.

Demography

- Minimal.

Economic

- Considerable cost of building such a pipeline system.

Social

- Safety due to cracking of pipeline.[36]

Institutional

- Which institutions would build the system?

c. Combination of existing and new pipelines

Advantages

- Lower capital cost than establishing a completely new system, and utilizes existing investment.[37]
- Reduced environmental impacts (although probably minor) of building a new network.

Barriers to Use

- Not certain that the problems inherent in using the current system can be overcome.

Impacts

- See previous sections.

d. Dirigibles

Advantages

- Volume transported.
- Ease of distribution.

Barriers to Use

- No real development has occurred in balloon technology in the past 20 years.[38]
- Cost--far larger than pipeline transport.[38]

Impacts

Values

- Would have to overcome fears of hydrogen in dirigibles--the Hindenburg complex.

Environment

- Very minor.

Demography

- Minimal.

Economic

- Limited investment in dirigibles and servicing equipment.

Social

- Major questions with regard to safety.

Institutional

- New institutions would have to be developed.
- New regulations for this mode of transportation.

2. Cryogenic

a. Tank car/railroad

Advantages

- Currently in use.[39]
- No technology problems to overcome.
- Smaller (capital) investment and have greater flexibility than pipeline.

Barriers to Use

- Small volume transportation--limited by the physical size of the vehicles.[40]

Impacts

Values

- Minimal.

Environment

- Minimal.

Demography

- Minimal.

Economic

- High cost of building a sufficient fleet of tank cars or railroad tankers.

Social

- Minor safety concerns.

Institutional

- Will depend upon the cost and rate of providing the necessary equipment.
- Can existing institutions handle this expense?

b. Tanker ships/barges

Advantages[41]

- Larger volume containers than the land-based transportation.
- Smaller (capital) investment and have greater flexibility than pipeline.[42]

Barriers to Use

- The insulation requirements for a liquid hydrogen tanker will be more severe (than for natural gas ships) because of the lower boiling temperature.[43]
- Cost of equipping such vehicles--existing investment in current equipment.
- The density of liquid hydrogen is so low that the loaded ship is almost "empty."[42]

Impacts

Values

- Minimal.

Environment

- What would be the impact of a major spill at sea (less than for natural gas)?

Demography

- Construction of new port cities handling facilities would require certain demographic changes.

Economic

- Major investment in shipping, storage, handling facilities, etc.
- Increased need for skilled seamen, handlers, etc.

Social

- Minimal.

Institutional

- Can the existing shipping firms finance the investment?

c. Pipeline

Advantages

- Conserves pumping power (considerably less for an incompressible liquid than for a gas).[44]

Barriers to Use

- Cost--highly expensive.[45]
- Requires a sealed vacuum jacket.[44]
- The very large temperature ranges would introduce severe thermal stress-induced mechanical problems.[44]

Impacts

Values

- Minimal.

Environmental

- These pipelines would be laid underground. The impact of lengths of cryogenic pipes might be considerable.

Demography

- Minimal.

Economic

- Represent a major investment

Social

- Minimal.

Institutional

- Would utilize existing institutions.
- Would probably require additional regulation.

d. Pipeline/electricity

Advantages

- Would reduce the cost of the electrical energy.
- More economic than a single-purpose electric system.[46]

Barriers to Use[47]

- Nitrogen has many advantages.
- Gaseous hydrogen must be available at one end of the line and liquid hydrogen is required at the other.

Impacts

- Same as in c. above.

E. HYDROGEN STORAGE

1. Gaseous

a. Pressurized tanks

Advantages

- Pressurized tanks are available.
- Technology is known and available.

Barriers to Use

- Natural gas storage tanks will store at design pressure only one-third as much energy when filled with hydrogen.[48]

Impacts

Values

- Minimal.

Environment

- Minimal--except to the extent that storage tanks are an eyesore.

Demography

- Minimal.

Economic

- A major investment in a network of such tanks.

Social

- Minimal.

Institutional

- Firms already in the gas storage business may move into this form of storage in competition or cooperation with the hydrogen manufacturers.

b. Underground

Advantages

- Such natural formations, depleted gas fields or acquifers are available in most parts of the country.

Barriers to Use

- Problems of leakage into surrounding strata. No experimental data is available which can be used to determine whether H_2 can be contained over long periods of time in the same geologic formations that hold natural gas.[44]

Impacts

Values

- Minimal.

Environment

- Difficult to judge since no data exists. Could, however, be a major factor.

Demography

- Minimal.

Economic

- Minimal.

Social

- Major convern over safety due to leakages/explosions.

Institutional

- Firms already in the gas storage business utilizing underground storage may move into this area.

2. Liquid

Advantages

- Liquid hydrogen storage has been practiced in volumes up to 4000 m^3 (1,000,000 gal). Because of the extremely low temperature of liquid hydrogen, use of premium insulation and the low specific volume will cause a much higher unit storage charge for liquid hydrogen than is experienced in conventional hydrocarbon systems. Evaporation losses from large liquid hydrogen storage systems make their feasibility on a small scale questionable.[50]

Barriers to Use[51]

- Safety problems and dangers of leakage.
- Larger size necessary.
- Long-term cryogenic liquid storage is not feasible unless provision is made for continuous refrigeration.[52]

Impacts

Values

- Requires acceptance of the widespread storage of liquid hydrogen.

Environment

- Minimal.

Demography

- Minimal.

Economic

- Considerable investment in the storage facilities.

Social

- Safety question.

Institutional

- Will the firms currently in the gas storage business enter this market or will the manufacturers integrate forward?

3. Metal Hydride

Advantages

- Small scale hydrogen reservoirs have been tested.[53]
- Offers high hydrogen storage density as well as long-term stability without refrigeration.[54]
- Safety is a real advantage--low safety measures and low pressure tanks are required. Thus, if a pressurized vehicle is punctured, reaction stops.

Impacts

Values

- Minimal.

Environment

- Minimal.

Demography

- Minimal.

Economic

- Requires an investment in the extraction and transportation of metal base.

Social

- Minimal.

Institutional

- Existing mining corporations may handle only the extractive activities; in which case, the manufacturers of hydrogen would probably integrate forward into storage activities.

F. DISTRIBUTION OF HYDROGEN

Utilizing Existing Natural Gas Distribution System

Advantages

- System exists.
- Since the distribution system is generally a low pressure system, it is possible that the existing natural gas distribution piping would be adequate to deliver the required volume of hydrogen gas without danger of hydrogen environment embrittlement.[55]

Barriers to Use

- Possibly embrittlement.

Impacts

Values

- Minimal.

Environment

- Minimal.

Demography

- Minimal.

Economic

- Will require some modifications; the cost, however, should be limited.

Social

- Minimal.

Institutional

- Minimal.

G. USAGE OF HYDROGEN

1. Industrial--Chemical

Barriers to Use

- Minimal. The use of utility hydrogen will basically replace the fossil fuel hydrogen.
- Cost of conversion.

Impacts

Values

- Minimal.

Environment

- Probably minimal.

Demography

- Minimal.

Economic

- Some companies might face capital problems in meeting the needs for the new processes.

Social

- Minimal.

Institutional

- New firms--new products.
- Stimulus for hydrogen producing firms to integrate forward into processes using hydrogen.

2. Industrial--Fuel

Advantages

- All industrial applications that use natural gas as a fuel for heating or power generation (electrical or shaft power) can be converted to the usage of hydrogen.[56]

Barriers to Usage

- It is unlikely that conversions will take place unless it is economically attractive. There will be a cost associated with modification--a cost that will vary from a few dollars to many thousands.
- The cost of the hydrogen supply.[57]

Impact

Values

- Minimal.

Environment

- Minimal--merely replaces the use of natural gas.

Demographic

- Minimal.

Economic

- Varying costs associated with the modification of existing equipment.
- Some conversion jobs--probably done by the firms themselves.

Social

- Minimal.

Institutional

- Minimal.

3. Electric Power Generation

Advantages

- The advantages of using hydrogen in electrical power generation will depend upon its availability and cost.
- A possible advantage, involving the use of pipeline hydrogen, is its flexibility in terms of local electricity generation and peak load generation.

Barriers to Use

Conversion of Existing Boilers

- Replacement of parts/compatibility.
- Flame-out detection.
- Pilot light/boiler draft systems.
- Conversion costs will vary from case to case.

The Aphodid Burner

- Requires an oxygen supply.

Air Breathing Rankine Cycle Boiler System

- Larger and less efficient than Aphodid burners.

Hydrogen Fueled Gas Turbines and Other Fueled Internal Combustion Engines

- None.

Fuel Cells

- Not sufficiently developed to be practical for large-scale electric generators.[58,59]

Impacts

Values

- Minimal.

Environment

- Minimal.

Demography

- Minimal.

Economic

- Cost of conversion of existing plants.

Social

- Minimal.

Institutional

- Minimal.

4. Residential and Commercial

Advantages

- The advantage of utilizing hydrogen in residential and commercial situations depends on the economics of the hydrogen supply versus the cost of natural gas.

Barriers to Use

- Cost of conversion/controls, pilot light.
- Procedures to convert.
- Safety.
- Pollution.
- Cost of new piping, regulators, meters.
- Development of suitable products.

Impacts

Values

- May require a change in attitudes towards hydrogen, and the perception of the dangers inherent in its usage.

Environment

- Minimal.

Demography

- Minimal.

Economic

- Cost of conversion.
- Will create jobs in terms of developing new products and modifying existing equipment.

Social

- Minimal.

Institutional

- Minimal.

5. Transporation

Advantages

- Increased range -- e.g., aircraft can extend their range by about 30 percent with no other changes other than those associated with the new fuel.[60]
- Could use conventional aluminum structures.[61]
- Superior energy content.[62]
- Bigger and will carry greater payloads than jet-fueled planes.[62]
- Take-off and landing runs may be shorter.[63]
- Fly higher than current planes.[63]

Barriers to Use

General Aviation

- Requires a liquid fuel.
- Extremely diversified market.
- Storage/safety problems at small airports.
- Problem of conversion of existing aircraft (privately owned).
- Dual system/cost.

Commercial/Military Aircraft

- Availability/storage at airports.
- Worldwide availability of liquid hydrogen.
- Environmental impact of water vapor in the stratosphere.
- Dual systems/cost.
- Safety.
- Compatibility with the air transport control system.
- Problem of designing components for hydrogen with the necessary life.
- Cost of hydrogen.[64]

Space Vehicles

- Already used.

b. Commercial vehicles.

Barriers to Use

Long Haul Vehicles

- Conversion of existing units.
- Availability of hydrogen.
- Safety/quality of station operators.
- Emission control.
- High capital investment.
- Problem of dual system.[65]

Hauling and Light Delivery

- Safety and handling/availability.
- Cost of conversion.
- Emission control.
- Problem of dual system.[65]

c. Public/ground

Barriers to Use

Intercity Trains

- Investment in replacement of existing equipment.
- Storage and handling of hydrogen.
- Availability of hydrogen at diverse locations.

Rapid Transit

- Storage, safety, and handling problems.
- Economics--the cost of delivered hydrogen.

d. Automobiles

e. Agricultural/construction vehicles

Barriers to Use

- Relatively few vehicles coupled with the problem of distributing and storing fuel over scattered areas.
- Likelihood that such vehicles will be regarded as critical to the economy and will thus continue to receive fossil fuel.

f. Oceanic

Barriers to Use

- Volume and boil-off problems will decrease cargo volume and range.
- Dual system/cost.

g. Recreational vehicles

Barriers to Use

- Handling and safety features (untrained and unskilled operators).
- Remote use location of many recreational vehicles.

h. Small power plants

Barriers to Use

- Major personal safety problems.
- Acute distribution problems.

Impacts of the use of hydrogen in the general transportation area[66]

Values

- The wider the usage of hydrogen in terms of the general public, the greater the concern over personal safety.

Environment

- The more extensive the usage, the greater the potential environmental impact. The use of liquid hydrogen in automobiles would require thousands of distribution points; the usage in commercial aviation would require a much more limited exposure and hence less potential for damage.

Demography

- The use of hydrogen might create a small number of additional jobs.
- Would certainly require additional skills and training.

Economic

- Virtually any widespread usage of hydrogen for transportational purposes will require massive capital investments in both the changeover in manufacturing and support facilities.
- For those uses where the "natural" pattern involves major product change, e.g., airline models, the incremental cost will be limited. Similarly, where the number

of service or supply points is small, the costs will be relatively limited.

Social

- The wider the usage of hydrogen as it impacts the general public, the greater the concern over handling and personal safety resulting from spillage, leakage, and accidents.

Institutional

- The existing institutions will probably adapt to the new technology although the changeover would probably offer outside organizations the opportunity to enter these markets.
- The insurance institutions will certainly be impacted by the widespread use of hydrogen.

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[1] E. Fein, A Hydrogen Based Energy System (Glastonbury: The Futures Group, 1972), p. 6.

[2] E. Fein, op. cit., p. 6.

[3] W. R. Parrish, et al., Selected Topics on Hydrogen Fuel, Boulder: Cryogenics Division, Institute for Basic Standards, Jan. 1975, p. 13.

[4] Adapted from Hydrogen and Other Synthetic Fuels, p. 53.

[5] Ibid., p. 56.

[6] R. E. Chao and K. E. Cox, "An Analysis of Hydrogen Production Via Closed-Cycle Schemes," THEME, Miami, 18-20 March 1974.

[7] D. P. Gregory, "The Hydrogen Economy, "Scientific American, Volume 228, No. 1, pp. 13-21, 1973.

[8] R. L. Savage, L. Blank, T. Cady, et al., A Hydrogen Energy Carrier, Volume I, Houston: Systems Design Institute, 1973, p. 25.

[9] R. E. Chao and K. E. Cox, op. cit.

[10] J. Douglas Balcomb and Lawrence A. Booth, "High-Temperance Nuclear Reactors as an Energy Source for Hydrogen Production," THEME, Miami Beach, 18-20 March 1974.

[11] F. Joly, "Economic Criteria of Selection for Closed Cycle Thermochemical Water Splitting Processes," THEME, Miami Beach, 18-20 March 1974. The conclusion states that it is vitally important to be able to guarantee the constancy of the recovery rate, "because of the disastrous economic and ecologic consequences the slightest variation of the recovery yield might have. When thinking of current recovery yields in present chemical processes with reagent recirculation this objective seems a formidable one indeed."

[12] This process, however, requires nonfeasible high temperatures in excess of 2773°K (2500°C). S. Dorner and C. Keller, "Hydrogen Production from Decomposition of Water by Means of Nuclear Reactor Heat," THEME, Miami Beach, 18-20 March 1974.

[13] Appreciable disassociation will not occur below 2755°K (4500°F). E. Fein, op. cit., p. 33.

[14] R. E. Chao and K. E. Cox, op. cit.

[15] S. N. Paleocrassas, "Photolysis of Water as a Solar Energy Conversion Process: An Assessment," THEME, Miami Beach, 18-20 March 1974.

[16] A Mitsui, "Utilization of Solar Energy for Hydrogen Production by Cell Free System of Photosynthetic Organisms," THEME, Miami Beach, 18-20 March 1974.

[17] W. R. Parrish, et al., op. cit., p. 19.

[18] W. J. D. Escher, "A Macro System for the Production of Storable, Transportable Energy from the Sun and Sea." Paper presented at the American Chemical Society 163rd National Meeting, Symposium on Non-Fossil Fuels, 13 April 1972, Boston.

[19] W. J. D. Escher and J. A. Hanson, "Ocean-Based Solar-to-Hydrogen Energy Conversion Macro System," THEME, Miami Beach, 18-20 March 1974.

[20] W. E. Heronemus, "Power From the Offshore Winds." Presented at the Marine Technology Society Eighth Annual Conference and Exposition, Washington, D. C., 11-13 September 1972.

[21] Could be 5 to 10% of the projected total energy demand of the year 2000. R. L. Savage, op. cit., P. 18.

[22] J. A. Hirschberg, "Hydrogen, the Ultimate Energy Source," THEME, Miami Beach, 18-20 March 1974.

[23] J. A. Hirschberg, op. cit.

[24] J. Powell, F. J. Salzano, and W. A. Sevian, "The Technology and Economies of Hydrogen Production from Fusion Reactors," THEME, Miami Beach, 18-20 March 1974.

[25] R. L. Savage, op. cit., p. 23.

[26] Therefore, use of this energy will necessitate development of large energy transmission and storage systems. F. Maslan and T. Gordon, "Geothermal Energy as a Primary Source in the Hydrogen Energy Economy," THEME, Miami Beach, 18-20 March 1974.

[27] The reason for the absence of steam or hot water is the scarcity of water.

[28] "Economic considerations dictate that the transmission and storage of gaseous hydrogen must be attempted using existing natural gas or oil pipelines," R.A. Langley, S.T. Picraux and F.L. Vook, "Hydrogen Distribution Profiling," THEME, Miami Beach, 18-20 March 1974.

[29] E. Fein, op. cit., p. 36.

[30] "Embrittlement is most significant at high pressures and ambient temperatures and is also significantly influenced by the purity of the hydrogen. Relatively impure gaseous hydrogen has been handled for commercial and industrial applications for many years with no serious material failure." W.R. Parrish, op. cit.

[31] Experience with common pipeline steels up to about 3.4 MN/m^2 (500 psia) has shown no problems of consequence, although there is some evidence that a certain amount of embrittlement might occur. However, when pressures up to 12.4 MN/m^2 (1800 psia) are considered, there is far less certainty about the behavior of materials. Very little controlled testing of normal pipeline steels has been carried out in hydrogen at such high pressures. D.P. Gregory, op. cit., p. 6-7.

[32] 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 have five times the compressor power. AHEC, p. 65. Quoted from D.P. Gregory, "A Hydrogen Energy System," op. cit.

[33] First of all, for hydrogen the compressors must handle a considerably greater volume of gas-- somewhere between three and four times the number of cubic feet for the same energy capacity. Secondly, the power required to drive a hydrogen compressor is considerably greater than the power required to drive a natural gas compressor of the same volume capacity. Thirdly, the design of rotary compressors commonly used for natural gas lines appear to be inadequate for hydrogen operation. D.P. Gregory, "Hydrogen Pipelines," Third International Pipeline Technology Convention, Houston, 13-15 January 1975.

[34] R.A. Reynolds and W.L. Slager, "Pipeline Transportation of Hydrogen," THEME, Miami Beach, 18-20 March 1974. In a properly designed system, the cost of hydrogen transmission by pipeline is between 30 and 50% higher than for an equal amount, in energy, of natural gas.

[35] D.P. Gregory, op. cit, p. 10.

[36] There is no evidence that such pipelines (specially designed for hydrogen) are any more dangerous than similar pipelines for other materials (see comments of D.P. Gregory).

[37] As was observed in R.L. Savage and others' study (op. cit., p. 66), "More practical, however, may be a hydrogen pipeline system for only the newly developed areas."

[38] E. Fein, op. cit., p. 52.

[39] "Long distance transport of liquid hydrogen is now routinely accomplished with trucks (13,000 gallon capacity) and railroad tankers (28,000 gallon capacity)." W. R. Parrish, op. cit., p. 4-21.

[40] Regarded as a likely methodology for delivery of hydrogen to small towns which are located on a gas line. R.L. Savage, et al., op. cit., p. 7.

[41] The advantage really lies in the location of the production facility rather than in the mode of transportation.

[42] E. Fein, op. cit., p. 49.

[43] W.R. Parrish, op. cit., p. 4-22.

[44] E. Fein, op. cit., p. 50.

[45] Pipeline transport of liquid hydrogen is by far too costly to be a competitive method of energy transport except over very short distances, or for transfer of energy blocks very much larger than are common in existing practice. J.E. Johnson, The Storage and Transportation of Synthetic Fuels, Oak Ridge National Lab., Tennessee, Report No. ORNL-TM-4307.

[46] R.L. Whitelaw, "Electric Power and Fuel Transmission by Liquid Hydrogen Superconductive Pipeline," THEME, Miami Beach, 18-20 March 1974.

[47] "Slush Hydrogen," which is mixture of up to 60% solid hydrogen in liquid may result in improved prospects for this approach. R.L. Savage, et al., op. cit., pp. 69-70.

[48] R.L. Savage et al., op. cit., p. 66.

[49] E. Fein, op. cit., p. 55.

[50] Hydrogen and Other Synthetic Fuels, op. cit., p. 72.

[51] No insurmountable technological or economic barriers to the storage of liquid hydrogen. Adapted from R.L. Savage et al., op. cit., p. 75.

[52] W.S. Yu, E. Suuberg, and C.H. Waide, "Modelling Studies of Fixed-Bed Metal-Hydride Storage Systems," THEME, Miami Beach, 18-20 March 1974.

[53] G. Strickland, J.J. Reilly, and R.H. Wismall, Jr., "An Engineering-Scale Energy Storage Reservoir of Iron Titanium Hydride," *THEME*, Miami Beach, 18-20 March 1974. The study of the feasibility of storing off-peak electrical energy through the use of a water electrolyzer, a hydride reservoir, and a fuel cell stack.

[54] W.S. Yu, E. Suuberg, and C. Waide, op. cit.

[55] R. L. Savage *et al.*, op. cit., p. 66.

[56] R. L. Savage *et al.*, op. cit., Volume II, p. 95.

[57] The existence of a suitable hydrogen supply in a plant situation may lead to its utilization as a fuel due simply to its availability.

[58] R. L. Savage, *et al.*, (op. cit.) Volume II, states (page 106) that "the fuel cell does not appear sufficiently developed to be practical for a large-scale electric generation.

[59] E. Yeager, "Fuel Cells-Their Status and Future Outlook," *Chem. Eng. Progr.* 64, 92-96, Sept. 1968.

[60] E. Fein, op. cit., p. 75.

[61] E. Fein, op. cit., p. 77.

[62] Peter F. Korycinski and Daniel B. Snow, "Hydrogen for Subsonic Transport," *THEME*, Miami Beach, 18-20 March 1974.

[63] Peter F. Korycinski and Daniel B. Snow, "Hydrogen for Subsonic Transport," *THEME*, Miami Beach, 18-20 March 1974.

[64] Robert D. Lessard, "Liquid Hydrogen as a Fuel for Future Commercial Aircraft," *THEME*, Miami Beach, 18-20 March 1974. Higher cost may be offset by the superior characteristics of liquid hydrogen.

[65] A dual system currently exists--electric and gasoline.

[66] The impact will depend, to a large extent, upon the form in which the hydrogen is used. Extensive shipment and storage of *liquid* hydrogen would have environmental impacts far more extensive than a similarly widespread usage of *gaseous* hydrogen.

EDITORS' NOTE

The foregoing Appendix is the report of a contracted task effort carried out for the HEST study by the Denver Research Institute, as indicated on p. I-1. Some statements in it, as to relationships or matters of technical detail, may be disputed by some readers as a few items have been by members of the HEST study team. Diversity of opinion is to be expected at this stage of hydrogen technology development. However, the essential first step of outlining and formatting the study of social/environmental impacts of hydrogen technology, is accomplished. The important next step is the application to the technical data base developed in the main report of the methodology developed above.

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APPENDIX J

UNIT CONVERSION FACTORS

Judy Foster and Bill Rossen

The International System of Units (designated SI units in all languages), is the System of Units of Measurements which has been adopted by 41 of the principal industrial nations of the world.

The National Bureau of Standards of the United States announced in February 1964 that:

> Henceforth it shall be the policy of the National Bureau of Standards to use the units of the International System (SI), as adopted by the Eleventh General Conference on Weights and Measures..., except when the use of these units would obviously impair communication or reduce the usefulness of a report to the primary recipients.

A similar position was enunciated by NASA on September 4, 1970:

> Measurement values employed in NASA Technical Reports... shall be expressed in the International System of Units (SI).*

Therefore, this report is written in SI units with the more conventional engineering units in current use given in parentheses. The basic and derived units and associated prefixes are given in Table J-1; key conversion factors for conventional and SI units are given in Table J-2.

Table J-3 contains principal energy unit quantities and conversions, in Btu and joules, and Table J-4 contains a variety of unit conversions.

Table J-1 Names and Symbols of SI Units and Prefixes

Quantity	Name of Unit	Symbol
SI Basic Units		
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol
SI Derived Units		
Area	square meter	m^2
Volume	cubic meter	m^3
Density	kilogram per cubic meter	kg/m^3
Force	Newton	N
Pressure	Newton/meter^2	N/m^2
Energy	Joule	J
Power	watt	W
Electromotive force	volt	V
Magnetomotive force	ampere	A

Factor	Prefix	Symbol
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

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*NASA SP-7012, "The International System of Units," E. A. Mechtly, University of Illinois, 1973.

Table J-2. Conventional-to-SI Conversion Factors

To Convert From:	To:	Multiply by
amperes/ft^2	A/m^2	10.7642
atmospheres	N/m^2	1.0132×10^{5}
barrel	m^3	1.5898×10^{-1}
barrels/ton	m^3/kg	1.75246×10^{-4}
Btu/barrel	J/m^3	6.64152×10^{3}
Btu/ft^2	J/m^2	1.1365×10^{4}
Btu/ft^3	J/m^3	3.7288×10^{4}
Btu/gal	J/m^3	2.7896×10^{5}
Btu/hr	Watts	0.2931
Btu/hr-ft-°R	J/s-m-°K	1.73204
Btu/hr-ft^2-°R/in	J/s-m-°K	0.1443366
Btu/kw-hr	J/J	2.9329×10^{-4}
Btu/lb_m	J/kg	2.3278×10^{3}
Btu/mile	J/km	656.227
Btu/seat nmi	J/seat km	5.7012×10^{2}
Btu/ton	J/kg	1.163903
ft	m	0.3048
ft^2	m^2	9.290×10^{-2}
ft^3	m^3	2.8316×10^{-2}
ft/sec	m/s	3.048×10^{-1}
ft^2/min	m^2/s	1.5483×10^{-4}
ft^3/barrel	m^3/m^3	1.7811×10^{-1}
ft^3/Btu	m^3/J	2.68176×10^{-5}
ft^3/lb_m	m^3/kg	6.2426×10^{-2}
ft^3/hr	m^3/s	7.86555×10^{-6}
ft^3/ton	m^3/kg	3.121321×10^{-5}
gallon	m^3	3.785×10^{-3}
gram/mile	g/km	0.621504
inch	m	2.54×10^{-2}
knot	m/s	5.1444×10^{-1}
kw-hr/Btu	J/J	3.4095×10^{3}
kw-sec/lb_m	J/g	2.202
kw-hr/lb_m	J/g	7.93668×10^{3}
lb_m	kg	0.45359
lb_f	N	4.44822
lb_m/ft^3	kg/m^3	6.64152×10^{3}
lb_m/sec	kg/s	4.5359×10^{-1}
lb_f/ft^2	N/m^2	47.8818
lb_f/in^2 (psi)	N/m^2	6.89475×10^{3}
mile	km	1.609
miles/gal	km/m^3	4.2509×10^{2}
miles/hr	m/s	4.4704×10^{-1}
nautical mile	km	1.852
temperature (°C)	°K	$t_K = t_C + 273.15$
temperature (°F)	°K	$t_K = (5/9)(t_F + 459.67)$
temperature (°R)	°K	$t_K = (5/9)t_R$
ton (long)	kg	1.01604×10^{3}
ton (short)	kg	9.0718×10^{2}
ton-mile	kg-km	1.45965×10^{3}
Watt-hr/lb_m	J/kg	7.9366×10^{3}

Table J-3. Energy Units and Quantities

To convert from:	To Btu's, Multiply by	To Joules Multiply by
Btu (mean)	1.0	1.05587×10^{3}
calories	3.9685×10^{-3}	4.19002
kilocalories	3.9685	4.19002×10^{3}
ergs	9.479×10^{-11}	1.0×10^{-7}
electron volts	1.519×10^{-22}	$1.6021917 \times 10^{-19}$
joules	9.479×10^{-4}	1.0
ft-lb	0.001285	1.356
kw-hr	3412.8	3.6×10^{6}
kw-sec	0.948	1.0×10^{3}
mw-hr	3.413×10^{6}	3.6×10^{9}
mw-yr	2.992×10^{10}	3.1560×10^{13}
hp-hr	2545	2.684×10^{6}
barrel crude oil	5.8×10^{6}	6.1240×10^{9}
barrel gasoline (motor fuel)	5.253×10^{6}	5.5465×10^{9}
barrel gasoline (aviation)	5.048×10^{6}	5.3300×10^{9}
barrel "natural gasoline"	4.62×10^{6}	4.8781×10^{9}
gallon gasoline	1.25×10^{5}	1.3198×10^{8}
barrel jet fuel (naphtha-type)	5.36×10^{6}	5.659×10^{9}
barrel jet fuel (commercial)	5.67×10^{6}	5.9868×10^{9}
barrel jet fuel (military)	5.355×10^{6}	5.650×10^{9}
barrel "special naphtha"	5.25×10^{6}	5.5433×10^{9}
barrel residual fuel oil	6.29×10^{6}	6.6414×10^{9}
barrel distillate fuel oil	5.825×10^{6}	6.1504×10^{9}
barrel heavy fuel oil	6.287×10^{6}	6.6383×10^{9}
barrel diesel oil	5.806×10^{6}	6.1304×10^{9}
barrel asphalt	6.640×10^{6}	7.0110×10^{9}
barrel petroleum coke	6.024×10^{6}	6.3606×10^{9}
barrel kerosene	5.670×10^{6}	5.9868×10^{9}
barrel lubricants	6.060×10^{6}	6.3986×10^{9}
barrel "misc. oils"	5.588×10^{6}	5.9002×10^{9}
barrel refinery still gas	$5.6 - 6.0 \times 10^{6}$	$5.93 - 6.34 \times 10^{9}$
barrel wax	$5.4 - 5.6 \times 10^{6}$	$5.7 - 5.93 \times 10^{9}$
ton anthracite coal	25.4×10^{6}	26.8×10^{9}
ton bituminous	26.2×10^{6}	27.7×10^{9}
ton sub-bituminous	19.0×10^{6}	20.1×10^{9}
ton briquettes & package fuels	28.0×10^{6}	29.6×10^{9}
ton coal coke	24.8×10^{6}	26.2×10^{9}
ton coke breeze	20×10^{6}	21.1×10^{9}
ton lignite coal	13.4×10^{6}	14.2×10^{9}

Table J-3. Energy Units and Quantities (Contd)

To Convert from:	To Btu's Multiply by	To Joules Multiply by
avg. ton coal used in 1969 electric production	24.7×10^{6}	26.1×10^{9}
gallon coal tar	150,000	1.5838×10^{8}
cu. ft. blast-furnace gas	100	1.05587×10^{3}
cu ft. coke-oven gas	550	5.8073×10^{5}
coke-oven man. gas products, light oils (barrel)	5.460×10^{6}	5.7545×10^{9}
cu. ft. natural gas (dry)	1031	1.0915×10^{6}
cu. ft. natural gas (wet)	1103	1.1646×10^{6}
barrel liquefied natural gas (avg.)	4.1×10^{6}	4.3291×10^{9}
barrel liquid butane	4.284×10^{6}	4.5233×10^{9}

To convert from:	To Btu's Multiply by	To Joules Multiply by
barrel liquid propane	3.843×10^{6}	4.0577×10^{9}
grams U_{235} fissioned	74.0×10^{6}	78.1×10^{9}
"tons uranium ore" (U_3O_8)	5.60×10^{11}	5.91×10^{14}
ton methanol	19.48×10^{6}	20.57×10^{9}
barrel methanol	2.717×10^{6}	2.869×10^{9}
gallon methanol	64,700	6.8315×10^{7}
lb. hydrogen	61,084	6.4497×10^{7}
ton hydrogen	1.222×10^{8}	1.2903×10^{11}
ft^3 hydrogen (gas)	325.1	3.433×10^{5}
gal. hydrogen (liq.)	35,600	3.7589×10^{7}
kw-yrs	29.9×10^{6}	31.571×10^{9}

barrel oil/day = 2.12×10^{9} Btu/yr

Table J-4. Energy Unit Conversion Factors

Converting From:	Multiply by: To Barrels Crude*	To kw-h	To Btu's	To Joules
kilocalories	4.33×10^{-5}	0.0738	3.9685	4.19002×10^{3}
kilowatt-hours	5.87×10^{-4}	---	3412.8	3.6×10^{6}
barrels crude oil	---	1699.4	5.8×10^{6}	6.1240×10^{9}
gallons gasoline	7.27×10^{-3}	36.6	1.25×10^{5}	1.3198×10^{8}
tons coal (avg.)	4.3 - 4.5	7300 - 7600	$25 - 26 \times 10^{6}$	$26.4 - 27.4 \times 10^{9}$
tons lignite coal	2.305	3926	13.4×10^{6}	14.2×10^{9}
cu. ft. natural gas	$1.77 - 1.9 \times 10^{-4}$	0.302 - 0.322	1030 - 1100	$1.088 - 1.161 \times 10^{6}$
barrels liq. natural gas	0.705	1201	4.1×10^{6}	4.329×10^{9}
tons hydrogen	.2107	357.3	1.222×10^{8}	1.2903×10^{11}
ft^3 hydrogen	5.6015×10^{-5}	.095	325.1	3.433×10^{5}
barrels methanol	.487	760	2.717×10^{6}	2.869×10^{9}
grams uranium-235 fissioned	12.7	21,682	74.0×10^{6}	78.1×10^{9}
tons uranium ore (U_3O_8)	96,300	1.64×10^{8}	5.6×10^{11}	5.91×10^{14}

*Based on heating value of crude and of the converted fuel unit.

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APPENDIX K
REVIEWER'S COMMENTS

The charge to the HEST Study Review Group was to critique the Study's approach, progress, and results, utilizing their diverse perspectives and backgrounds in hydrogen and related disciplines. A specific opportunity was established for the Reviewers to express individual critical comments, independent of their many contributions to the Study's evolution, as a part of this Report. The letters received from Review Group members for this purpose follow.

Dr. Ab Flowers
Manager, Residential, Commercial, and Industrial R&E
American Gas Association
Arlington, Virginia

November 14, 1975

Dear Jim:

In response to your letter of November 7, 1975, lack of time has prevented a detailed page by page critical review of your final report. However, after a cursory review, you are to be complimented for a substantially improved report which I recommend for publication.

Sincerely,
Ab

Dr. James Funk
Dean, College of Engineering and
Director, Institute for Mining and Materials Research
University of Kentucky
Lexington, Kentucky

December 3, 1975

Dear Jim:

The HEST Study Report, "Hydrogen Tomorrow," clearly outlines the state-of-the-art in hydrogen demand, production, and end use. The projections made in the report will provide a sound basis for program planning and future action. This report will serve as a reference for workers in the hydrogen field for many years to come. The University of Kentucky group is pleased to have been involved in the hydrogen production part of the study. Our ability to contribute to the thermochemical production activity was a direct result of the foresight of NASA-Lewis in establishing our program and supporting it for the past three years.

The general question of the production of truly synthetic fuels from thermal energy is one which will be of great technological and economic importance to the United States in the future. Hydrogen from water is clearly one of the most important components in the search for such synthetic fuels and JPL has made a fine contribution to this effort. The emphasis on production techniques, efficiency and cost is well placed, since the availability of inexpensive hydrogen will encourage its application and use for many purposes. The need now is for action and I hope the results of the HEST Study will be used to spur the formulation and implementation of the required action programs.

Sincerely,
James E. Funk

Mr. Thomas H. Jenkins
Engineering Executive
Oil, Gas, and Petrochemical Industry
Houston, Texas

December 5, 1975

Dear Jim:

I have reviewed the Review Draft of the Hydrogen Tomorrow Report and I wish to congratulate you and your staff on an excellent job, well done.

Since this report will be read by many individuals from equally as many disciplines, your treatment of the subject matter with the special arrangements of the sections and their particular data and descriptive material is well organized and presented.

In the Executive Summary, for those who will read only this section, I would have desired that more capital costs, material and personnel requirements plus operating costs be included.

Sincerely,
Thos. H. Jenkins

Dr. Oskar Morgenstern
Chairman of the Board
Mathematica Inc.
Princeton, New Jersey and
Professor of Economics
New York University

November 21, 1975

Dear Mr. Kelley:

Your letter arrived while I was out of town; so I could not reply in time. But at any rate the time span given to digest — critically at that! — a complicated report would have been very short. I have now read it in large parts and can assure you that I think that it is a fine piece which should be of great value to NASA (and the country in general). I only hope that the matter will not rest with this report, but rather be carried forward actively. I was recently a member of a new advisory committee to the National Science Foundation. They have turned over most of their energy work to ERDA — not necessarily a good development: too much concentration in one spot. I hope JPL and NASA will stay in the energy business so that all avenues are properly being explored. If I can be of some assistance, please get in touch with me; Mathematica may also be useful in further studies.

With best regards and congratulations to a job well done

Sincerely,
O. Morgenstern

Mr. James Mulvihill, Research Supervisor,
Environment and Conservation
Pittsburgh Energy Research Center
Energy Research and Development Administration
Pittsburgh, Pennsylvania

December 5, 1975

Dear Jim:

I noticed that the report has been extensively revised since our May review and I must compliment you and your staff on the outstanding improvements of the report.

The Hydrogen Production Cost evaluation given in Chapter VII is quite useful and informative. However, the Environmental Assessment was not covered in depth in Chapter VIII. I believe it would require a study of almost the same amount of effort that was put into the HEST Study. You may want to consider the environmental aspects as a separate future study. I would be interested in learning of your thoughts on such a program.

Sincerely,
J. W. Mulvihill

Dr. Rex Riley
Energy Supply Studies Program
Energy Systems Environment and
Conservation Division
Electric Power Research Institute
Palo Alto, Calif.

December 1, 1975

Dear Jim:

I would first like to thank you for inviting me to participate in the HEST Review Panel. It has been a very informative and rewarding experience. This letter contains my own comments and those of other EPRI staff members. Unfortunately, due to the large volume of material and the short review period, we did not review the entire document in detail.

The report is a major improvement over the previous draft, providing a consistent presentation of the hydrogen energy picture. The material in the report adequately answers the stated research goals. The Executive Summary is quite good and we generally agree with its contents.

Likewise, the presentation in Part I has been greatly enhanced by the condensation and new organization. The relationship of the production scenarios to the consumption scenarios is clearly described. The charts and tables presenting these scenarios have been greatly improved. Although there seems to be some minor discrepancies between the high and low production scenarios and the FTFB consumption scenario, these do not affect the content of the Report.

Additional detail can only be provided by a more complex systems analysis of the hydrogen energy supply and demand economics. This must be done in conjunction with all types of energy and this in turn must be done within the framework of a long-term macro-economic forecasting model with sufficient detail disaggregation in the energy sector. This reviewer again singles out the work in the demand portion as being excellent and worthy of special praise.

The importance of the natural resources utilized in the various technologies seems underemphasized. Figure IV-1 shows the relationship of hydrogen research to technology requirements. This figure and some of the supporting text implies that research on the basic feedstocks can be delayed for some time. The implementation of various hydrogen technologies is an important function of the resource availability. Much work needs to be done to increase knowledge of the resource base and the associated supply economics. This work should commence as soon as possible.

Finally, I am very happy to note that the criticisms provided by the panel were incorporated into the final report. I now feel the report reads well and is more representative of the high quality research which went into the HEST study.

Sincerely,
Rex E. Riley

Dr. Warren Sharratt
Area Director
National Fertilizer Development Center
Tennessee Valley Authority
Department of Soils & Plant Nutrition
University of California
Davis, California

November 17, 1975

Dear Mr. Kelley:

I commend you and your staff for the efforts you have made in assembling, compiling, and presenting a very comprehensive report in a systematic manner under the title "Hydrogen Tomorrow: Demands and Technology Requirements". I am particularly pleased with the report's organization. The use of the Executive Summary, followed by Analysis and Conclusions, and concluding with Supporting Data (including the appendix), makes the report of value to both the layman and the trained scientist, who may wish to delve into the facts and details on which you've based your conclusions. Thus, I believe your report can be of significant benefit to those who will make decisions regarding future sources of hydrogen.

Although it is organizationally sound, I feel it lacks completeness in at least one particular area where I would feel qualified to make an evaluation. As a reviewer, I would be remiss if I did not bring to the attention of your study groups and potential readers a problem that may arise in future hydrogen production.

Your report suggests (and I believe correctly) that between now and the year 2 000 coal could become our principal hydrogen and energy source. Thus, coal will serve as a hydrogen source during an interim time period while research is carried forward to develop the technology for production of hydrogen by more sophisticated routes, e.g. the electrolyzers, thermochemical cycles, and direct water splitting.

Neither the Executive Summary, the Analysis and Conclusions section, nor the Appendix I gives sufficient gravity to the environmental consequences of making coal an interim source of hydrogen. I believe one who is in a decision making capacity could read the previously mentioned sections of the report and be quite ignorant of the impact coal, as an interim source of fuel, would have on the environment. Section III A-3 of the report mentions carbon dioxide enrichment to the atmosphere, and others may be concerned with the scarring of landscape that occurs with massive mining operations, particularly when the more economical strip mining occurs. I believe the first objection is still an open question and the objection to strip mining can possibly be overcome through the use of good reclamation procedures as evidenced in certain areas of the Southwest at this time.

I believe the most difficult environmental question to be faced in the use of coal will be adequate supplies of process water to carry out gasification in the production of hydrogen. The principal bodies of coal, economically attractive to exploit, are located in the arid West (Montana, the Dakotas, Wyoming, and the four corner states of the Southwest).

Nearly every water use tends to increase the salts in the water and thus reduce water quality. This is equally true of manufacturing. Coal gasification requires large quantities of water. The quantities required are well documented by the United States Bureau of Reclamation. When the water leaves the process it will be higher in salts and lower in quality than prior to its use. The water is, therefore, less desirable for subsequent municipal/industrial and agricultural use. The problem is compounded by the scarcity of water in the areas having the large coal deposits. Thus, out of necessity, the water may be reused several times at coal gasification sites along a major river and its tributaries. If this continues, the water soon becomes unfit for municipal/industrial, agricultural, and recreational uses of water. Geographic areas also vie vigorously for this resource, as witnessed by the prolonged litigation that recently occurred on the Colorado River Compact. This competition for water has been fostered by increasing population and leisure time available for recreation. Within the past few years, U. S. agriculture is assuming an increasingly important role in feeding a world short of food, and in assisting in the alleviation of a domestic balance of payments problem by way of agricultural exports. Thus, national policy may give agriculture a high priority in its demands for available water.

Logic compels me to agree that coal gasification could serve as an interim route to meeting hydrogen needs. However, to do so some very serious environmental questions must be answered and perhaps the most important concerns availability of water.

If you are interested in further study of the salinity and quality problem of waters in the West and its effects on commerce and agriculture, I would suggest a paper by Dr. Ralph W. Johnson entitled "Legal and Institutional Problems in the Management of Salinity". Dr. Johnson is a professor of law at the University of Washington in Seattle, Washington (ZIP 98195).

You have cited the need for strong priorities in the use of natural gas and oil in Section G of the Executive Summary. I would simply like to add additional emphasis to the need for these priorities, not only for the previously mentioned feedstocks, but also for hydrogen derived from other sources, e.g. coal. Hydrogen will be absolutely essential for some purposes, e.g. certain petro-chemicals, ammonia, etc. Establishing the priority of these various needs should be done at an early date to enable all users sufficient lead time to chart alternatives. Failure to do so will lead to disruptions in the various industries dependent on hydrogen feedstock.

I wish to thank you and others at JPL for inviting me to be a part of the review group. I have benefited from becoming better acquainted and more knowledgable of hydrogen technology. I enjoyed my meetings and association with you and other members of JPL's staff.

Respectfully yours,
Warren J. Sharratt