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SYNTHETIC FUEL GENERATION CAPABILITIES
OF NUCLEAR POWER PLANTS WITH APPLICATIONS
TO NAVAL SHIP TECHNOLOGY

Robin Paul Bushore

SYNTHETIC FUEL GENERATION CAPABILITIES OF NUCLEAR
POWER PLANTS WITH APPLICATIONS TO NAVAL SHIP TECHNOLOGY

by

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(1970)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREES OF

OCEAN ENGINEER

and

MASTER OF SCIENCE IN NUCLEAR ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MAY 1977

B9245

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POWER PLANTS WITH APPLICATIONS TO NAVAL SHIP TECHNOLOGY

by

ROBIN PAUL BUSHORE

Submitted to the Department of Ocean Engineering
on 12 May 1977 in partial fulfillment of the requirements
for the Degrees of Ocean Engineer and
Master of Science in Nuclear Engineering

ABSTRACT

The generation of synthetic fuel (gasoline and/or jet fuel), using a nuclear power plant as a source of heat and electricity, from hydrogen (obtained by decomposition of (sea)water) and carbon dioxide (obtained by absorptive stripping of seawater) is examined for use both as a commercial alternative to coal conversion or petroleum, and as a means of providing all of the fuel and energy requirements for a nuclear powered aircraft carrier.

High-Temperature Gas-cooled Reactors (HTGR's) in general, and a Westinghouse version of a Very High Temperature Reactor (VHTR), in particular, are identified as being potentially advantageous for both commercial and shipboard installations. A synthetic fuel generation plant which consumes off-peak energy to maintain base loading of a nuclear-electric utility appears to be an economically viable alternative to coal conversion, producing jet fuel at an estimated cost of about 40 ¢/gallon. This mode of operation, however, could only satisfy something less than 10% of projected U.S. transportation needs.

Synthetic fuel generation plants for nuclear powered aircraft carriers are shown to be conceptually feasible in that reactors installed for propulsion purposes can provide enough surplus energy to synthesize respectable inventories of jet fuels. However, these installations are not currently justifiable on economics alone: projected on-board jet fuel costs are about twice that obtainable by coal conversion. The weight and volume impact of the synthetic fuel plant are discussed qualitatively, and are identified as a major area requiring further study. Also noted are technological improvements, most of which are the objective of current R & D programs in the energy field, which would improve the prospects for successful application of this concept.

Thesis Supervisor:

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Associate Professor of Nuclear Engineering

ACKNOWLEDGEMENTS

I would like to extend my thanks and appreciation to Professor Michael J. Driscoll, who not only introduced me to the subject of this thesis, but spent many additional hours as my advisor providing much-needed advice, background material, and professional experience. I would also like to thank Dr. Thomas Reed of MIT's Lincoln Laboratory for presenting this idea, first to Prof. Driscoll, and then to me, and exciting my interest to continue with his preliminary work.

I would also like to thank my wife, Kathryn, for recognizing the special requirements of this work and doing her best to minimize the interferences of family life.

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TABLE OF CONTENTS

<u>ITEM</u>	<u>PAGE</u>
Abstract	2
Acknowledgements	3
Table of Contents	4
List of Figures	7
List of Tables	8
Chapter 1. Introduction	9
1.1 Foreword	9
1.2 Background	10
1.3 Outline	12
Chapter 2. Transportation Fuels	14
2.1 Introduction	14
2.2 Propulsive Devices	15
2.3 Alternative Fuels	18
2.4 Jet Fuel Specifications	21
2.5 Fuel Supply and Demand	24
Chapter 3. Synthetic Fuel Production	31
3.1 Introduction	31
3.2 Methanol Production	32
3.2.1 Methanol: Uses and Properties	32
3.2.2 Hydrogen Production	33
3.2.3 Carbon Dioxide Production	41
3.2.4 Methanol Synthesis	42

TABLE OF CONTENTS - Continued

<u>ITEM</u>	<u>PAGE</u>
3.3 Gasoline Production	43
3.3.1 Synthesis from Methanol	43
3.3.2 Synthesis from Hydrogen and Carbon Dioxide	44
3.4 Jet Fuel Production	45
3.4.1 Synthesis from Methanol	45
3.4.2 Synthesis from Hydrogen and Carbon Dioxide	46
3.5 Other Uses for Synthesis Processes	46
3.5.1 Coal Conversion	46
3.5.2 Natural Gas Conversion	47
3.5.3 Biochemical Energy	48
3.6 Added Benefits	48
3.6.1 Oxygen Production	48
3.6.2 Environmental	49
Chapter 4. Nuclear Powered Synthetic Fuel Plants	52
4.1 Introduction	52
4.2 Light Water Reactors	54
4.3 High Temperature Reactors	55
4.3.1 Fission Reactors	55
4.3.2 Fusion Reactors	61
4.4 Sizing and Configuration of Combined Plant	62
4.4.1 Aircraft Carrier Plant	62
4.4.2 Commercial Plants	67

TABLE OF CONTENTS - Continued

<u>ITEM</u>	<u>PAGE</u>
4.5 Shipboard Impact	70
Chapter 5. Economic Analysis	76
5.1 Introduction	76
5.2 Commercial Plant Economics	78
5.3 Aircraft Carrier Operations	80
5.4 Cost of Synthetic Fuel from Coal	85
Chapter 6. Summary and Conclusions	87
5.1 Summary	87
5.2 Conclusions	91
5.3 Recommendations	98
Appendix A. References	101

LIST OF FIGURES

<u>FIG.</u>	<u>TITLE</u>	<u>PAGE</u>
2.1	Projected U.S. Consumption of Energy for Transportation Use	26
2.2	World Supply and U.S. Demand for Oil	26
2.3	World Crude Oil Resources	27
2.4	World Production of Fossil Fuels	28
2.5	OECD Energy Demand (Excluding Australia and New Zealand)	29
3.1	System Flow Diagram for Synthesis of JP-5 or Gasoline	34
3.2	Hydrogen Generation with Nuclear Plant Interaction	40
4.1	Very High Temperature Reactor (VHTR)	58
4.2	System Diagram of a Very High Temperature Reactor for Process Heat Applications	59
4.3	Light Weight Nuclear Powerplant	60
4.4	Propulsion Plant Specific Weights	75

Chapter 1

INTRODUCTION

1.1 Foreword

Present sources of fuels for transportation needs are being rapidly depleted. The time is approaching when the fossil fuels which we are using today will no longer be available at acceptable prices. However, combination of nuclear power plants with synthetic fuel generation plants can provide a reliable source of hydrocarbon fuels for the future.

While the long term prospects for such technology are good, in the near term it is likely that only specialty applications will prove attractive. Just as submarine nuclear propulsion promoted an accelerated pressurized water reactor development, the initial motivation for process development must come from applications which will benefit most. One such application in the nuclear synthetic fuel area involves addition of a synthetic fuel generation plant to a nuclear powered aircraft carrier to satisfy its need for aviation fuel. This stratagem greatly improves its reliability and military effectiveness. Hence the purpose of this thesis will be to evaluate the shipboard nuclear synthetic fuel process to determine whether it can be currently justified as the lead application of the new technology.

1.2 Background

Coal conversion processes are being advanced to provide an alternate source of hydrocarbon fuels as petroleum and natural gas supplies are depleted. This will result in increased damage to the environment due to strip mining, coal conversion residue, and the burning of coal and its products. While it may be necessary in the short term, a more promising alternative for the long term may well be the use of nuclear energy to provide for our fuel needs. In any event coal conversion is of interest to present objectives for two reasons: it will serve as the most likely source of competition to establish a breakeven price for synfuel; and some of the chemistry and chemical engineering involved in fuel synthesis and modification will be the same for all synfuel processes.

To fully achieve the maximum benefits of this nuclear synfuel concept, it will be necessary to use a nuclear power plant as a source of thermal and electrical energy to operate a synthetic fuel generation plant using the basic raw materials hydrogen (from water) and carbon dioxide (from air or water) to produce hydrocarbon fuels such as gasoline or jet fuel. Ref. (S2) gives a **brief** but thorough look at the mechanics and economics. It is hoped that eventually fusion reactors will be available to provide a non-polluting total energy system. Ref. (S4) has a thorough analysis of methanol production utilizing fusion power.

In the meantime fission reactors are capable of satisfying system power source requirements with less environmental detriment than will be achieved by coal conversion processes.

This system has features which are particularly attractive for shipboard use. A nuclear powered aircraft carrier, when not operating at full power, could be made capable of providing all the fuel needed for its aircraft and possibly for non-nuclear propelled escort ships as well. This would allow an all-nuclear task force to travel at high speed to get to a given station, and then operate independently for long periods of time. The need for separate fuel logistics support would be ended. Only provisions and munitions would require occasional replenishment. The effectiveness of the carrier would be significantly improved. It is also inevitable that a time will eventually come when conventional fossil or fossil-derived fuels for aircraft are more expensive than nuclear-generated syn-fuel, even if no credit is taken for these operational benefits.

Another possible adaptation is to place modular nuclear-powered process plants on ships such as oilers, so that the fuel for non-nuclear ships, or any other use, could be provided wherever it was needed. It would then be difficult for another nation to deny us the means of supplying our own fuel needs.

The cost of synthesizing fuel in this manner is difficult to determine, since there is no complete system (and just as important, no full-scale system) in operation. As demand diverges more from supply, it is expected that fuel synthesis will eventually be economically competitive with conventional sources. As this time approaches, the incentive to build such pilot plants, and eventual production units, will increase. In the interim it is possible to piece together a reasonably complete picture of this operation, in a non-optimized form, by examining proven processes such as the synthesis of methanol from carbon dioxide or carbon monoxide and hydrogen.

1.3 Outline

It is the purpose of the present work to conduct a feasibility study of a synthetic fuel generation plant combined with a nuclear power plant as a source of energy. In pursuit of this goal, Chapter 2 looks into the fuel requirements of the transportation industry, with consideration given to the alternate fuels which may be suitable. Emphasis is placed on the current fuel requirements of U.S. aircraft. Chapter 3 deals with the applicable fuel synthesis processes for the fuels under consideration: gasoline and jet fuel. In Chapter 4 the nuclear power plant and process plant are sized to meet suitable nominal capacities, and consideration is given to how they interact

with one another, or, in the case of the aircraft carrier, with other shipboard systems. Chapter 5 contains an economic analysis which estimates the actual delivered cost per gallon of fuel. Finally, Chapter 6 summarizes the results, and makes recommendations based on them.

Chapter 2

TRANSPORTATION FUELS

2.1 Introduction

Transportation vehicles such as aircraft, small ships, automobiles, and trucks require compact propulsion systems and easy fueling methods in order to maintain their mobility. They are not suitable for nuclear propulsion systems, but require some form of chemical energy and a mechanical conversion device. Some transportation systems, such as trains and buses, can use fixed electrical power transmission systems--given a sufficiently large capital investment, and accepting a corresponding degradation in mobility. Some buses and automobiles can operate on batteries, but with either limited range or with a large capital investment penalty when interchangeable battery packs are used. Hence, in general, it appears that most transportation systems will continue to require some form of liquid chemical fuel.

The natural sources of chemical fuels, in particular petroleum, are in increasing demand, while production is nearing its peak level and discovery of new deposits appears to have already gone into decline. Hence it is appropriate to look at the alternative fuels available, the requirements for all fuels in the future, and the propulsive devices that will be available to utilize the fuels.

2.2 Propulsive Devices

There are a number of fuels which are suitable for general transportation use, including gasoline, diesel oil, kerosene, methanol, and hydrogen. Most surface transportation uses gasoline-consuming engines. They also benefit from "commercial inertia": due to the extensive capital investment involved, the economy would have to bear a severe financial burden during conversion of present systems to another fuel. Gasoline engines are characterized by high fuel consumption, high maintenance costs, and high pollutant levels. They do, however, have the advantages of using a fuel which is easily handled and stored and which has a high energy content, both on a mass and on a volume basis (Table 2.1). In addition high power can be achieved in relatively small units.

Most trucks, buses, and ships use diesel engines. Recently there has been an increased interest in diesel engines in automobiles as more stringent exhaust emission standards are imposed, and fuel economy standards are about to be imposed. The 1978 model year should mark the first year of use for diesel units in American automobiles as a factory option. Diesel units are characterized by high specific weight (mass per unit horsepower), clanging noises when idling, unpleasant exhaust odors, low acceleration, and difficulty in meeting NO_x emission standards. They do

Table 2.1

ENERGY PROPERTIES OF SELECTED FUELS

<u>Fuel</u>	<u>Density (lb/ft³)</u>	<u>Mass Basis Heating Value (btu/lb)</u>	<u>Volume Basis Heating Value (btu/ft³)</u>
Methanol	49.7	8,650	429,900
Gasoline	43.8	19,060	834,800
JP-4	48.4	18,400	890,600
JP-5	50.9	18,300	931,500
Hydrogen	4.43	51,590	228,500

have the advantages of using a fuel which is easily handled and stored, and can be varied over the range of kerosene-base fuels to utilize distillate, diesel oil, or JP-5. In addition, they have low specific fuel consumption, low maintenance costs, and can be built over a wide range of sizes from less than 100 to over 20,000 horsepower. Combined systems utilizing waste heat from the cooling jacket have been constructed to improve the overall efficiency (C3).

Marine steam plants are generally used in applications where high power is necessary. They are characterized by low specific weight, low maintenance costs, and high reliability, but are less efficient than diesels to operate and require more personnel to operate. They will operate on somewhat lower grade heavy fuels such as distillate fuel, since combustion is by unconfined burning (C3).

Gas turbine engines are used on aircraft and some ships. They generally operate on a kerosene-base fuel such as JP-5, but can also be made to operate on distillate or diesel oil. They have the advantages of low specific weight, easy handling and storage of fuel, ease of removal for maintenance, rapid response time, and adaptability for remote control. They suffer from high specific fuel consumption (although combined steam-gas turbine cycles are being used to lower it), require additional separate maintenance facilities, and have relatively short operating time between overhauls.

For aviation use there are presently no suitable alternatives to the gas turbine engine, which provides a reliable, compact unit.

As mentioned previously, there is also the possibility of electric propulsion. A fixed electrical transmission system, (replaceable) batteries, or possibly fuel cells (with storage and weight problems) could be utilized. These devices are considered to have limited usefulness to the transportation industry as a whole due to the severe restrictions on mobility.

With suitable combustors, hydrogen could be used as a fuel for the gas turbine and internal combustion engine. The most difficult problem is how to carry the necessary fuel due to the low heating value on a volume basis (Table 2.1), as will be discussed later. Methanol is a possible fuel for the automobile engine, but also suffers from volume and weight problems, as will be discussed further.

2.3 Alternative Fuels

As indicated in the previous section, gasoline, diesel oil, and aviation fuels are chemical fuels which are most in demand by the transportation industry. Their current availability and cost are tied fairly closely to the existing fossil-fuel refining industry. Two alternative fuels which have a variety of possible sources (as discussed

further in Chapter 3) are hydrogen and methanol.

Methanol can be used directly as a fuel, or it can be mixed with gasoline. It has a heating value, both on a mass and on a volume basis, that is about half that for gasoline (Table 2.1). Hence it requires about twice as much fuel to be carried in order to travel the same distance. It would require a special carburetion system to be used alone with the internal combustion engine. Combustion products are mostly carbon dioxide and water, resulting in very low levels of pollutants. When used in mixtures up to 30% methanol with gasoline, no special devices are needed, while the methanol raises the octane rating of the fuel such that anti-knock additives are not needed, efficiency is improved, and pollutant levels are reduced. Methanol has a major disadvantage in that its affinity for water requires that special steps be taken to keep it dry. Transportation charges would be high on an energy basis since twice the volume/mass must be shipped to do the same amount of work. There are a number of studies on the advantages of changing to a methanol vice gasoline economy, but the capital investment in gasoline engines tends to make any such changes unlikely, unless the change is somehow legislated (K1,L1,R1,S1,Y1,K3).

Hydrogen is another potential fuel which shows more promise than even methanol due to the ease of production.

It is also used as a primary chemical feedstock in the production of other fuels (such as methanol during liquefaction of coal). Hydrogen has a very high heating value on a mass basis, but a low heating value on a volume basis since it exists as a gas except at very low temperature (Table 2.1). There has been a surge of interest in hydrogen as a low-polluting source of energy (V1). Since it can be produced by the electrolysis of water, it is looked upon with favor by solar power advocates as a complementary energy carrier.

A study has been made of the potential for liquid hydrogen fueled aircraft (B4). Because of the large volume of fuel that is needed, radical changes are needed in current design of aircraft. Although the weight of the fuel is lower than for JP-5 or other jet fuel, the increased volume creates increased drag or reduced payload. Despite the design problems, hydrogen offers potential advantages in improved aircraft performance, reduced noise, reduced pollution, and eventually lower fuel costs coupled with more widespread availability as petroleum supplies are depleted.

Although the aircraft industry expects that aircraft fuel needs will surpass those of the passenger automobile in the next 30 years (Figure 2.1), the emphasis has not been on how to find alternate fuels or aircraft propulsors,

but rather on how to get other energy users such as power plants, industrial processes, and the automobile to convert to other fuels such as methanol and coal while reserving most of the valuable hydrocarbon fuel for aviation use (P1).

2.4 Jet Fuel Specifications

Jet fuel specifications are formulated to be sufficiently rigid to ensure the safety of an aircraft's operation. If the engine on an automobile malfunctions or catches fire, it is generally easy to stop and correct the problem or at least get away from the hazard. If a ship propulsion system malfunctions or catches fire, it may be possible to keep operating while correcting the problem, and it is usually possible to get away from the hazard if necessary. When an aircraft malfunctions, it is usually necessary to land before full corrective action can be taken. Thus preventive measures must be taken by establishing fuel specifications and quality control standards. For military aircraft there is also a special need for stability of fuel under anti-aircraft fire. For use by shipboard-based aircraft and gas turbine propulsion, fire safety is of utmost importance.

There are three basic grades of military jet fuels: wide cut, high flash point, and kerosene. Only the first two are currently in use in the United States. Their

properties are as follows:

1."Wide cut fuels--the majority of land based military aircraft use wide cut fuel because of its potential maximum availability in times of emergency. Wide cut fuel also has excellent low temperature properties which are of advantage for military operations. The major exception is the United Kingdom who now operate most of their military aircraft on kerosene. Specification MIL-T-5624 (Grade JP-4) is used as a basis for the majority of national wide cut fuel specifications and the term JP-4 has become synonymous with this type of fuel. Within the NATO structure several nations have their own specifications which are basically the same as MIL-T-5624 (G1)."

2."High flash point fuels--to satisfy shipboard safety regulations a high flash point ($140^{\circ}\text{F}(60^{\circ}\text{C})$), low freeze point kerosene is specified for turbine powered aircraft onboard ships. As with the wide cut fuel, the U.S. military specification is the basis for other national specifications (G1)."

JP-4 is currently being used by the U.S. Air Force, while JP-5 is being used for the U.S. Navy. JP-4 has a higher fraction of volatiles, allowing a higher production yield, while JP-5 is primarily made up of the heavier paraffins, with a smaller fraction of volatiles and a generally smaller yield in production due to use of the less-available hydrocarbons. It can be expected that the Air Force, due to the need for additional protection against anti-aircraft attack, will have to find an alternate fuel with better flammability characteristics (Table 2.2), such as JP-5 or JP-8. A much more available substitute would be diesel fuel, which does have a high ignition temperature.

Table 2.2

RESULTS OF LIQUID-PHASE FUEL GUNFIRE TESTS (B5)

<u>Fuel</u>	<u>Flash Point (°F)</u>	<u>No. of Tests</u>	<u>% Sustained Fires</u>
JP-4	0	61	78.7
JP-8	110	47	4.3
JP-5	140	44	0.0

For low temperature conditions, fuel tank heaters would be a possible solution for extended high altitude flight, considering the higher freezing point of the less volatile fuels (L2).

In consideration of the fact that the Navy uses JP-5 exclusively for its carrier aircraft and for some ship propulsion, plus the special interest in applications for U.S. Navy use in the present work, subsequent development of a synthetic fuel generation plant will be focused on production of a JP-5 grade jet fuel for shipboard use. The yield of JP-5 is usually only 25% that of JP-4, but in a synthetic fuel generating process the products can be controlled sufficiently that an adequate yield can be obtained.

2.5 Fuel Supply and Demand

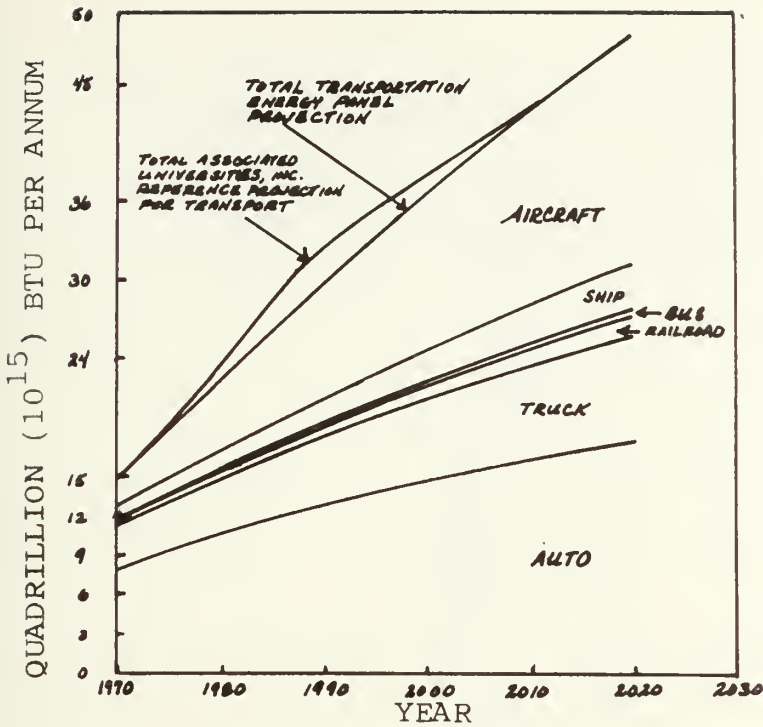
When the industrial revolution began over two hundred years ago, few envisioned that the day might come when the revolution might run out of energy. Water wheels and wood were the first energy sources used. Gradually coal was adopted as the preferred fuel to drive the engines and provide the energy for growth. In the late 1800's, as the first practical automobiles were being developed, petroleum gained favor as a convenient fuel, and gradually displaced coal as the primary energy supply. Using this cheap, easy-to-obtain fuel, world-wide industry in general and U.S.

industry in particular continued to grow exponentially through the first three quarters of the twentieth century.

The high standard of living in the United States has not come without cost. With only about 6% of the world population, the United States, until about 10-15 years ago, was consuming over half of the world's oil production (Figure 2.2), although this is in part due to the major role of the U.S. in supplying industrial products for the rest of the world, a role which requires considerable energy input.

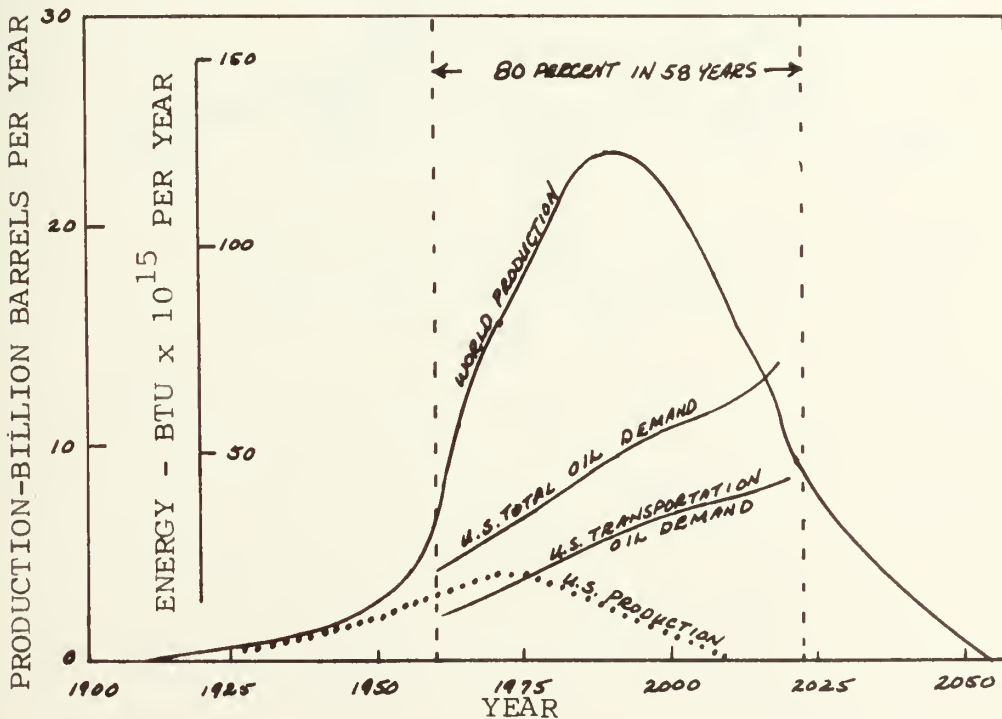
Most reliable sources (B4,C2,M4,M5) project a sharp drop in oil production in the near future, as present resources are depleted faster than new oil fields are found and developed. Figures 2.2, 2.3, and 2.4 show world production peaking in the time span 1990 to 2060. A recent CIA report (C2) projects that world petroleum production will peak between 1980 and 1985, as current resource estimates indicate that previous predictions of total world oil reserves were too optimistic. United States domestic oil production has already fallen below the peak levels of 1969-1970, although the impact of the Alaska pipeline will act to slow the decline in production level.

The exact year when production of oil peaks should not be an issue. As shown in Figs. 2.1, 2.2, and 2.5, the demand for fuels is steadily increasing. The OPEC oil embargo of 1973 forced a temporary drop in demand, but users



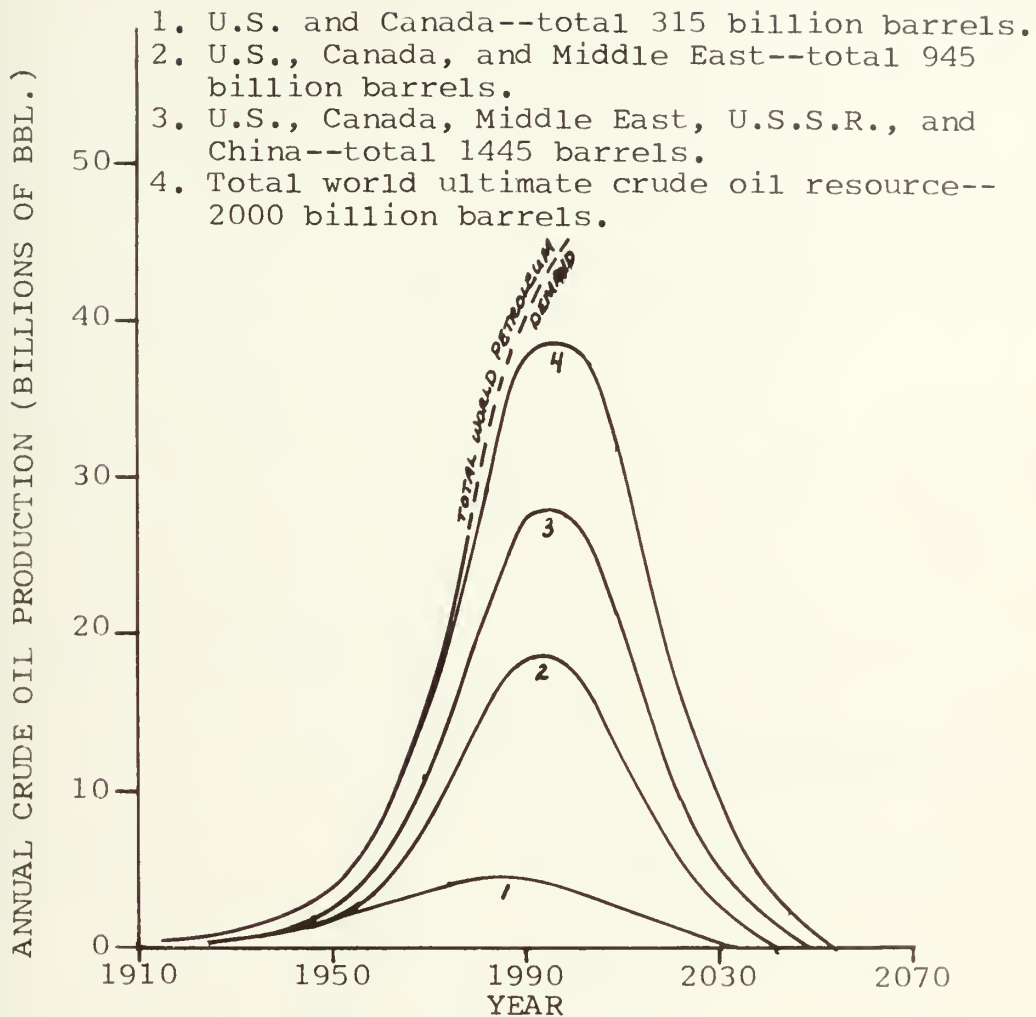
PROJECTED U.S. CONSUMPTION OF ENERGY FOR TRANSPORTATION (B4)

Figure 2.1



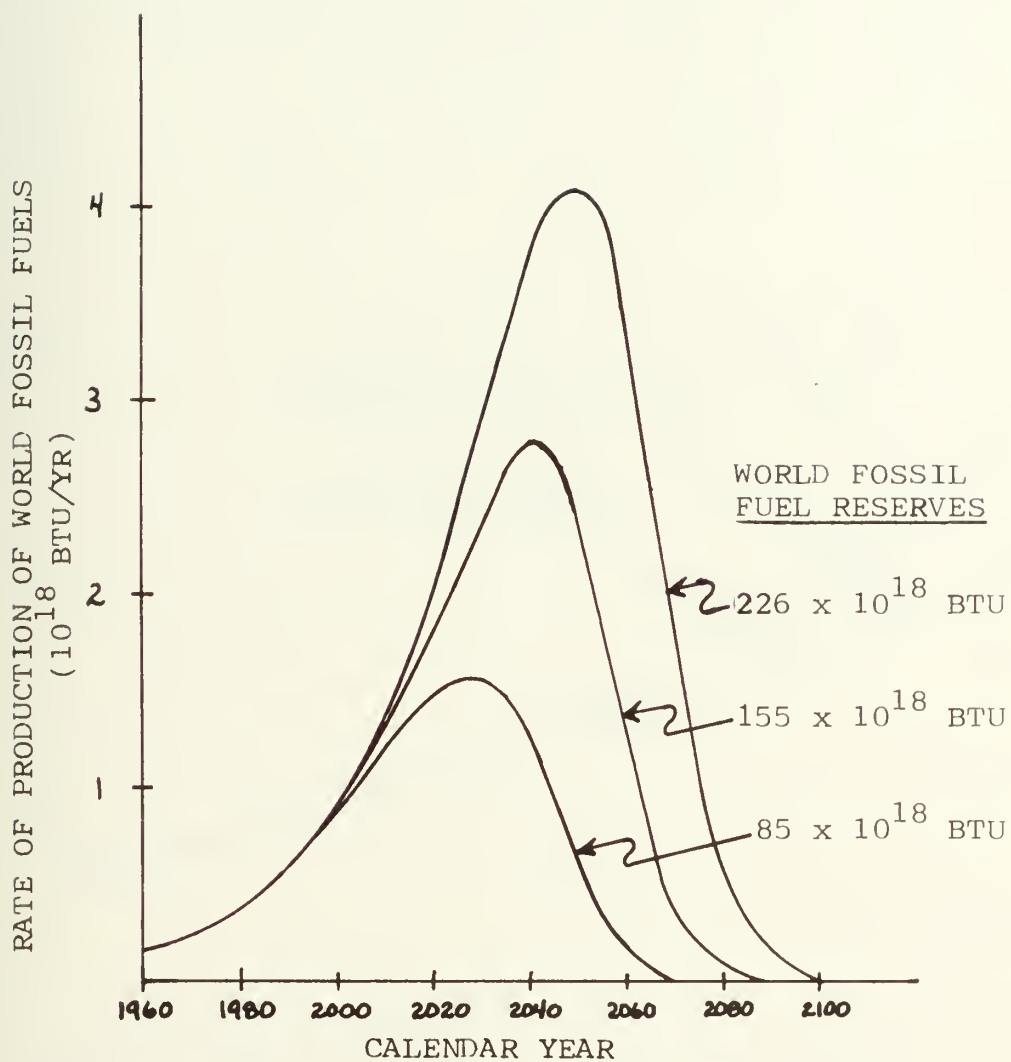
WORLD SUPPLY AND U.S. DEMAND FOR OIL (B4)

Figure 2.2



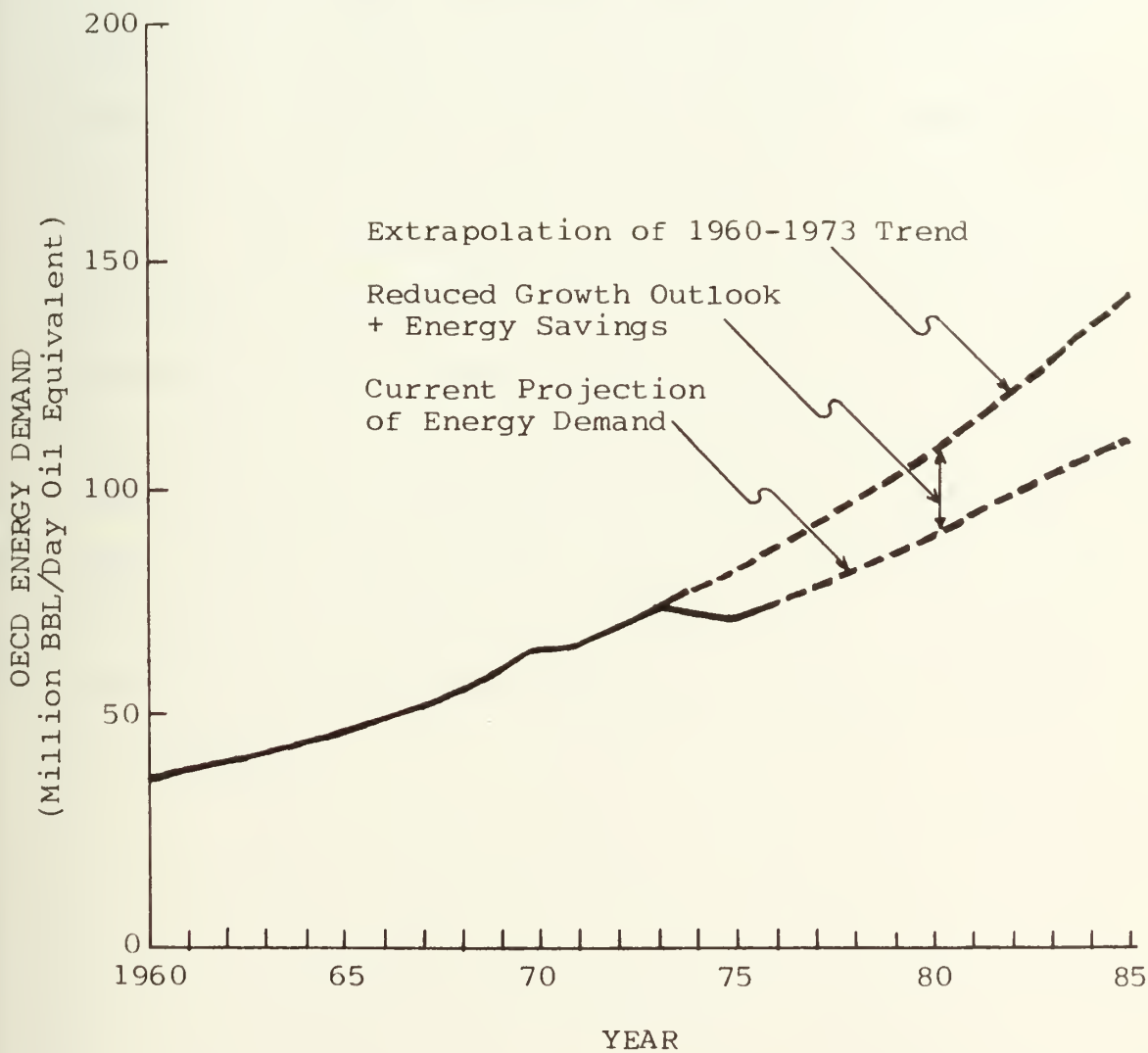
WORLD CRUDE OIL RESOURCES (M5)

Figure 2.3



WORLD PRODUCTION OF FOSSIL FUELS (M4)

Figure 2.4



OECD ENERGY DEMAND (C2)
 (Excluding Australia and New Zealand)

Figure 2.5

will continue to compete for the fuels they need to operate currently installed energy systems. When fuels become even less available, growth becomes stifled, fuel prices escalate rapidly under seller's market conditions, and the economies of user nations are shaken.

While the need for energy conservation is obvious, it should also be apparent that the shortages can only be postponed. In order to meet the projected energy requirements of Figs. 2.1 or 2.5, alternate fuel supplies are necessary. Coal conversion is the most likely candidate to meet short term domestic needs, since the United States, unlike many other industrialized nations, has extensive coal reserves. Use of nuclear fission energy to synthesize fuels is another attractive alternative. Fusion power and solar energy offer the only currently envisioned alternatives which are capable of providing for our needs when all reasonably-priced fossil fuels and fissionable materials are exhausted.

Chapter 3

SYNTHETIC FUEL PRODUCTION

3.1 Introduction

Petroleum production in the United States has dropped from peak levels. World petroleum production is expected to reach its peak in the next 5 to 25 years, while demand for petroleum products continues to climb (B4,C2,M4,M5). Other sources for hydrocarbon fuels and industrial feed materials must be developed in order to supplant petroleum and meet expected demand as present supplies are depleted.

United States energy policy dictates an increased reliance on coal and coal conversion processes to meet our energy needs. While the need for this is recognized, it also is important to understand that coal mining, conversion, and combustion will further degrade our already polluted environment.

There is another track which can be followed with far less impact on the environment. While nuclear power cannot satisfy all our energy requirements, it can be used to meet the need for all chemical fuels. A synthetic fuel generation plant which uses a nuclear power plant (either fission or fusion) as a source of heat and electricity can convert basic raw materials into hydrocarbon fuels (B2,B3,01,P2,P3,S2-S7). Indeed energy can serve as a "raw material"

for the production of many ersatz chemicals of commerce. The processes of concern in this report involve combining hydrogen (from water) and carbon dioxide (from air or water) to produce methanol or jet fuel.

3.2 Methanol Production

3.2.1 Methanol: Uses and Properties

Methanol is often referred to as methyl alcohol or wood alcohol, and has the chemical formula CH_3OH . Methanol is a satisfactory fuel for many applications and burns cleanly to yield carbon dioxide and water. Since it has the disadvantage of low energy content both on a mass and on a volume basis (Table 2.1), and requires engine carburetion modifications except when mixed with gasoline, the main interest in methanol here is as an intermediate step in the production of other substances such as gasoline or as feed stock in other chemical processes (S1,Y1).

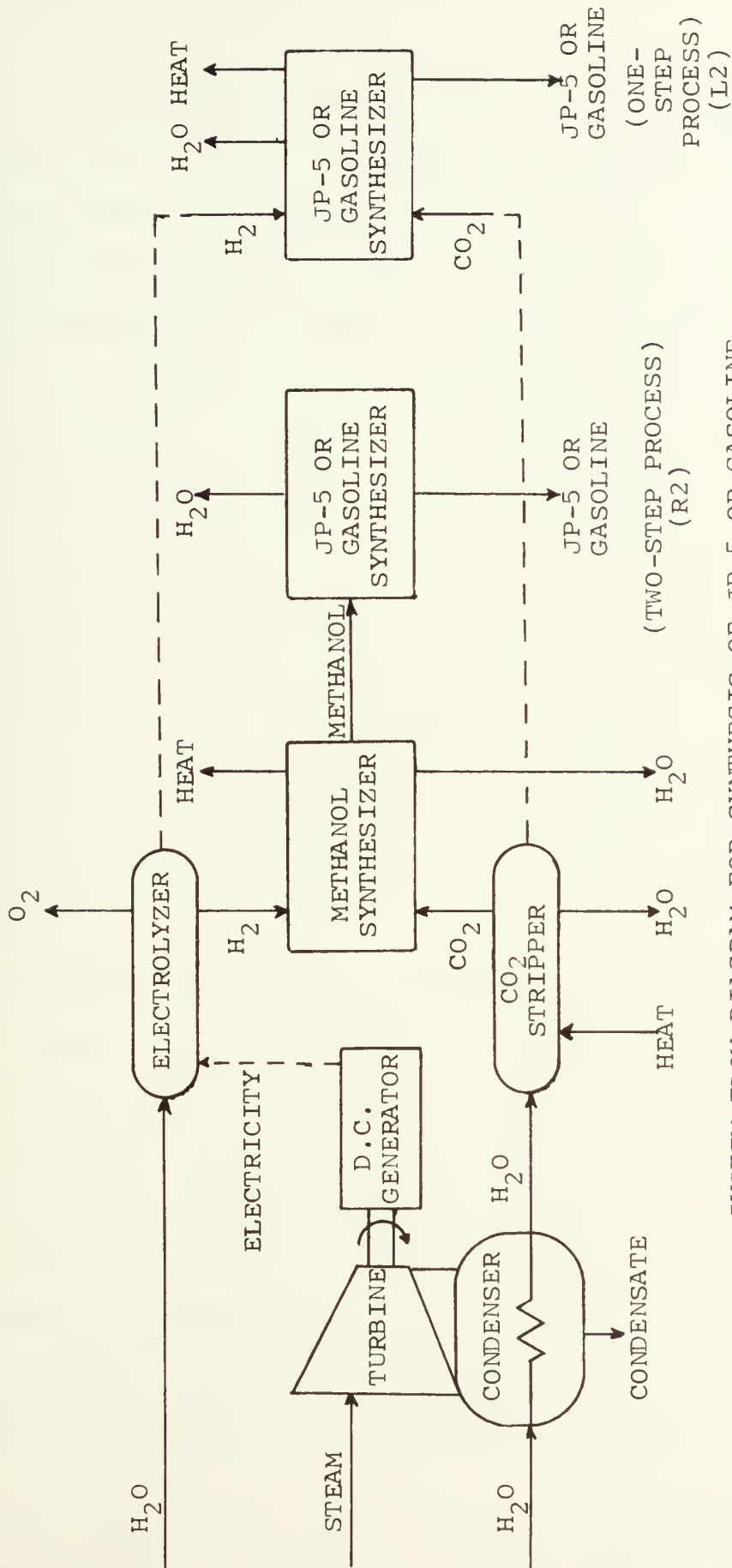
References (R1) and (L1) present arguments for converting from a gasoline-based to a methanol-based economy. There is also interest in methanol as a way to utilize the natural gas which is currently being flared at some oil fields, by installing plants which convert methane to methanol. Thus it would be possible to utilize conventional tankers for shipping instead of requiring special liquefaction plants and special purpose LNG carriers.

Since most oil and natural gas fields are in remote areas which have little economic value once the natural resources are depleted, at least in the Middle East, and both methane liquefaction and methanol conversion plants require a large capital investment, it is understandable that the owners or governments involved are not currently prepared to advance the needed capital (L2). A recent ERDA report (E1), while not available at the time of this writing, should provide additional information on the methanol change-over question and problems.

Methanol can be produced from many sources: petroleum, coal, shale oil, natural gas, refuse materials, wood, and from such basic raw materials as hydrogen and carbon dioxide or carbon monoxide. For present purposes, the synthesis of methanol from hydrogen and carbon dioxide is the process of concern (Figure 3.1); generation of these two feed streams is discussed in the following sections.

3.2.2 Hydrogen Production

Hydrogen is of increasing importance in coal liquefaction, as a feed material for various chemical process industries, as a fuel for special propulsion engines for space flight, and as a potential non-polluting alternative fuel for general use. Although it has a very high energy on a mass basis, it has a low energy on a volume basis



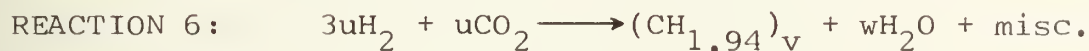
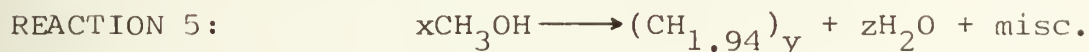
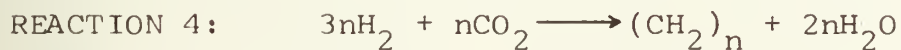
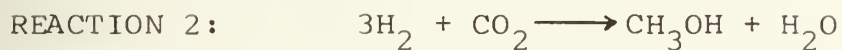
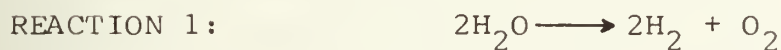
SYSTEM FLOW DIAGRAM FOR SYNTHESIS OF JP-5 OR GASOLINE

Figure 3.1

(Table 2.1) since it exists as a gas except at extremely low temperature (33.3°K). Hydrogen liquefaction, while well established on a commercial basis, is not convenient for transportation applications. It appears that the most promising adaptation for transportation is by using metal hydrides as a storage device, but the method is still under development. In such a form it may well serve as a very useful energy source as long as the weight of the storage tank itself is not too great. Hydrogen will be considered here only as a feed material for synthesizing conventional hydrocarbon fuels, although it is important to recognize the long term prospect for hydrogen itself as a fuel since this will help motivate work on complementary applications (such as thermal decomposition of water). Reference (M4) expands further on the future prospects for hydrogen.

The hydrogen utilized in the synthetic fuel generation process under consideration here is obtained by the decomposition of water (which may be seawater), as shown by Reaction 1 of Table 3.1. This process may involve one or more of the following decomposition methods: electrolysis, thermal decomposition, chemical decomposition, and radiological decomposition. Only the first three processes are currently of significance, although research may lead to more effective use of all the methods of decomposition.

Table 3.1

CHEMICAL REACTIONS

Decomposition of water requires a substantial energy input (14.7 kwhr/lb H₂ at 100% efficiency) and is the most expensive step in the fuel synthesis process.

Currently available commercial electrolysis units achieve only 60 to 70% efficiency, requiring energy inputs of 21 to 24.5 kwhr(e)/lb H₂. It is expected that improved versions will allow 80 to 90% efficiency to be obtained on a commercial basis. Approaches which achieve the largest reduction in the electrical energy requirements, such as by using combined decomposition methods, will result in the lowest overall cost of product fuel, since electrical energy is the most inefficient. For aircraft carrier applications, this is particularly important, due to the need for installation of additional electrical generators and/or D.C. converters. These generators and/or converters represent a large investment in space, weight, and expense which no ship can easily afford to give up. Ships designed to utilize electric drive propulsion may be able to realize a significant advantage over conventional shaft-driven units by transferring some of the electrical load from the propulsion motor to the electrolytic production systems, without requiring any additional generators.

One reason electrolysis is so costly is that the thermal-to-electric conversion efficiency of the power plant providing electricity is low (usually 30 to 40%). By oper-

ating electrolysis units at elevated temperatures, the overall efficiency can be improved, because the thermal energy provides some of the energy required for decomposition. The temperatures available from nuclear reactors are ultimately limited by restrictions on allowable fuel temperatures. For Light Water Reactors, temperatures are normally kept under 600°F because of the additional need to maintain acceptably low system pressures and to avoid heat transfer problems (burnout). Some special reactor types, such as liquid-metal-cooled (LMFBR) or high-temperature-gas-cooled (HTGR) reactors, are able to operate at higher temperatures, giving hope for the eventual use of thermal water-decomposition processes.

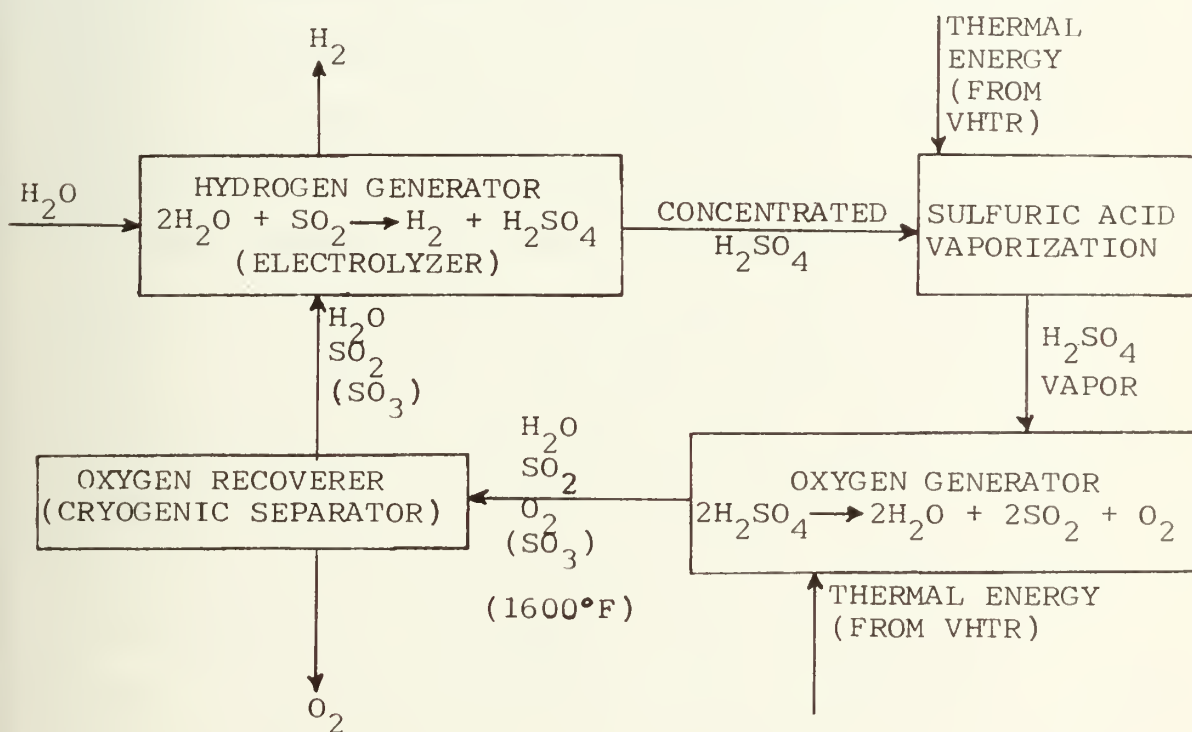
Thermal decomposition alone is impractical at currently available process temperatures, but thermo-chemical processes can be used to make the process proceed more easily. Usually several reaction steps are involved, and thermal and electrical energy are an input at given steps. For the most part, multi-step thermo-chemical processes have not been tested in full-scale operation. Currently a great deal of effort is being spent on finding improved methods for generating hydrogen to justify shifting to a hydrogen economy (E2,F3,F4,M2-M4,V1,W1).

Westinghouse has proposed a thermo-chemo-electrical cycle for production of hydrogen (and byproduct oxygen)

which is integrated with a Very-High-Temperature-Reactor (VHTR), an HTGR type of design developed from nuclear rocket engine (NERVA) studies, which provides the desirable high process temperatures. The chosen cycle is based on sulfur dioxide and is shown in Figure 3.2 (F2). The reactor is designed to provide process heat at 1700°F (maximum) which allows use of chemical reactions which require high temperature to go to completion. Hydrogen generation by this process is expected to allow a thermal efficiency in excess of 50% in the production of hydrogen, which compares with overall efficiencies of 20 to 25% when a PWR and electrolysis unit are used to generate hydrogen, since the efficiency of the cell must be multiplied by the efficiency of the power unit.

Economical production of hydrogen requires advancements in the following areas: (1) improved efficiency of electrolysis units, (2) reduced requirements for electrical energy by using thermal energy, and (3) improved efficiency of the power plant which is providing electricity. It is also likely that hydrogen production could be used to maintain base loading during off-peak demand periods to lower the cost of central station power. Since electrolysis can proceed at nearly constant efficiency over a range of 25 to 100% (approximately) of capacity, and is energy rather than capital intensive, it is a good choice as an alternative use of off-peak power.

Figure 3.2

HYDROGEN GENERATION WITH NUCLEAR PLANT INTERACTION (F2)

3.2.3 Carbon Dioxide Production

As a consequence of various manufacturing processes and of burning hydrocarbon fuels, carbon dioxide levels have steadily built up in the atmosphere, since natural removal processes (such as photosynthesis) have been unable to keep pace with production. The long term effect of these higher carbon dioxide levels is predicted to result in more heating of the atmosphere by the sun, resulting in a gradual increase in temperature, and eventual changes in global weather patterns (R3).

The synthetic fuel generation method proposed here would use environmentally available carbon dioxide and help to alleviate the unbalance, in effect trading off gaseous wastes (CO_2 , SO_x , NO_x) for the nuclear waste of the power plant. Carbon dioxide concentrations in seawater are in equilibrium with the air. Carbon dioxide is available as a component of air, from solution in water, or from solid materials such as limestone. A thorough analysis (S4) of the various methods of obtaining carbon dioxide for methanol synthesis indicated that the most economically attractive process using available state-of-the-art technology was found to be absorptive stripping of carbon dioxide from seawater. They chose the next more expensive process, absorptive stripping of CO_2 from air by K_2CO_3 solution, as the recommended method so that

the nuclear powered methanol plant could be sited anywhere instead of being immediately adjacent to a large body of water. Due to the focus of the present work on use aboard ship, the removal of carbon dioxide from seawater was selected as the preferred alternative. While waste heat is used to remove carbon dioxide from solution, there are pumping requirements of 0.26 kwhr(e)/1b CO₂ (S4). It was also assumed that 75% of the bicarbonates and carbonates dissolved in seawater are also stripped along with the dissolved carbon dioxide at the stripping temperature of 100°C; 240 lb of seawater would then be required to obtain 1 lb of carbon dioxide.

3.2.4 Methanol Synthesis

The process for methanol synthesis is well tested. The overall reaction process is shown in Reaction 2 of Table 3.1. Carbon dioxide and hydrogen are compressed, at a cost of 0.1 kwhr(e)/1b Methanol (S4), then passed over a catalyst under pressure (270 atmospheres and 300°C over ZnO or 50 atmospheres and 350°C over CuO), and finally passed through a highly selective molecular sieve to remove the water. Analyses of this process have been conducted using a fission reactor (B1,S2) or a fusion reactor (B2,P2,P3,S4,S5) as a primary source of power (Fig. 3.1).

There is need for further research to develop catalysts

which are more active and are more selective for the end product. Lack of petroleum during World War II led Germany to use Fischer-Tropsch synthesis to make methanol for its fuel needs, but the catalysts used were not as effective. Only government control of imports and gasoline prices allows South Africa, which has very limited petroleum but large coal deposits, to economically produce synthetic oil from coal at its SASOL plant today. With the emphasis on energy alternatives in the United States, new research is being conducted on catalytic reactions (C_2, H_1, K_2). Although aimed at use in coal liquefaction, the research may make methanol synthesis from hydrogen and carbon dioxide an even better alternative.

3.3 Gasoline Production

3.3.1 Synthesis from Methanol

Under contract to ERDA, Mobil Oil Corporation has developed a zeolite catalyst and molecular sieve which converts methanol to a mixture of hydrocarbons from which a 90% yield by weight (based on CH_2) of gasoline is possible, and from which the remainder (as a gaseous product) can be drawn off to be used as liquefied petroleum gas (LPG). A pilot plant is now being built to test this operation on a larger scale (M1, V2-4).

Gasoline is a mixture of long chain molecules with a

nominal composition $(CH_2)_n$. Reaction 3 of Table 3.1 shows the basic process for gasoline synthesis from methanol. Mobil estimates a production cost of approximately 5 cents per gallon of gasoline, with 2.4 gallons of Methanol being required on a stoichiometric basis for every gallon of gasoline produced. The economic feasibility of the process is a function of the cost of producing the methanol feed chemical. Since methanol currently has a higher cost per unit energy than gasoline, it would not appear to be a cost effective process. But when methanol and gasoline are no longer being produced from petroleum, the costs will change. If methanol is produced on a large scale basis, the cost will drop, since it is currently used primarily as a feed chemical for special processes.

3.3.2 Synthesis from Hydrogen and Carbon Dioxide

According to Longwell (L2), the process described in the preceding section, being a two-step process, has built-in inefficiency. If the end product desired is gasoline, then the catalyst should be designed to take the original feed materials, hydrogen and carbon dioxide, and combine them in a one-step process. The catalyst will very likely be the same as presently used in the two-step process, but the resultant yield should be higher, capital costs are lower (only one synthesizer unit), and operating expenses would be lower (only 1 catalyst). The basic one-step

process is shown in Reaction 4 of Table 3.1, and by following the dashed lines in Figure 3.1. This is posed as a contemporary challenge to the catalyst expert. Expected yields can only be estimated at this point, but this is the process that would be expected to lead to a synthetic fuel generating plant that is more economical and easier to operate and maintain. It would be time-consuming, operationally complex, and wasteful of both weight and space to maintain two catalytic synthesizers where one might suffice.

In the case of a shipboard installation, the LPG is not marketable, so it would have to be either burned or vented overboard. The one-step process would make for more favorable economics by minimizing this potential waste of hydrocarbon and energy. Catalysis experts recognize the need for fundamental research to help in satisfying our energy requirements (H1).

3.4 Jet Fuel Production

3.4.1 Synthesis from Methanol

In the same manner as gasoline is synthesized from methanol, it should also be possible to design a catalyst which favors the production of JP-5. JP-5 is hydrogen-poor compared to gasoline, and has a nominal composition $\text{CH}_{1.94}$ although it consists of a variety of hydrocarbons with a higher percentage of paraffins and a resultant

higher freezing point and flash temperature. Once again, fundamental catalysis research is needed to select the catalyst and structure which is best at producing a high yield of JP-5. An exact relationship cannot be shown, but Reaction 5 of Table 3.1 and Figure 3.1 show the basic process.

3.4.2 Synthesis from Hydrogen and Carbon Dioxide

As was the case for gasoline synthesis, it is expected that a more efficient process for production of JP-5 will be the one-step process shown by the dashed lines of Figure 3.1 and Reaction 6 of Table 3.2. Hydrogen and carbon dioxide can be combined over a suitable catalyst to produce a sufficiently high yield of JP-5.

3.5 Other Uses for Synthesis Processes

3.5.1 Coal Conversion

The Fischer-Tropsch synthesis of methanol from hydrogen and carbon dioxide has direct application to coal liquefaction. Combination of hydrogen and carbon monoxide in somewhat different ratios will produce the same end products as when carbon dioxide and hydrogen are used, using the same catalytic conditions, although product yields can be expected to be somewhat lower.

The most frequent coal conversion method starts with steam reformation of coal, according to the following

reaction: $C + H_2O(\text{steam}) \longrightarrow CO + H_2$ (synthesis gas) .

For methanol synthesis, the Fischer-Tropsch reaction proceeds as follows: $CO + 2H_2 \longrightarrow CH_3OH$. Additional hydrogen is required to supplement that produced from hydrocracking coal. It is more likely that innovations in catalysis engineering will come as a result of coal liquefaction techniques, since there is more on-going development in that area, so that the synthesis of fuel from hydrogen and carbon dioxide will most likely get its start from a process developed for coal conversion (C4,H1,K2). Methods of recovery and expected availability of coal in the United States can be found in Reference (N1).

3.5.2 Natural Gas Conversion

Natural gas reserves in the United States, while substantial, are already over-committed for current domestic use. Natural gas is a byproduct of petroleum production but is mostly burned (flared) at the well because of the difficulties involved in transporting it. The natural gas, unless used for domestic purposes, must either be liquefied or converted by some means to a liquid. The capital cost of a liquefaction plant is high, the LNG carriers are expensive to build, and long trade routes are discouraged due to the rapid boiloff and necessary venting of LNG. Since natural gas is primarily composed of methane (CH_4), the possibility of converting it to

methanol is being considered, since it could then be carried by conventional tankers. The question of whether any type of plant will be built is dependent on the willingness of the producer nations to make large capital investments in the vicinity of their petroleum fields, which are generally in remote locations. A study has been made on the feasibility of liquefaction plants for Saudi Arabia (S8), but indications are that nothing may be built. For nations which have no petroleum reserves, but have natural gas resources, Fischer-Tropsch synthesis would allow them to synthesize methanol and gasoline for their own uses.

The reactions of concern are: $\text{CH}_4 + \text{H}_2\text{O} \longrightarrow \text{CO} + 3\text{H}_2$ and $\text{CO} + 2\text{H}_2 \longrightarrow \text{CH}_3\text{OH}$ (S1).

3.5.3 Biochemical Energy

Another limited application of Fischer-Tropsch synthesis is for obtaining energy from conversion of biological wastes to usable gases. A major product of this process is methane, so it is adaptable to the same process as in the previous section on natural gas conversion.

3.6 Added Benefits

3.6.1 Oxygen Production

During the decomposition of water to generate hydrogen, oxygen is available as a co-product. It has many of the same handling problems as hydrogen; for example, the

requirement for cryogenic facilities for liquefaction. Since oxygen is needed to support a number of chemical processes, it is a marketable commodity which can be credited to reduce the cost of producing fuel. An aircraft carrier needs its own oxygen plant to remove oxygen from the air for air crew needs during high altitude flying or other pressurized flights. The space, weight, and personnel could be available for the synthetic fuel plant, since it will provide the necessary oxygen.

3.6.2 Environmental

The concept of utilizing nuclear power plants as the source of heat and energy for synthetic fuel generation will require a substantial increase in the number of nuclear plant installations that are contemplated. Supplying all of the U.S.'s estimated transportation needs of 2×10^{16} BTU/year would take an estimated 1456 1000MW(e) PWR's fully dedicated to producing gasoline (90% capacity factor, 8000 barrels/day) (S2), which should be viewed in the light of plans for only 200 power reactors in operation by 1985 for electrical power needs.

The projected impact of increased radioactive wastes, when isolated by adequate geological disposal, is considered to have less net environmental impact than will result from coal mining, conversion, and combustion. The mining practices themselves are fairly similar in hazard

of mining operations, but approximately 100 ft³ of coal must be mined to provide the same energy as 1 ft³ of uranium ore. In addition to the damage done by strip mining, one-third (approximately) of the input coal to a conversion plant is burned, contributing to proportionately more atmospheric pollution. There is a substantial amount of waste material which needs to be disposed of from any coal burning plant. Approximately 10 tons of ash and 10 tons of limestone sludge (for SO₂ removal) result from burning 100 tons of coal. Assuming radioactive waste can be safely handled, it is much less detrimental to the environment than the coal-related practices evaluated in Reference (N1) (D1,U2).

As discussed earlier in Section 3.2.3, burning of hydrocarbon fuels increases the carbon dioxide levels in the atmosphere (R3). If all fuels were synthetically produced using nuclear energy, a closed cycle would result, and carbon dioxide levels would stabilize until natural devices (e.g. plants, oceanic absorption) were able to once again reduce carbon dioxide levels.

If fusion reactors become available, the radioactive waste problem would, for all practical purposes, no longer exist, and there would be a nearly inexhaustible source of fuel (limited only by lithium resources for deuterium-tritium fusion devices). Synthetic fuel generating plants

could provide fuel for all other energy needs which could not be supplied by electricity. The remaining environmental problem, which is an irremedial problem with all power plants and manufacturing processes, will be how to dispose of the waste heat.

Chapter 4

NUCLEAR POWERED SYNTHETIC FUEL PLANTS

4.1 Introduction

The need for developing a synthetic fuel generating capability has been recognized by a number of people. Dr. Thomas Reed (R2) of MIT's Lincoln Laboratories first introduced the author to the concept of placing a synthetic fuel generating plant onboard a nuclear powered aircraft carrier. He presented some basic calculations on mass and energy flow, and called attention to the work of Steinberg (B1,B3, S3-S7) and his associates at Brookhaven National Laboratory on fusion-powered methanol synthesis plants, as well as, most recently, methanol and gasoline synthesis using nuclear fission power (S2), with recognition of the suitability of the process for producing jet fuel onboard an aircraft carrier in order to provide for the needs of the aircraft. The author is also familiar with the work of Farbman and his associates (F1-4,J1,T1,W1) at Westinghouse Astronuclear Laboratory concerning two very high temperature reactor (VHTR) designs with special features considered to be particularly valuable to the applications of this paper. The concepts advanced by these three groups provide promise for a satisfactory operational system.

Current light water reactor designs cannot make as good use of the synthetic fuel generation process as

systems having a higher temperature capability. Since PWR's are presently, and may remain, the only approved nuclear power source for U.S. naval vessels, they must be given due consideration to determine the limits of applicability of this system.

It should also be recognized that, in order for the U.S. Navy to look favorably upon plans for installation of any such total energy system aboard a new aircraft carrier, it would want to see an operating prototype that would clearly show the advantages of the system, to determine the military value of an aircraft carrier with its inherent mission capabilities. It is also just as likely that no such land prototype would be built in the near future unless the U.S. Navy sponsored such a demonstration. It is not intended here to come up with a blueprint for an optimized design, but rather to sketch a series of potential designs which are realizable with near term commercial technology.

The ultimate need for the system is almost self-evident. Even if nothing specific is done along these lines, the spin-off from other work in progress should improve the prospects for ultimate application of this or a related system package. It is left to the potential user to decide at what point the technical prospects are sufficiently bright, and breakeven fuel costs high enough, to justify commitment to the pilot plant stage.

4.2 Light Water Reactors

All present U.S. Naval Reactors are of the pressurized water reactor (PWR) type. The PWR also represents a significant fraction of all central station power reactors currently operable, under construction, or on order: 67% of U.S. reactors and 55% of all reactors world-wide (N3). Light water reactors (pressurized or boiling water reactors) comprise over 98% of all U.S. units and 80% world-wide: the boiling water reactor (BWR), however, is less suitable for shipboard use. Hence for the purposes of this study, PWR's will be analyzed whenever a conventional reactor is under consideration.

Water as a coolant and moderator has the advantages of being inexpensive and readily available, as well as having a low level of long-lived activation. Water does have the disadvantage of requiring high pressures to remain in the liquid state at plant operating temperatures. Because of this, and because of temperature limits on fuel and clad materials, PWR secondary steam plant temperatures should be expected to remain below about 550°F (and the corresponding saturation pressures). Hence neither land-based nor marine PWR's provide thermal conditions which would aid greatly in production of hydrogen (T2).

The thermal efficiency of central station PWR's is about 30 to 35%. For naval reactors, thermal efficiency

should be closer to 25%, as they have a simpler steam plant design and are designed for operability over a wide range of speeds, rather than for optimum economic operation under base load conditions. In the present work, 32% efficiency will be assumed for a commercial PWR, and 25% efficiency will be assumed for a naval PWR.

4.3 High Temperature Reactors

4.3.1 Fission Reactors

There are two major types of fission reactors which are of importance to this discussion: liquid-metal-cooled and gas-cooled. Both are capable of attaining high temperatures for process applications, operate at relatively low pressures, and are capable of 40 to 45% thermal efficiency (T2).

Liquid-metal-(sodium)-cooled reactors are currently being developed for breeder (LMFBR) use. Coolant exit temperatures from the core on the order of 1000°F are planned (fuel reprocessing and LMFBR development, however, have been given low priority in the U.S. of late.).

A sodium cooled reactor with a conventional secondary steam plant was initially installed on the U.S. submarine Seawolf. It was later replaced with a conventional PWR due in part to superheater failure during sea trials and, perhaps more importantly, due to the perception of its

higher level of inherent hazards relative to those of the PWR in the highly successful Nautilus: liquid metals react with water to release thermal energy, form caustic solutions, and liberate hydrogen, which is explosively flammable in air; sodium activation (Na-24) limits post-shutdown accessibility; and special trace heating techniques must be utilized to maintain the coolant in a liquid state. Hence liquid-metal-cooled reactors are not considered desirable for shipboard use. They are of interest for terrestrial use, but will not be considered further in this study, as gas-cooled reactors offer a more desirable alternative.

High-temperature-gas-cooled reactors (HTGR's) have a number of significant inherent advantages over other reactor designs, although U.S. development of this reactor type has recently been curtailed. Process temperatures of 1500 to 2000°F (compared to about 1200°F maximum for liquid-metal-cooled reactors) are possible. The coolant employed is an inert gas (helium), and the moderator is graphite, both of which have properties favorable to high temperature operation. In the U.S., General Atomic has promoted central station HTGR development, while in Europe a pebble bed design is under development by the Germans (T2). Westinghouse has used the technology developed in its NERVA nuclear rocket engine program to design a special HTGR, the very high temperature reactor, which has particular

advantages for the present applications.

Two variations of the very-high-temperature reactor (VHTR) have been explored: (1) a nuclear heat source for process heat applications (Figures 4.1 and 4.2) which is capable of providing temperatures of 1600 to 2000 F, and (2) a light weight nuclear powerplant (LWNP) which provides a low specific weight power plant which utilizes superconducting generators and motors (for electric drive) and is intended for naval applications such as the high speed surface effect ship (SES) which requires high power and low weight for successful operation (F1-4,J1,T1,W1). The LWNP is shown in Figure 4.3.

A VHTR design suitable for combined propulsion/synfuel applications might take advantage of both concepts. A compact, low specific weight plant is always desirable for naval reactor use. Since propulsive power is provided by electric drive, no separate generators would be needed for electrolysis of water. Even more important is the availability of high temperatures which allow the use of the thermo-chemical cycle shown in Figure 3.2, minimizing the electrical requirements (less than 15% of that for electrolysis alone) and thereby reducing the energy required for decomposition. The cryogenic plant required to sustain superconductivity can also be used to cool the oxygen obtained during the process for shipboard use. In addition

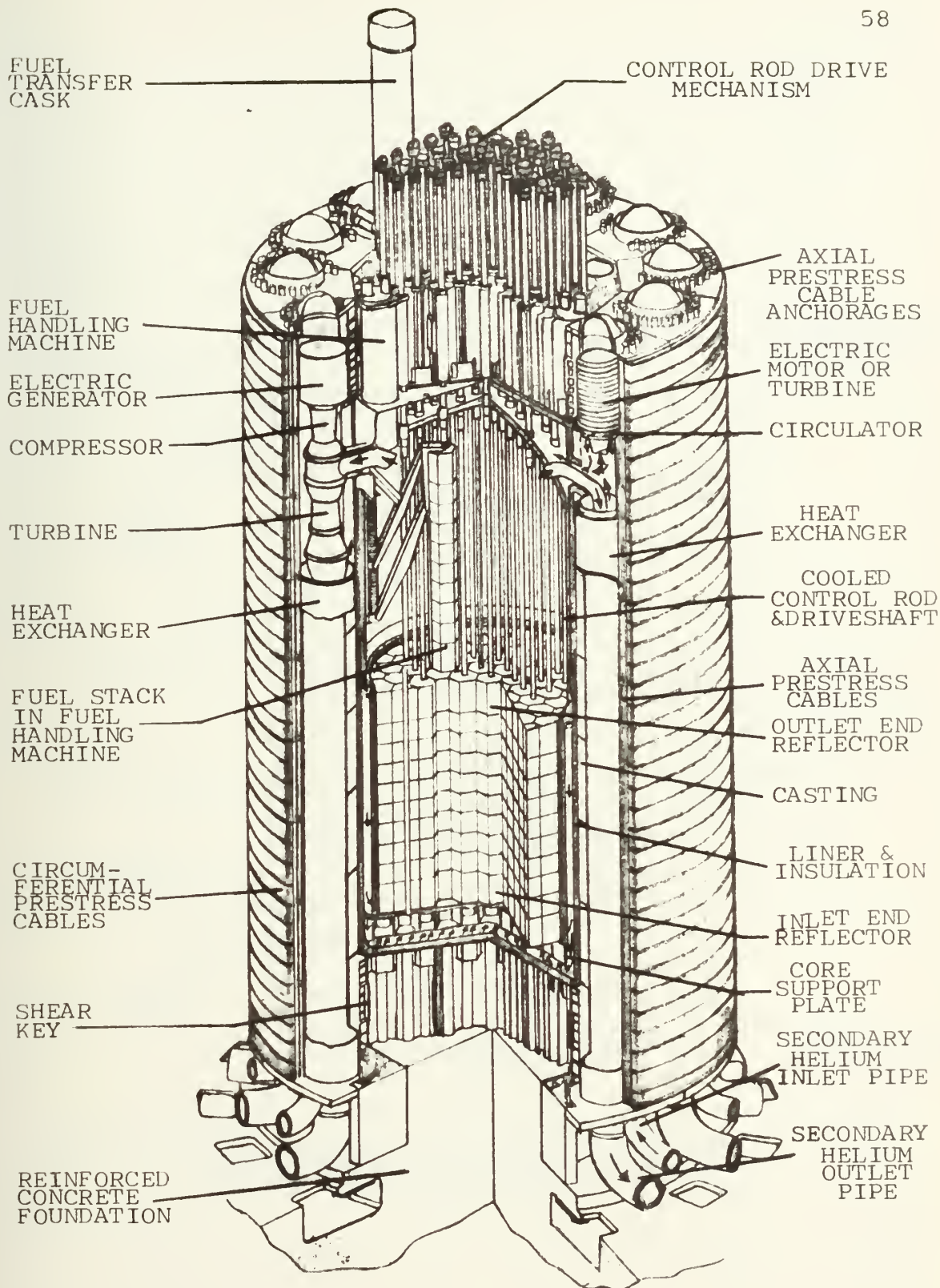
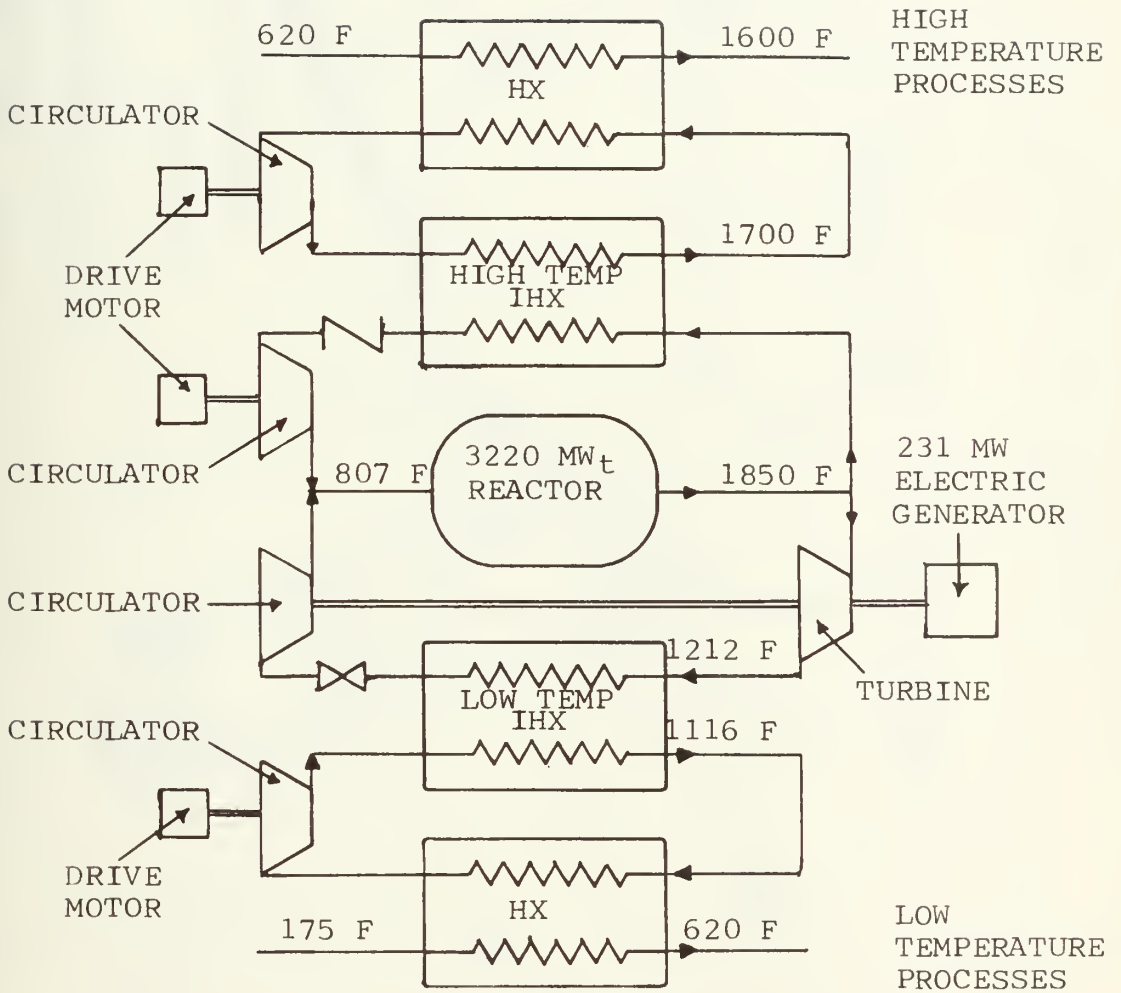


Figure 4.1 VERY HIGH TEMPERATURE REACTOR (VHTR) (W1)



SYSTEM DIAGRAM OF A VERY HIGH TEMPERATURE REACTOR (VHTR)
FOR PROCESS HEAT APPLICATIONS (F2)

Figure 4.2

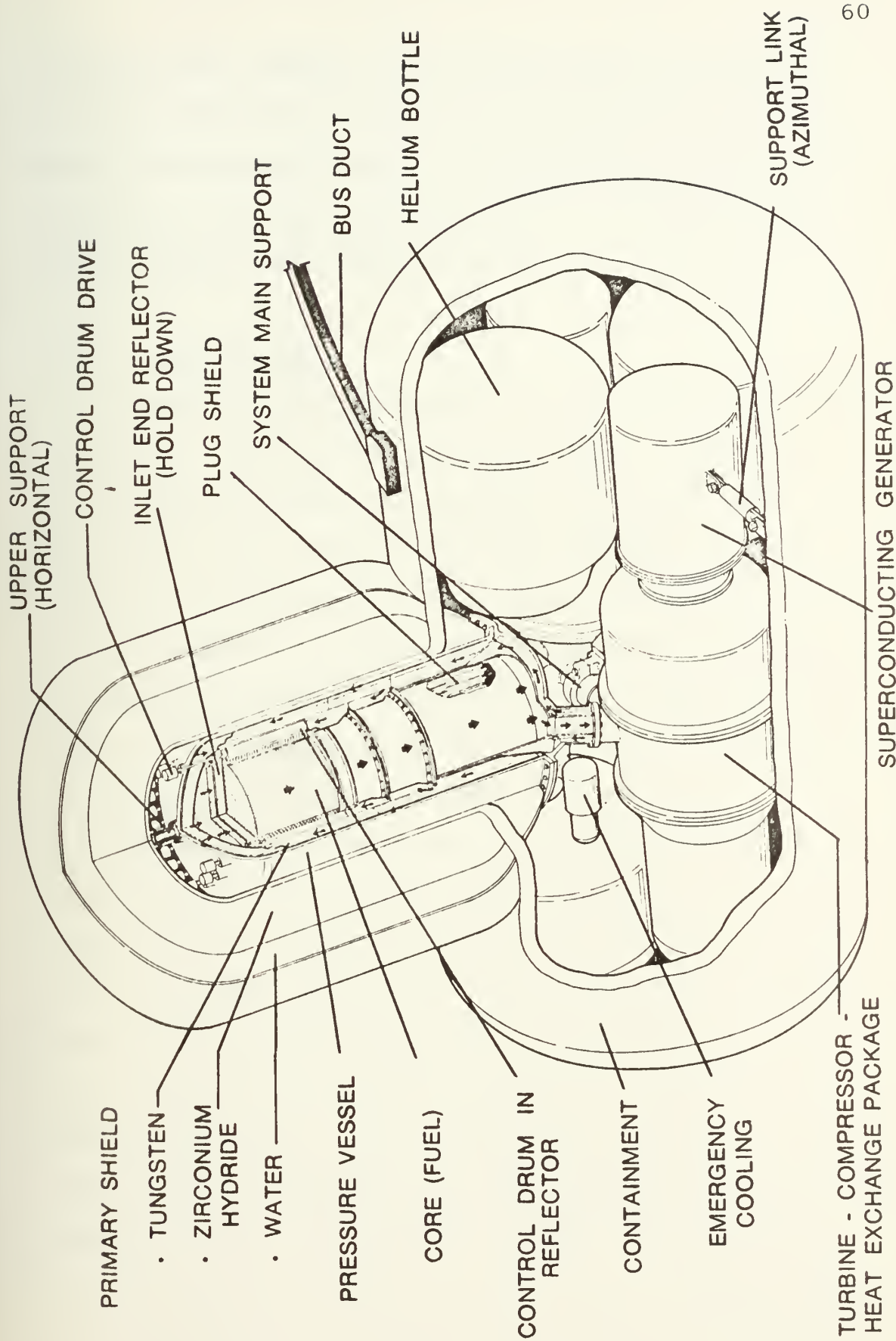


Figure 4.3 LIGHT WEIGHT NUCLEAR POWERPLANT (F2)

a considerable savings in weight and space is possible. A thermal efficiency of 42% will be assumed for the commercial VHTR process plant, while the marine version, with a combined propulsion/process unit, will be assumed to have a thermal efficiency of 35%.

4.3.2 Fusion Reactors

A promising energy source for the future lies in fusion power. The necessary fuels, deuterium and lithium (for tritium breeding) are expected to be sufficient to provide for world energy needs for thousands of years. However the engineering requirements for design and control are not presently known with any certainty. Moreover, it is unlikely that there will be any power plants of this type operational before the year 2000 (R4). Thus estimates of the cost of fusion power have little meaning. The potential advantages with respect to synthetic fuel generation have been thoroughly studied (B2,P2-3,S3-5). Not only does the fusion reactor have the potential for providing the high temperatures needed for thermal decomposition, but other reactions, such as radiological decomposition, may also improve the efficiency of the hydrogen generation process. Due to the lack of suitable or relevant data, analysis of a fusion-powered synthetic fuel generation plant will not be considered further here.

4.4 Sizing and Configuration of Combined Plant

4.4.1 Aircraft Carrier Plant

Due to the sensitive nature of naval nuclear power plant characteristics, it will be necessary to generate unclassified values of certain characteristics such as the installed reactor power aboard a nuclear powered aircraft carrier. One would expect the actual figures to be reasonably close, and the results of this analysis can be readily corrected by substituting in the correct values.

First it is necessary to determine what size of fuel synthesis unit is desirable for installation on an aircraft carrier. The Nimitz Class aircraft carrier is designed to carry 11,172 tons of JP-5, approximately 3.68 million gallons, and this value will be used for the reference carrier (C5). For moderate levels of combat operations, it has been estimated that the Nimitz could operate for 387 hours, while flying sorties 12 hours per day, before requiring replenishment for JP-5 while retaining enough fuel for two more days of operations (S9). This allows a JP-5 usage rate of 203,000 gallons per day to be calculated for the aircraft carrier. A fuel synthesis capacity of 100,000 gallons per day, giving a net usage rate of 103,000 GPD, was selected as the desired plant rating. This would allow the aircraft carrier to continue sorties for a total of 809 hours with a 2 day supply remaining, thus more than

doubling the length of time that the carrier could conduct independent operations. This assumes, however, that the fuel carrying capabilities remain the same. It also is expected that there will be a tendency to utilize fuel at a higher rate to take advantage of the increased operational flexibility that the fuel synthesis plant can provide.

Commonly quoted figures (M6) estimate that the U.S.S. Enterprise (CVN-65) can attain a top speed of about 35kts with 280,000 SHP. The figures on the Nimitz class are 30+kts at 260,000 SHP, but based on sea trials the reactor rating has been increased so that the 2 A4W reactors have the same total power as the 8 A2W reactors on Enterprise, and the SHP limits have also been raised somewhat. Although it is not anticipated that the synthetic fuel generation plant will be used as a retrofit on existing ships, the plant characteristics of the Enterprise will be assumed as suitable for a new carrier design. With an assumed thermal efficiency of 25%, 835 MW(th) is available for propulsion use. Assuming that ship hotel loads are taking 10% of the capacity, total reactor power is estimated to be 930 MW(th).

Ship powering requirements are such that propulsive power is approximately proportional to the cube of the ship's speed. Thus if the ship travels at an average of half of maximum speed, it is utilizing only one-eighth of

the available propulsive power, leaving 730MW(th) available for use to synthesize JP-5. By designing the synfuel plant for these conditions, the plant will be capable of operating at full capacity at all speeds up to 17.5 kts.

Calculations will be made for two types of propulsion plant configurations: (1) a typical naval PWR with a normal electrolysis unit, and (2) a VHTR utilizing a sulfur-cycle decomposition unit and superconducting electric propulsion. The efficiency of the electrolysis unit is 90%, as is projected for large-scale commercial units. Thus 16.3 kwhr(e)/lb H₂ is required for electrolytic decomposition of water. A net thermal efficiency of 50% is assumed for the sulfur-cycle decomposition. Additional requirements for both plants are: 0.26 kwhr(e)/lb CO₂ as pumping requirements for CO₂ stripping (S4) and 0.1 kwhr(e)/lb methanol for compression of hydrogen and carbon dioxide in the synthesis unit (S2). Due to an expected 90% yield of JP-5 with respect to gasoline, and since 2.4 gallons of methanol are required to produce 1 gallon of gasoline on a stoichiometric basis (M1), it is estimated that 2.7 gallons of methanol are required to produce 1 gallon of JP-5. The VHTR is assumed to have the same thermal power rating as the PWR, allowing **more** thermal power to be used for fuel synthesis. In actual practice, a unit might be installed with a lower thermal power rating.

Comparison of the two reactor scenarios is shown in Table 4.1. There are indications of a clear advantage for the VHTR over the PWR as a power source, since it can produce more than twice as much fuel when the same thermal power is being provided for propulsion and synthesis. Based on the claims of its proponents, there are considerable savings available in both weight and space by using a VHTR.

It should be noted, however, that current Naval Reactors leadership has expressed dissatisfaction with the Westinghouse VHTR design, although the reasons are not available to the general public. Thus some or all of the projected advantages may not materialize, particularly since no reactor of this type has ever been built, nor has the sulfur-cycle decomposition process been demonstrated in a pilot plant to assess its efficiency in producing hydrogen.

In order to utilize conventional PWR's to supply synthetic JP-5 onboard a nuclear-powered aircraft carrier, it will be necessary or desirable to: (1) increase rated core thermal power, (2) improve power plant cycle efficiency, and (3) develop new methods for water decomposition which are energy efficient at the temperatures available from a PWR.

Table 4.1

COMPARISON OF TWO FUEL SYNTHESIS SCENARIOS
FOR A NUCLEAR AIRCRAFT CARRIER

	<u>PWR</u>	<u>VHTR</u>
Ship speed--knots	17.5	17.5
Plant thermal efficiency	25%	35%
Reactor power less hotel loads--MW(th)	835	835
H ₂ generation needs-- kwhr(th)/gal JP-5	219.2*	98.9**
CO ₂ generation needs-- kwhr(th)/gal JP-5	25.6*	18.3*
Gas compression-- kwhr(th)/gal JP-5	7.2*	5.1*
Total synfuel energy-- kwhr(th)/gal JP-5	252.0*	122.3**
Fuel synthesis capacity --gal JP-5/day	69,500	149,100

* in form of electrical energy

** in form of electrical and thermal energy

4.4.2 Commercial Plants

For commercial plant applications, a comparison will again be made between the PWR and the VHTR. The VHTR does not offer significant advantages compared to other HTGR designs for commercial use, since compact size and low weight are not a problem area, although Westinghouse indicates that higher process temperatures should be available from the VHTR due to the fuel bead design. The German pebble bed design HTGR appears to be equally capable, and an operating prototype has been constructed. Hence this version of the HTGR should be considered as the leading contender. The Japanese are also working on a high temperature HTGR design. Thus the term VHTR should be considered as a general designation rather than being confined to a proprietary design. For central station units, efficiencies of 32% for the PWR and 42% for the VHTR will be utilized.

The Nuclear Regulatory Commission currently restricts nuclear reactors to a maximum of 3800 MW(th), although plants have been designed up to a 10,000 MW(th) rating. A nominal rating of 2000 MW(th) was chosen for purposes of the present analysis to provide plant sizes of the same order as other studies (S2). The capacity of the fuel synthesis unit is directly proportional to the size of the reactor, so adjustments are readily made to determine unit size for different reactor power ratings.

Two different modes of operation will be considered for commercial units: (1) the nuclear-powered synthetic fuel generation plant is dedicated entirely to production of fuel and does not provide electricity except for its own needs, and (2) the synthesis unit operates on a varying load basis during off-peak power conditions in conjunction with a nuclear-electric generating plant to maintain base loading on the reactor. The following assumptions will be made for off-peak power operations: the utility grid is all-nuclear, the synthesis plant utilizes 75% of the available power when the hydrogen generator is operating at full capacity, and the capacity of the synthesis unit is established with the hydrogen generator operating at 50% of maximum (by use of a gas storage facility).

Since a commercial installation is able to take advantage of co-products such as LPG from fuel synthesis by selling them as a byproduct, their energy value can be credited to the JP-5 production. The calculations will reflect this adjustment by assuming that the JP-5 yield is 100% that of gasoline. Thus it will be assumed that 2.4 gallons of methanol are needed to produce 1 gallon of JP-5. Actual production figures would not be 100% JP-5.

A comparison of the two fuel synthesis scenarios is shown in Table 4.2 for both dedicated plant and off-peak operations. Since the VHTR produces about 70% more fuel

Table 4.2

COMPARISON OF TWO FUEL SYNTHESIS SCENARIOS
FOR COMMERCIAL APPLICATION

	<u>PWR</u>	<u>VHTR or HTGR</u>
Plant thermal efficiency	32%	42%
Reactor power--MW(th)	2000	2000
H ₂ generation needs-- kwhr(th)/gal JP-5	152.2*	87.9**
CO ₂ generation needs-- kwhr(th)/gal JP-5	17.8*	13.6*
Gas compression-- kwhr(th)/gal JP-5	5.0*	3.8*
Total synfuel energy-- kwhr(th)/gal JP-5	175.0*	105.3**
Dedicated plant fuel synthesis capacity-- gal JP-5/day	274,300	455,850
Off-peak plant fuel synthesis capacity-- gal JP-5/day	102,850	170,950

* in form of electrical energy

** in form of electrical and thermal energy

than the PWR for equal thermal power ratings, it would take considerably fewer reactors to provide for the fuel needs of the transportation sector. Assuming that it was decided that we would build as many 3800 MW(th) dedicated plants (with an 80% capacity factor) as are necessary to supply projected U.S. transportation energy requirements of 2×10^{16} BTU/yr, we would need 635 VHTR's or 1055 PWR's. On the basis of this analysis, the VHTR has a clear advantage over the PWR as a source of power for a synthetic fuel generating plant. The economic distinctions between the two will be considered in the next chapter of this paper.

4.5 Shipboard Impact

Items which involve significant weight or volume changes are important in assessing the impact of installing components on a ship. After specifying the areas of concern, an attempt will be made to determine how well the systems fit onboard ship as well as any recommendations which will improve the adaptability.

The volume displaced by the carbon dioxide stripping units is one significant area for concern. An analysis of the means of obtaining carbon dioxide gives an estimate of the size of the unit and the seawater flow rates that are required (S4). A shore installation is estimated to

require 30 seawater stripping/absorption towers, each 140 feet in diameter and 22 feet high, for a methanol synthesis plant producing 21,700 BBL/day (corresponds to 337,555 gallons JP-5/day). This gives a space requirement of about 3,000,000 ft³ for a 100,000 GPD (gallons JP-5/day) unit, which is nearly an order of magnitude larger than the 492,000 ft³ allotted for JP-5 tanks. For a 100,000 GPD unit, a seawater flow rate of about 385,500 ft³/hr would be needed. Since the stripping unit functions in a manner similar to a deaerating feed tank, another estimate can be developed by a reasonable transit time for a unit volume of seawater to be heated, have CO₂ and dissolved carbonates and bicarbonates removed, and be discharged overboard. Using a 15 minute stay time, considered by the author to be conservative, a stripping/absorption tank volume of 144,500 ft³ is obtained by considering that about two-thirds of the volume would be taken up by seawater. At a density about equal to that of seawater for the unit, it is estimated to weigh 4130 tons.

The electrolysis unit is another area for concern. A 5 MW(e), 5000 lb, 3ft diameter by 6 ft electrolyzer escalates to a 16,400 ft³, 87 ton unit at a capacity of 100,000 GPD (V1). As no sulfur-cycle plant has yet been built, it is hypothesized that 10 times the volume of the equivalent electrolyzer would be required (due in part to the greater

number of steps involved), as well as 10 times the weight. In comparison, the electrolyzer would take up a volume equivalent to only about 3% of the JP-5 carried, while the sulfur-cycle unit would (on the basis of an admittedly rough estimate) take up a volume equivalent to about 33% of the JP-5 capacity: a very large impact.

The other major item which impacts significantly on the ship is the requirement for an additional 182 MW(e) of electrical generation capability. Since the LWNP is designed for electric drive propulsion, it does not require additional generators, but rather is able to shift electrical energy from the propulsion unit to the synthesis unit. The electrical needs of the PWR-powered synfuel plant provide substantial incentive to use electric propulsion drive there as well.

Electric drive propulsion has the following advantages: (1) less noise generation by the power plant during operation because reduction gears are not required, thus making detection by sonar less likely, (2) shaft length minimized by placing the motor in the aftermost space, just before the shaft passes through the skin of the ship, resulting in savings in shaft weight and an increase in reliability due to the vulnerability of shaft bearings and reduction gears to shock damage, (3) capability of providing large amounts of electrical power for emergency use ashore, and (4) capability of powering motors from different prime

movers.

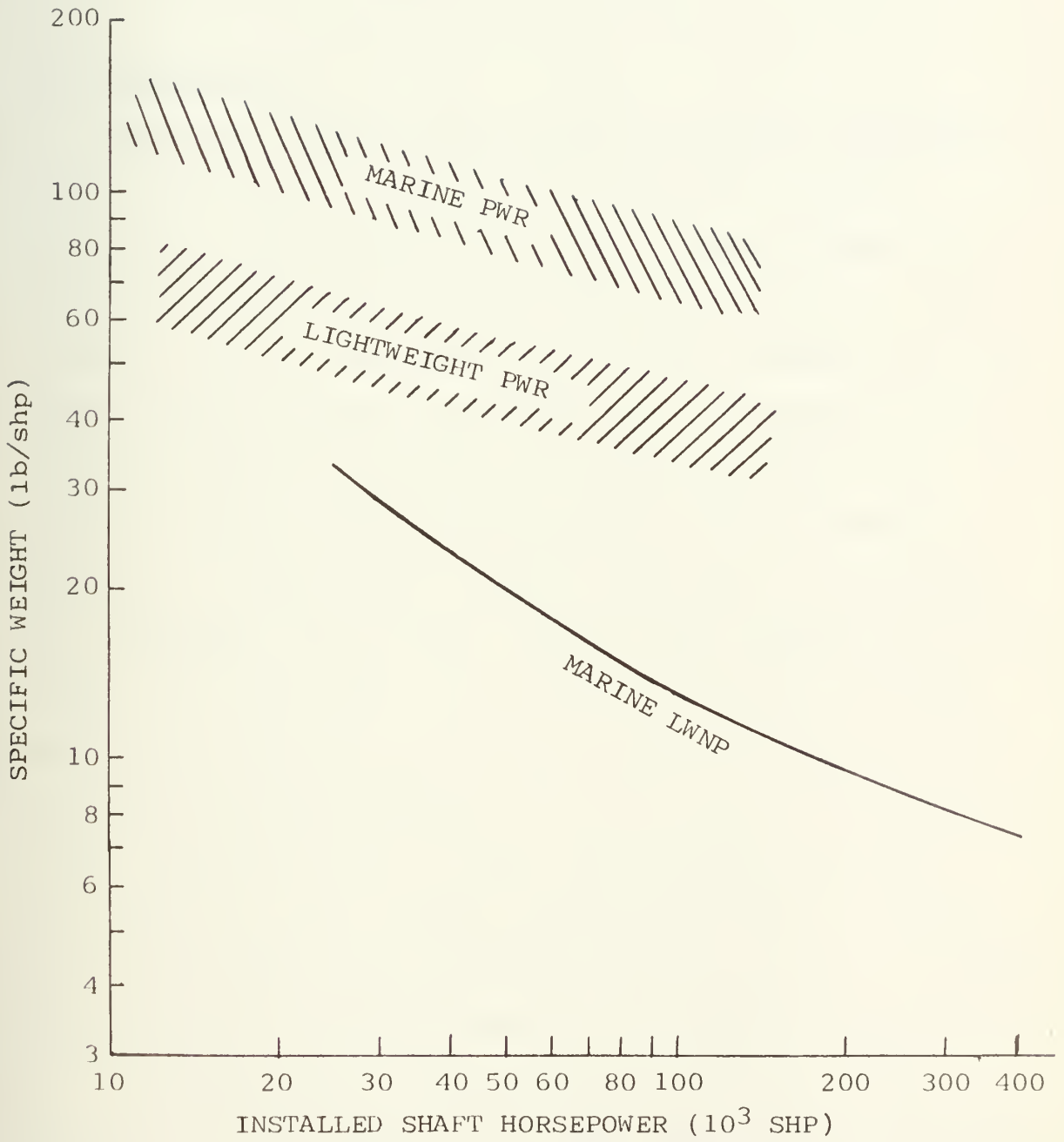
Conventional electric drive has the following disadvantages: (1) greater mechanical energy input to make up for resistive losses and conversion inefficiencies in the motor and generator, (2) increased volume requirements, since a generator takes up approximately the same volume as the turbine which is driving it, and the motor would require about the same volume as well, and (3) extensive cable runs utilize scarce and costly conductors which are subject to possible damage.

The U.S. Navy is interested in development of superconducting generators and motors for electrical drive propulsion. The electrical units can be quite compact due to the very low resistance (super-conductivity) exhibited by some materials at extremely low temperatures, which allows the super-conductor to pass electricity with minimal losses. A special cryogenic plant is required to maintain the low temperatures needed. These devices are, however, still in the development stage, and their operability in a marine or combat environment has yet to be demonstrated.

The LWNP is designed to take advantage of superconducting motors and generators to achieve a compact power plant design with low specific weight. Use of superconducting generators with a PWR could also be envisioned, to make electric drive a viable alternative.

Figure 4.4 indicates a major potential weight and volume benefit for VHTR installations. A two reactor plant using two 140,000 SHP LWNP units weighs a total of about 1900 tons (at 15 lb/SHP) compared with two PWR's which total about 10,000 tons (at 80 lb/SHP). The difference in propulsion plant weight/volume by using the VHTR might provide sufficient weight and volume to install the synthesis unit without exceeding the weight and volume presently being utilized by PWR units, although the specific propulsion plant weight of the VHTR actually installed will be higher than that for the LWNP because the process heat requirements require installation of additional heat exchangers and piping.

On the positive side with respect to shipboard impact: since oxygen is produced as a co-product along with hydrogen, no oxygen separation plant is needed to supply oxygen for flight crew needs. The space and weight normally assigned to such a plant can then be credited to the synthetic fuel process plant. In addition, it might be desirable to shift some fuel volume resources and utilize the space to carry additional ordnance, if an adequate level and length of independent carrier operations can still be supported.



PROPULSION PLANT SPECIFIC WEIGHTS (T1)

Figure 4.4

Chapter 5

ECONOMIC ANALYSIS

5.1 Introduction

Economic analyses of the cost of producing synthetic fuel using nuclear power are influenced by a number of parameters, including capital cost, interest charges, operation and maintenance costs, fuel cycle costs, and the capacity factors achievable (D1). While nuclear-electric generating plants have in the past only achieved capacity factors averaging about 60%, by using a synthetic fuel plant to achieve a more uniform load, and by increased emphasis on reliability, capacity factor can in principle be increased to 80 or 90%. Peaking units such as gas turbines, with their poor fuel economy, would not be needed, and bus bar costs of electricity would be reduced. By operating the energy intensive hydrogen units at off-peak times (together with a diurnal gas storage capability), the effective cost of energy can be quite low for production of hydrogen, with incremental energy charges (primarily fuel charges) that may be under 5 mills/kwhr(e) (B1,S2).

Since the cost of synfuel production is a strong function of the thermal and/or electrical energy required, and the capital cost of the chemical processing plant is independent of the power source, the cost of synthetic fuel can be related to the expected electrical energy cost

(mills/kwhr(e)) delivered by a particular power plant. Available cost data from References (F4,M1,M7,S2,S4) will be utilized where applicable for the purposes of this analysis.

For aircraft carrier installations, since energy cost data is not generally available, a cost applicable to small land-based civilian units will be used as a basis (M7), but the figures will then be doubled to account for some of the additional expenses for the special requirements of naval nuclear reactors (As suggested in Ref. H2, capital costs of naval nuclear propulsion units in the 1960's were approximately 2400 \$/kw, which are on the order of twice that for a comparably-sized civilian unit.). The relative difference between the two reactor types will still remain. The comparison of interest will be between the fuel synthesis cost of JP-5 versus the delivered total cost of JP-5 from the replenishment ship. Since the average transportation and handling charges were nearly half of the delivered cost for the Navy (U1), the breakeven cost for competitive fuel is effectively doubled.

Since natural petroleum is not considered to be available as a reliable source of fuel in the future, comparisons will be made between the cost of nuclear-generated synthetic fuel and the projected cost of synthetic fuel from coal. All costs will be adjusted to reflect 1977 dollars, assuming an inflation rate of 6%.

5.2 Commercial Plant Economics

Nuclear-powered synthetic fuel generating plants can be built for two uses: shore-based plants which can be sited close to the areas which need the fuel, or modular units which could be placed on ships or barges to make fuel available wherever it is needed. The shore facility will be utilized for economic analysis due to the wider availability of cost and operational data.

Estimates of HTGR and PWR total electric rates for 2000 MW(th) at an 80% capacity factor are 19.68 and 19.02 mills/kwhr(e), respectively, in 1985 dollars, yielding 12.35 and 11.93 mills/kwhr(e), respectively, in 1977 dollars. In the same manner, fuel cycle costs of 3.32 and 3.11 mills/kwhr(e) are estimated for the HTGR and PWR, respectively, in 1977 dollars.

The following relationships have been determined (P4) parametrically for the cost analysis of the commercial plant, and converted to 1977 dollars:

$$(1) \text{ Capital cost of CO}_2 \text{ absorption/stripping equipment-- } \$12,532 \times \text{GPD}^{0.6} \quad (S4)$$

$$(2) \text{ Capital cost of synthesizing equipment-- } \$25,471 \times \text{GPD}^{0.6} \quad (S4)$$

$$(3) \text{ Capital cost of sulfur-cycle decomposition plant-- } \$115,912 \times \text{GPD}^{0.6} \quad (F4)$$

- (4) Capital cost of electrolysis unit--
 dedicated plant: \$56/kw(e) (S2)
 off-peak plant: \$112/kw(e) (S2,M7)
- (5) Capital cost of storage--
 \$232 x GPD (M7)
- (6) Catalyst-- 0.7¢/gallon JP-5 (S4)
- (7) Operation and Maintenance--
 19.9 ¢/gallon JP-5 x GPD^{-0.225} (S4)

Fuel costs for the case of off-peak power must now be calculated as an incremental energy cost. Since the fuel is being burned up at a faster rate than normal, an additional charge is added because of additional fueling outages. In going from 80% capacity to 100% capacity, it is necessary to account for 25% more refueling time during a refueling cycle. Assuming refueling time is 0.4 year during a four year refueling cycle, $\Delta e = \frac{0.25 \times 0.4}{4} e_t$, where Δe is the refueling increment and e_t is the normal charge for central station power.

Capital costs can now be calculated for the commercial plants: PWR, dedicated plant, (1) + (2) + (4) = \$167.03M; PWR, off-peak plant, (1) + (2) + (4) + (5) = \$253.44M; VHTR, dedicated plant, (1) + (2) + (3) = \$382.45M; and VHTR, off-peak plant, (1) + (2) + (3) + (5) = \$334.45M. The capital is then distributed over the life of the plant, 30 years, at a 10% cost of money, along with the power unit.

Oxygen is sold as a co-product from the decomposition of water, and is credited to the overall fuel costs at \$10/ton. The total cost of producing fuel is shown in Table 5.1 for the PWR and VHTR during dedicated and off-peak power operations. The dedicated VHTR showed a clear margin of victory. In consideration of the fact that the dedicated VHTR also produces the most fuel, it appears to have the greatest competitive potential. Note however that the marginal case has been penalized to a certain extent by limiting synthesis plant size to that supportable by a single reactor.

5.3 Aircraft Carrier Operations

An aircraft carrier is designed to accomplish a given mission. While conventional financial cost is certainly important, it is not necessarily a decisive factor in any decision-making process. There is, moreover, a great deal of uncertainty in this analysis due to lack of available operational or economic data, but an attempt will instead be made to obtain a rough estimate under the given assumptions. In order to estimate the effect on capacity factor, the following levels of ship operations are postulated:

(1) Carrier without synthetic fuel plant--

In port 1/3 of time at 0% power; at sea 2/3 of time at 50% (average) power; net 33.3% capacity factor.

Table 5.1

COMMERCIAL JP-5 PRODUCTION COST (CENTS PER GALLON)

<u>COST</u>	<u>DEDICATED PWR</u>	<u>OFF-PEAK PWR</u>	<u>DEDICATED VHTR</u>	<u>OFF-PEAK VHTR</u>
ENERGY	66.8	19.1	54.6	16.9
CAPITAL	22.1	89.5 *	30.5	71.1 *
CATALYST	0.7	0.7	0.7	0.7
O & M	1.2	1.5	1.1	1.3
<u>OXYGEN</u>	<u>(10.7)</u>	<u>(10.7)</u>	<u>(10.7)</u>	<u>(10.7)</u>
TOTAL	80.1	100.1	76.2	79.3

* This value is substantially higher than for the dedicated plant because of the need to greatly oversize the hydrogen-generating unit and to install a one-day's worth storage capacity. In addition the unit productive capacity is much lower for the off-peak plants since it has been assumed that only one reactor is available to deliver off-peak energy.

(2) Carrier with synthetic fuel plant--

In port 1/3 of time at 0% power; at sea 2/3 of time at 75% (average) power; net 50% capacity factor.

A refueling situation of a 1.5 year refueling in a 12 year period of operations will be used to determine the impact of the increased fuel usage. Since the capacity was increased by 50%, the following adjustment will be made on energy costs, both for a dedicated basis analysis and a marginal cost basis: $e = \frac{1.5 \times 1.5 \text{ yrs}}{12 \text{ yrs}} e_t$.

The following fuel and energy costs correspond to twice that expected for civilian reactors of the same size, but the cost is based on two reactors rather than for eight as is the case for the Enterprise; total electric rate 44.92 mills/kwhr(e) for the PWR and 37.32 for the VHTR; fuel cycle cost 7.10 mills/kwhr(e) for the PWR and 7.46 mills/kwhr(e) for the VHTR.

The following relationships have been determined (P4) parametrically for the cost analysis of the aircraft carrier plant, in 1977 dollars:

$$(1) \text{ Capital cost of CO}_2 \text{ absorption/stripping equipment-- } \$13,450 \times \text{GPD}^{0.6} \quad (S4)$$

$$(2) \text{ Capital cost of synthesizing equipment-- } \$27,336 \times \text{GPD}^{0.6} \quad (S4)$$

- (3) Capital cost of sulfur-cycle decomposition plant--
 $\$124,399 \times \text{GPD}^{0.6}$ (F4)
- (4) Capital cost of electrolysis unit--
 $\$56/\text{kw}(e)$ (S2)
- (5) Catalyst-- $0.8\text{\$/gallon JP-5}$ (S4)
- (6) Operation and Maintenance--
 $21.8 \text{ \$/gallon JP-5} \times \text{GPD}^{-0.225}$ (S4)
- (7) Additional steam plant turbine and electric
generator-- $\$117,628/\text{MW}(e)$ (F4)

Capital costs can now be calculated for the two plant types: PWR, $(1) + (2) + (4) + (7) = \62.48M , and VHTR, $(1) + (2) + (3) = \$209.92\text{M}$. The capital is discounted over a 30 year life at 10% interest to determine annual costs.

The winner of the aircraft carrier competition is not clearly seen in the summary of Table 5.2. Marginal cost accounting is included because the synthetic fuel generation plant, as an auxiliary service aboard the aircraft carrier, should not have to support the capital investment already aboard to enable the ship to accomplish its military mission. On a marginal cost basis, the PWR holds a significant advantage over the VHTR. This is primarily due to the projected extremely high capital investment for the sulfur-cycle decomposition plant, which may well decrease to a much lower

Table 5.2

AIRCRAFT CARRIER JP-5 PRODUCTION COST (CENTS PER GALLON)

<u>COST</u>	<u>DEDICATED BASIS PWR</u>	<u>MARGINAL BASIS PWR</u>	<u>DEDICATED BASIS VHTR</u>	<u>MARGINAL BASIS VHTR</u>
ENERGY	336.0	97.8	189.7	61.9
CAPITAL	156.8	156.8	245.6	245.6
CATALYST	0.8	0.8	0.8	0.8
<u>O & M</u>	<u>1.8</u>	<u>1.8</u>	<u>1.5</u>	<u>1.5</u>
TOTAL	495.4	257.2	437.6	309.8

value upon further analysis. In any case, a VHTR with an electrolysis unit would clearly outperform the PWR due to its higher thermal efficiency and with no need for capital investment in additional electric generators. However, that design was not analyzed because the ultimate cost of the thermal decomposition system was expected to be much lower, and offers a considerable savings in energy.

Due to the large number of assumptions which have been made during this analysis, the specific results are not sufficiently reliable to support any quantitative conclusions. However, the methodology utilized here should be of value in conducting further analyses when more accurate information is available.

5.4 Cost of Synthetic Fuel from Coal

In order to make a fair economic comparison, the cost of synthetic fuel from coal will be used to determine any cost differential between alternate energy sources, since coal will be the most likely primary fossil energy source when petroleum resources are exhausted. A reasonable basis of prices is on an energy-equivalence basis. It has been estimated that synthesis gas can be produced at an average cost of \$4.64/MBTU (H₂). Gasoline costs (K₂) run about 10% higher normally, and on this basis would result in a cost of about 64 cents per gallon of JP-5, on an energy-equivalence basis with gasoline, or about \$27 per

barrel. By comparison, the U.S. Navy's fuel cost was about \$14/BBL in 1975 (U1), with petroleum as the source of supply.

To make a reasonable comparison of fuel costs for naval purposes, the cost of storing, handling, transporting, and delivering fuel must be added. The estimated cost of supplying the fuel to an aircraft carrier, or any other user was about \$12/BBL (U1). This corresponds to an increment of about 32 cents per gallon which must be added to the purchase price. Thus synthetic JP-5 from coal could be expected to cost the aircraft carrier 96 cents per gallon.

Chapter 6

SUMMARY AND CONCLUSIONS

6.1 Summary

The need to develop alternative sources for, and new types of fuel for, transportation use is evident. World oil production will probably peak in the 1980-1990 time frame; U.S. production has already peaked. The economic impact on the economies of user nations will be severe unless fuel requirements are reduced, which is difficult, or other means are developed to produce needed fuels. Significant shortfalls in oil supply are expected as early as 1985, according to a recent Central Intelligence Agency report (C2). A review of the needs of the transportation industry indicates that requirements for gasoline and JP-5 will not diminish in the near future, and in fact increasing usage of both are projected through the end of the century. This makes it quite clear that rapid development of alternative energy sources is needed.

A method of producing synthetic hydrocarbon fuels independent of the availability of fossil resources is presented in Chapter Three of this study. Using nuclear power as a source of electrical and thermal energy, together with means for removing carbon dioxide from seawater, means of decomposition of water to generate hydrogen, and through use of catalyzed reactions, the hydrogen and carbon dioxide

can be converted into methanol, gasoline, or jet fuel, as needed, by Fischer-Tropsch synthesis.

Many of the reactions which are discussed for fuel synthesis could also be adapted for coal liquefaction (or vice versa). The first step in coal conversion is usually to form synthesis gas by steam reformation of coal (i.e., $C + H_2O \longrightarrow CO + H_2$). Carbon monoxide and hydrogen can be converted to methanol, gasoline, or jet fuel using the same catalysts (e.g. $CO + 2H_2 \longrightarrow CH_3OH$). One objection to widespread use of coal liquefaction for our future supply of hydrocarbon fuels is the considerable damage to the environment due to strip mining, conversion and combustion residues, and impurities such as the oxides of sulfur, which add to atmospheric pollutant levels, or which give rise to large amounts of chemical sludge effluent from stack gas scrubbers. The volume of mining waste is on the order of 100 times that for production of an energy-equivalent amount of ore for nuclear reactors. While the potential radiological impact of the nuclear fuel cycle on the environment requires assessment, the volume of radioactive waste from nuclear reactors is not that substantial (D1,U2).

Suitable forms of nuclear powered synthetic fuel generating plants were modeled in Chapter Four. Two specific nuclear reactor types, the PWR and the VHTR (Very High Temperature Reactor developed by Westinghouse) were

selected for comparison. The PWR, as the major reactor type in use world-wide, has the advantage of available technology. The VHTR has the advantages of high thermal efficiency, adaptability to high temperature processes such as thermal decomposition of water, and easier refueling methods, particularly if the German pebble-bed concept were adopted. Although the AVR prototype reactor has been extremely successful, many aspects of the novel VHTR design involve untested technology, with uncertain reliability, efficiency and cost.

Two applications were analyzed for the two reactor types: a shipboard installation for aircraft carrier use to generate JP-5 for aircraft fueling requirements (with 835 MW(th) power available for propulsion and synthetic fuel requirements), and a commercial installation using a 2000 MW(th) reactor plant to produce jet fuel for sale. Plant size, however, can be readily scaled to suit the needs of the consumer; there may well be incentive to go to very large size (10,000 MW(th)) to achieve substantial economy of scale for terrestrial application.

Westinghouse has already done considerable study on the applications of the VHTR to thermal process industries. Feasibility studies and preliminary arrangement studies have been conducted on a VHTR that is completely dedicated to the production of hydrogen by thermo-electrical means, which is assisted by the multi-step thermo-chemical process

shown in Figure 3.2. Until a pilot unit is built, however, the energetics and economics of the chemical process cannot be known with certainty, as illustrated by difficulties experienced with previous multi-step processes to generate hydrogen (V1). As hydrogen demand increases for use as a fuel or feed material, there will be more incentive to optimize specific designs for thermo-chemical units.

The shipboard PWR was found to be capable of supporting a 69,500 GPD (peak) JP-5 synthesis unit (only 70% of the design unit capacity), while the VHTR was able to support a 149,100 GPD (peak) JP-5 synthesis unit (nearly 50% above design capacity). Thus the PWR would probably require an increase in reactor rating unless the efficiency of the synthesis unit is significantly improved.

For commercial operations, the analyses were performed assuming energy was being obtained from single reactor units of equal thermal power rating. This appeared to be particularly appropriate for thermal decomposition processes, where long distance energy transport is impractical, although a multiple reactor site could support a larger synfuel capacity. Thus off-peak power synthesis units had considerably lower capacities than for dedicated plants due to the smaller average thermal power available. This had an important impact on the economic evaluation, since unit capital cost increases as the unit size is made smaller. The results shown in Table 4.2 indicate that the

VHTR can provide the greatest fuel synthesis capacity. The size of the synthesis units could be increased if electricity were purchased from a large utility grid, but in that case it would appear appropriate to include transmission costs in the marginal cost of energy.

The analysis of commercial plant economics shows that, while the required fuel charges (Table 5.1) are somewhat greater than projected costs of synthetic fuel from coal (76.2 ¢/gallon (minimum) versus 64¢/gallon), the two are at least reasonably close. Off-peak power operations should offer significant advantages if the capital cost of the decomposition units can be reduced and large capacity units are available. Also, coal costs will probably escalate faster than nuclear plant or chemical plant costs, since there are economic factors at work which motivate pricing coal at just below alternative fuel/oil prices. Thus the future for nuclear generated synfuel should get brighter.

6.2 Conclusions

It was a major objective of this work to develop a non-optimized conceptual design for a nuclear-powered synthetic fuel generation plant which was sufficiently attractive for use aboard a nuclear aircraft carrier that it would provide the incentive for initiation of a broader-based development effort. The economic analyses of the various

scenarios, utilizing PWR or VHTR power sources, and dedicated or off-peak accounting methods indicated: (1) even under marginal cost accounting, the cost of JP-5 produced on board was more than $2\frac{1}{2}$ times the delivered cost of JP-5 derived from coal, (2) while a commercial VHTR was capable of producing much larger quantities of fuel than a PWR having the same thermal power rating, synthesis units using off-peak power from a single nuclear unit did not demonstrate an expected economic advantage, and (3) the price of JP-5 from the cheapest commercial unit, the dedicated VHTR plant, was still nearly 20% higher than JP-5 derived from coal. The projected high capital cost of the sulfur-cycle hydrogen generator suggested by Westinghouse for use with their VHTR design acted to negate the energy savings achieved by use of thermo-chemical hydrogen generation. Thus one is led to consider changes in the original conceptual design.

It is anticipated that a thermo-electric water decomposition method (i.e. high temperature electrolysis) can eventually be developed which will provide high efficiency at reasonable cost (M3,V1), which can then be used to an advantage in the synthetic fuel generation process. Thus emphasis, for the near term at least, should be focused on electrolysis for the present application.

As we have just noted, the VHTR was unfairly penalized with respect to the PWR due to the projected high capital

cost of the sulfur-cycle decomposition unit. To provide guidelines for future work, further approximate analyses were performed after substituting a conventional electrolyzer (with no credit taken for any increased efficiency due to thermal decomposition) for the sulfur-cycle decomposition unit in each of the VHTR plants previously analyzed.

Table 6.1 indicates that, on a marginal cost basis (fuel cost + additional refueling charges), a marine VHTR-powered synthetic fuel generating plant (with electrolytic generation of hydrogen) may produce JP-5 for a cost of about \$1.89/gallon, or slightly under twice the (estimated) delivered cost of JP-5 from coal. If suitable low-capital, thermo-electrical decomposition units can be developed, the synfuel cost could be lower yet. Should this possibility eventually materialize, the additional military effectiveness given to the aircraft carrier may provide sufficient additional incentive to merit more intensive work on this concept. It can only be said here that this process is not an unreasonable alternative fuel source. The words of Smith and Foster (S9) are particularly enlightening in this regard:

"The possible constraint of resupplying our mobile logistic forces from U.S. controlled bases, or even exclusively from continental U.S. bases, emphasizes the importance of combat endurance of our carrier forces if required to operate at great distances from the U.S. Logistic forces are more

TABLE 6.1

AIRCRAFT CARRIER JP-5 PRODUCTION COST (CENTS PER GALLON)
(MARINE VHTR WITH ELECTROLYZER VICE SULFUR CYCLE)

PLANT CHARACTERISTICS

Reactor power less hotel loads--MW(th)	835
H ₂ generation requirements--kwhr(th)/gallon JP-5	156.6
CO ₂ generation requirements--kwhr(th)/gallon JP-5	18.3
Gas compression needs--kwhr(th)/gallon JP-5	5.1
Total synfuel energy--kwhr(th)/gallon JP-5	180.0
Fuel synthesis capacity--gallons JP-5/day	101,330

<u>COST</u>	<u>DEDICATED BASIS</u>	<u>MARGINAL BASIS</u>
ENERGY	279.2	91.1
CAPITAL	96.4	96.4
CATALYST	0.8	0.8
<u>O & M</u>	<u>1.6</u>	<u>1.6</u>
TOTAL	378.0	189.9

vulnerable to enemy action than combatants, require escort forces, and thus should be kept to a minimum. New aircraft carrier concepts should include increased carrier endurance for lower life-cycle support requirements in realistic combatant environments. Range, mobility, and flexibility afforded ships with high combat endurance cannot be neglected in ship characteristics 'trade-offs.' Mobility and flexibility are not easily quantified, but their value to a Force Commander may mean the difference between a successful mission or one not even attempted."

Table 6.2 indicates a marked improvement in the cost of producing JP-5 on a commercial basis by replacing the sulfur-cycle unit with an electrolyzer. Since the hydrogen generator for the dedicated VHTR operated at full capacity while the hydrogen unit for the off-peak VHTR operated at an average of half of its maximum, the off-peak VHTR syn-fuel plant was much more capital intensive. Hence when the electrolyzer was substituted, the cost of fuel from a VHTR-powered synthetic fuel generation plant producing only fuel drops only about 5%, to 72.4 ¢/gallon, while the cost of fuel from the VHTR-powered, off-peak, synthetic fuel generation plant drops nearly 50%, to 40.6 ¢/gallon. While the dedicated plant costs are still about 13% higher than those for coal-derived fuel, the off-peak plant costs are about 36% lower than those expected for coal-derived fuel, and, indeed, can compete with JP-5 derived from oil at about 12 \$/BBL.

The analyses of this work present economic evidence sufficient to justify development of an optimized design

TABLE 6.2

COMMERCIAL JP-5 PRODUCTION COST (CENTS PER GALLON)
(VHTR WITH ELECTROLYZER VICE SULFUR CYCLE)

PLANT CHARACTERISTICS

Reactor power--MW(th)	2000
H ₂ generation requirements-- kwhr(th)/gallon JP-5	116.0
CO ₂ generation requirements-- kwhr(th)/gallon JP-5	13.6
Gas compression needs-- kwhr(th)/gallon JP-5	3.8
Total synfuel energy-- kwhr(th)/gallon JP-5	133.4
Dedicated plant fuel synthesis capacity--gallons JP-5/day	359,820
Off-peak plant fuel synthesis capacity--gallons JP-5/day	134,930

<u>COST</u>	<u>DEDICATED PLANT</u>	<u>OFF-PEAK PLANT</u>
ENERGY	69.2	20.3
CAPITAL	12.1	28.9
CATALYST	0.7	0.7
O & M	1.1	1.4
<u>OXYGEN</u>	<u>(10.7)</u>	<u>(10.7)</u>
TOTAL	72.4	40.6

for producing synthetic fuel utilizing a VHTR, HTGR, or other reactor capable of high thermal efficiency. For such information to be available on a timely basis, these analyses should be performed in the near future. There are technological gaps to bridge, and all nuclear power plants or sizable industrial process plants take a significant (greater than 5 years) amount of time to design, license, build, and test. Hence anticipated deployment in, say, 15 years, requires current action.

The number of off-peak power units which could be built are not sufficient to meet our needs for hydrocarbon fuels. Electrical power only supplies about 10% of our demand for energy, therefore it is unable to make a large dent in our transportation needs of about 50% of the total demand. Thus combination of off-peak and dedicated synthetic fuel generation plants is needed. It may well be that the dedicated units cannot compete with gasoline-from-coal units, in which case nuclear-generated synfuel will remain a minor contributor in the marketplace: supplying no more than about 10% of transportation fuels, utilizing off-peak plants.

The prospects for application of synthetic fuel generation to naval nuclear power plants are even more difficult to evaluate. The need for electric drive propulsion appears to be a requirement in this special application. The impact of the synthetic fuel generation plant on the

limited space and weight available for its inclusion on an aircraft carrier has not been fully determined. It may well be that a complete redesign of the ship systems is implied.

6.3 Recommendations

On the basis of the analyses performed here, as regards commercial applications, it is recommended that the following steps be taken concerning nuclear powered synthetic fuel generation plants:

(1) Place greater emphasis (reversing current trends in the U.S.) on developing reactors having higher-temperature capabilities than the PWR, such as the HTGR or LMFBR, since they appear to be inherently better suited to the task of fuel synthesis regardless of the processes ultimately selected for use.

(2) Continue to provide support for funding of hydrogen production research, since hydrogen production methods have the greatest impact on the overall costs of the process.

(3) Continue efforts to improve coal conversion techniques in order to provide an alternative, interim energy source, and to provide advanced chemical and/or catalytic processes which may be utilized in nuclear powered synthetic fuel generation processes as well.

(4) Foster basic catalysis research to enable

generation of needed chemicals independent of a particular resource, such as petroleum.

(5) Support a continuing effort to develop and optimize synthetic fuel generation plant designs.

As regards applications to naval ship technology, in order to provide fuel for aircraft operations on a nuclear powered aircraft carrier, the following additional steps are recommended concerning synthetic fuel generation:

(1) Re-evaluate the suitability of the Westinghouse LWNP or a suitable modification thereof, for special purpose shipboard applications.

(2) Evaluate the use of electric drive propulsion for nuclear powered surface ships.

(3) Carry out an in-depth examination of the carbon dioxide stripping/absorption process to determine a suitable configuration for use at sea with attention given to minimizing the space and weight of the unit. Laboratory-scale experimentation is also in order at this point.

(4) Design a modular electrolysis unit which is suitable for installation on naval vessels.

(5) Perform a more detailed process design of a 100,000 GPD synfuel unit, including detailed characterization of all major components; perform an overall heat balance check on utilization of heat from the endothermic chemical reactions, determine the need for regenerative heat exchangers in the carbon dioxide stripping process

and/or the use of low pressure steam from the propulsion plant. Determine the feasibility of dual use of already installed propulsion plant components such as main seawater circulating pumps.

(6) Carry out (probably on a classified basis) an analysis of the incentive for equipping an aircraft carrier with the increased operational capabilities provided by on-board fuel generation in order to provide those at the decision-making level with sufficient information to permit objective evaluation of this concept.

APPENDIX A

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