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# LONG-RANGE MILITARY IMPLICATIONS OF PETROLEUM AVAILABILITY FOR NAVY PLANNING STUDY

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**CENTER FOR NAVAL ANALYSES**

**DEPARTMENT OF THE NAVY**
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Encl:   (1)  CNA Study 1165 "Long Range Military Implications
             of Petroleum Availability for Navy Planning Study"
             (PETRO AVAIL), Unclassified, November 1981

1.   In the past decade the world's energy supply status has
received much attention because of changes in perception,
exploration, drilling success, known reserves, production,
distribution, consumption, world politics, and pricing.  The
petroleum supply disruptions of 1973-1974 and 1979 serve to
highlight the tenuous nature of some major sources of supply.
There is an emerging awareness that the availability and
affordability of petroleum supplies for operating the Navy are
likely to impose significant and  potentially unacceptable
limits, especially if petroleum related problems and
contingencies are not adequately dealt with and prepared for
well in advance.

2.   At the direction of the CNO, the Center for Naval
Analyses, in cooperation with the CNO Long Range Planning
Group, has undertaken to better define the Navy's future
petroleum environment and its implications.  The main
objectives were to evaluate the likely availability of
petroleum products for the fleet to the year 2010 and to
identify the probable effects of petroleum availability on the
conduct of naval warfare, the selection of weapons, and
mobility.  The resulting study examines the factors affecting
current and future petroleum availability, looks at alternate
means of coping with the expected petroleum environment, draws
conclusions, and makes some recommendations to help meet the
challenges the Navy will face in the future.

3.   The study finds there are two general types of problems the
Navy will face.  The first problem is the near certainty that
over the long term the real cost of fuel will continue to rise.
Part of the cost will result from the need to adapt to wider
variations in the quality of fuel available in the future.  The
other problem is that import interruptions are almost certain
to occur and will likely be at least as severe as those
experienced in the 1970s.  These problems will present the Navy
with enduring challenges, because affordability will remain a
continuing problem and major supply disruptions will have

significant international and U.S. Navy impact.  Although there
is uncertainty over the exact nature of the likely disruptions,
the resulting international uncertainties and operational
considerations will pose challenges just as demanding as those
arising from affordability considerations.  Change and
discontinuities are difficult to address in any planning
effort, but the petroleum arena is likely to be turbulent in
the decades ahead.  The Navy must hedge now against these
uncertainties in order to be better prepared to deal with
disruptions, increased real costs, and other challenges that
may arise as a result of dependence on petroleum supplies.

4.  The study provides the following recommendations:

● The Navy needs strong management of energy-related
  matters to implement conservation and to help it adjust
  to the constraints imposed by higher costs, lower
  availability, and poorer quality of fuel.  All relevant
  energy information--including that pertaining to nuclear
  energy--should be available to Navy planners for a
  complete management perspective on the Navy's energy
  problems and options.

● A strong and comprehensive research and development (R&D)
  program should be maintained to increase fuel efficiencies
  and to prepare for problems of degraded fuel quality.

● The life-cycle costs of individual nuclear-powered ships
  are higher than those of conventionally power ships,
  based on the then current fuel price of $52.50 per barrel
  used in the study.  However, the FY82 cost of $57.40 a
  barrel is very close to the cost crossover point for
  aircraft carriers (CV vs CVN) on an undiscounted basis.
  Thus, the prospect of even higher petroleum prices and
  interrupted fuel supplies, combined with military
  effectiveness advantages of nuclear power, argues that
  all large ships of the future should continue to be
  strong candidates for nuclear propulsion.

● Because of their efficiency and tolerance for varying
  fuel  quality, diesel engines should be used more widely
  on smaller ships.

Subj: "Long Range Military Implications of Petroleum
Availability for Navy Planning Study"

- Large civilian and military reserves of petroleum give
significant protection against disruptions in the market
and curtailed supplies of fuel.  They should be
vigorously supported.

5.  Enclosure (1) is forwarded.


C. A. H. TROST
VICE ADMIRAL, U.S. NAVY
DIRECTOR, NAVY PROGRAM PLANNING


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# LONG-RANGE MILITARY IMPLICATIONS OF PETROLEUM AVAILABILITY FOR NAVY PLANNING STUDY

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*Naval Warfare Analysis Group*

**CENTER FOR NAVAL ANALYSES**

# ABSTRACT

This study evaluates petroleum issues facing the Navy over the next 20 years. It analyzes the threat of reduced availability of petroleum and the probable effects on naval warfare, on the selection of weapons, and on mobility. There are four areas of investigation: the current oil market, production forecasts, the prospect of import interruptions, and Navy options.

The study addresses the changes in the oil market since the embargo of 1973. It explains how those changes in the market have affected Navy budgets and eroded steaming and flying hours. Published forecasts of lowered production of petroleum and the threat of interruptions of imports are evaluated for their potential to disrupt world markets out to the year 2000. Several aspects of future petroleum supplies are quantified. The study concludes by recommending measures the Navy can take to deal with the problems of reduced fuel availability and quality.

# EXECUTIVE SUMMARY

This study evaluates petroleum issues facing the Navy over the next 20 to 30 years. It responds to concerns expressed by the Chief of Naval Operations about the implications of petroleum availability for the Navy in the long term. The work was sponsored by the Navy's Long Range Planning Group, Op-00X.

## OBJECTIVES

The study has two main objectives:

- To evaluate the likely availability of petroleum products for the fleet to the year 2010

- To identify the probable effects of the availability of petroleum on the conduct of naval warfare, the selection of weapons, and mobility.

## OVERVIEW OF PETROLEUM AVAILABILITY

The industrialized world is experiencing a major transition in energy resources as heavy reliance on conventional petroleum gives way to more diversified forms of energy. This change has significant implications for the Navy because its ships and aircraft will continue to depend on petroleum for mobility fuels well into the 21st century.

Petroleum products are expected to be generally available to the fleet, even though production of conventional oil in the world is projected to begin declining around the year 2000. However, the Navy can expect two kinds of problems. The first is the near certainty that fuel costs will continue to increase despite occasional leveling of prices resulting from such factors as short-term production excesses and the policies of the Organization of Petroleum Exporting Countries (OPEC). Greater costs will result from higher real prices and from the need to adapt to wider variations in the quality of fuel. Fuel of degraded quality is likely to become more prevalent as synthetic crudes from heavy oil, shale, and coal supplement declining supplies of conventional crudes.

The second problem is that of import interruptions. Such interruptions are almost certain to occur and are likely to be at least as severe as those experienced in the 1970s. In theory, the Navy will have priority access to the petroleum needed for its missions. In practice, however, uncertainties about the length of interruptions and political reluctance to transfer scarce petroleum supplies from the civil sector are likely to result in problems of reduced fuel availability with potentially serious impact on the operating forces.

Prior to 1973, petroleum was a minor constraint in Navy planning, and the nation was much less vulnerable to interruptions in petroleum imports than it is today. Adapting the Navy to the harsher conditions of fuel availability mentioned above will require continuing management attention to energy-related issues.

## FORECASTS OF THE SUPPLY OF PETROLEUM

The rate at which new oil has been found in the non-Communist world has been declining for about 30 years. In the past 10 years, the world's petroleum has been produced and consumed faster than new replacement oil has been found. This fact underlies grim geological estimates that worldwide production will peak within two or three decades. Production in the U.S. has already peaked and is estimated to be in a long-term decline.

Economic theory tends to ameliorate the more pessimistic geological outlook. According to the theory, the unfettered market will compensate for the depletion of a scarce resource by raising fuel prices. Increased prices in turn will retard demand, stretch the remaining supplies, and stimulate the production of substitutes. The theory will probably prove to be valid over the long term; however, the problem is the transition through the next 20 to 30 years. The modern world lacks experience with depletion of a resource as critical as petroleum. Furthermore, a world oil market that is politically unencumbered is an abstraction that will never be fully attained in practice. In addition, there are large uncertainties about when substitute products will be available in sufficient quantities and at acceptable levels of quality. Finally, on the issue of quality, it is important to recognize that the chemistry of petroleum-like substitutes and its implications for engines are only partially understood.

Figure I illustrates two projections of the production of world oil and gives a perspective on the relative position of U.S. production. One projection peaks before the year 2000 and follows a bell-shaped profile. It reflects the rate at which one energy expert has estimated that remaining conventional oil might be produced. In contrast, Exxon projects a lower, flatter plateau extending to the year 2000.

Assuming no prolonged stagnation in the world's economies, an Exxon projection of 1-percent-per-year growth in demand would not force production against a physical ceiling until after the year 2000. However, if the annual growth in demand is about 3 percent--still less than half of what it was in the 1970s--then the production of conventional oil is likely to peak before the year 2000.

The principal conclusion drawn from our evaluation of the forecasts is that fuel from petroleum or petroleum-like liquids will be generally available in the world market as products from conventional oil are supplemented with products refined from heavy oil, shale, and coal.

However, it should be recognized that as conventional oil production peaks, fuel will almost certainly cost more. It will also vary widely in quality, but overall quality will decline. Two other significant conclusions emerged from our evaluation:

● The U.S. and other Western industrialized nations will continue to import large quantities of petroleum for the foreseeable future.

● From 50 to 60 percent of the ultimately recoverable conventional oil remaining in the world is estimated to be in the region of the Persian Gulf.
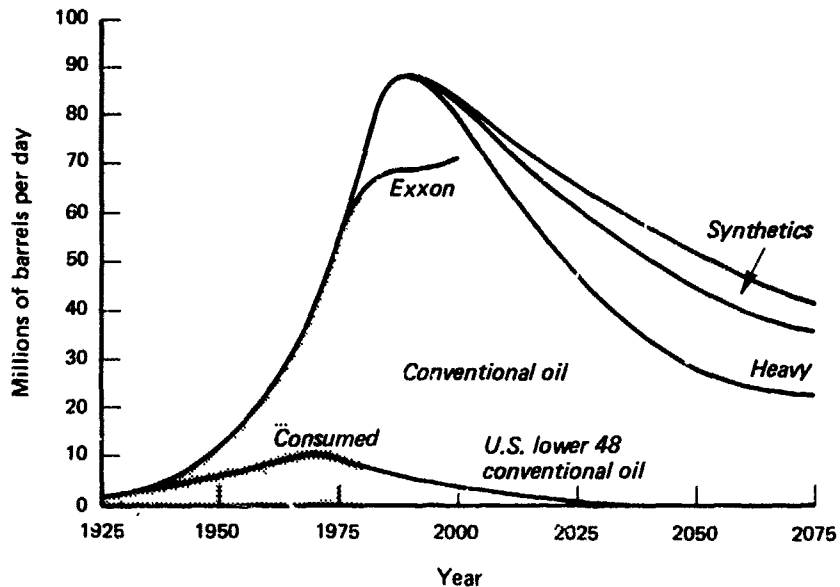


FIG. I: PROJECTIONS OF WORLD OIL PRODUCTION

IMPORT INTERRUPTIONS AND PETROLEUM AVAILABILITY

The significant reserves of the world's remaining conventional oil are heavily concentrated in a few producer countries. Partly because of this unequal distribution, interruptions in the supply of petroleum to the world market, at least as severe as those experienced in the 1970s, are estimated to be a near certainty over the next 20 years.

U.S. domestic production of all petroleum liquids is expected to drop from 10 million barrels per day (mmb/d) in 1980 to 7-8 mmb/d by the year 2000. As a consequence, the U.S. will continue to rely on imported petroleum and be vulnerable to supply interruptions. High levels of

reserve stocks of both crude oil and products can supplement domestic
production and reduce vulnerability. Additional help can come from
conservation programs, from greater use of substitutes for conventional
petroleum, and possibly from the existing international agreements to
share shortages among the importing nations.

Figure II gives two estimates of usable U.S. petroleum stocks in
the year 2000 and shows how high levels could offset the loss of imports
for a few months. The Strategic Petroleum Reserve (SPR) is expected to
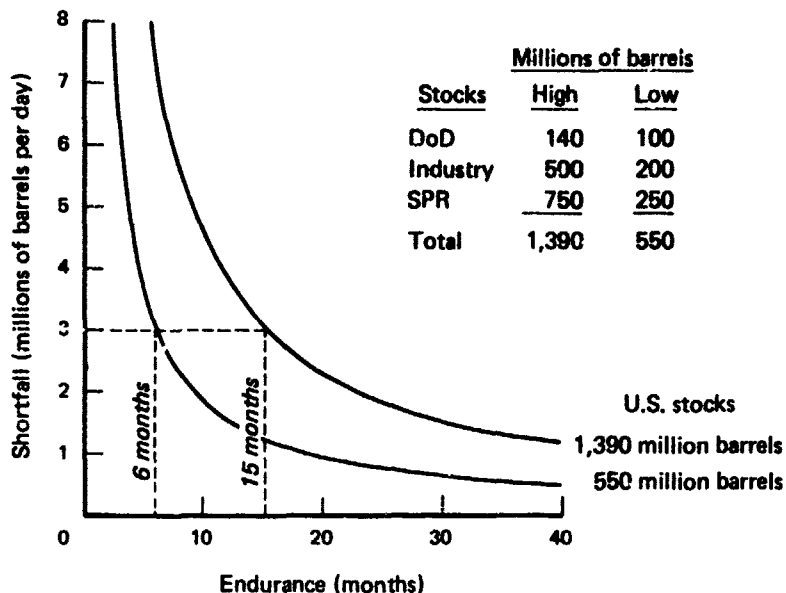be particularly important if supplies are interrupted.

| Stocks | Millions of barrels | |
|---|---|---|
| | High | Low |
| DoD | 140 | 100 |
| Industry | 500 | 200 |
| SPR | 750 | 250 |
| Total | 1,390 | 550 |

U.S. stocks
1,390 million barrels
550 million barrels

FIG. II: ENDURANCE OF U.S. OIL STOCKS DURING AN IMPORT
INTERRUPTION IN YEAR 2000

## Effects of Disruptions on Military Supplies

The Department of Defense is a relatively small user of total U.S.
petroleum products. For example, in 1980, it used about 3 percent and
the Navy about 1 percent of the total U.S. demand for petroleum
liquids. In the first year of a war, direct consumption by U.S. forces
might climb to as much as four times peacetime levels. Table I shows
year 2000 estimates of the direct Defense burden on U.S. petroleum
supplies under different assumptions about import interruptions and the
availability of reserve stocks. Under these scenarios, Defense needs
are expressed as a percentage of the available supply in the U.S. They
range from 3.8 to 7 percent in peacetime and from 15 to 29 percent in
wartime.

## TABLE I

### DEFENSE PETROLEUM CONSUMPTION IN YEAR 2000 RELATIVE TO U.S. SUPPLIES

| Scenario | Supplies (mmb/d) | | | DoD usage as a percent of U.S. supplies | |
| --- | --- | --- | --- | --- | --- |
| | U.S. production | Imports | Reserve drawdown | Total | Peacetime[a] | Wartime[b] |
| Best case[c] | 7 | 6 | 0 | 13.0 | 3.8 | 15 |
| Partial interruption | 7 | 3 | 1.5[d] | 11.5 | 4.3 | 17 |
| Complete interruption | 7 | 0 | 1.5 | 8.5 | 5.8 | 24 |
| Worst case[e] | 7 | 0 | 0 | 7.0 | 7.1 | 29 |

[a]DoD consumption of 0.5 mmb/d.
[b]DoD consumption of 2.0 mmb/d.
[c]Best case assumes no interruption of imports and a peacetime demand of 13 mmb/d.
[d]Average rate of drawdown to empty a reserve of 550 million barrels in 1 year.
[e]Assumes exhausted reserves and complete interruption of imports.

Even though the Department of Defense is both a high-priority and relatively small user of petroleum in peacetime, it is unlikely to be immune from the adverse effects of future interruptions in imports. In the past, shortages of Defense fuels resulted from command decisions to conserve during crises of uncertain length and from Defense's inability to contract for all of its fuel requirements in a turbulent market. Future crises may not differ significantly. Such realities as political reluctance to deprive the domestic economy of scarce petroleum supplies are likely to result in periodic shortages to some military users. Less urgent and training missions may be particularly vulnerable to severe market disruptions.

Even though petroleum products and close substitutes are expected to be generally available for Navy use through the remainder of the century, import interruptions are likely to have adverse effects on the Navy in the form of intermittent fuel shortages and higher prices. Maintaining the proper level of preparedness to deal with this significant problem will require the continuing attention of the Navy's leadership to a broad range of measures including support for adequate reserves.

COST OF FUEL

In addition to the problem of import interruptions, a major problem over the long term will be the day-to-day management of the higher cost of fuel.

The Navy has already experienced over a fourfold increase in the real price of fuel in less than a decade. Some of the past effects of these increases are shown in figures III and IV. As the figures indicate, the cost of fuel is now a major constraint, accounting for about one-third of the direct operating and support (O&S) costs of mobile weapon systems.

Future prices could make fuel costs even more burdensome. Figure V shows the effect of three hypothetical growth rates on the price the Navy pays for a barrel of a composite of DFM (marine diesel fuel) and JP-5 (aviation fue'). Considering past increases, an average annual price growth, in real terms, of 5 or even 10 percent is plausible. For example, since 1960, the real price of fuel has increased at an average annual rate of 8 percent. If 1973 is taken as the base, the average rate of increase has been 23 percent per year.

With no real growth in Navy budgets, future increases in the price of fuel could severely erode Navy programs. This potential is illustrated in figures VI and VII, using the hypothetical price increases of 2, 5, and 10 percent annually. Requirements for larger budgets are depicted in figure VIII.
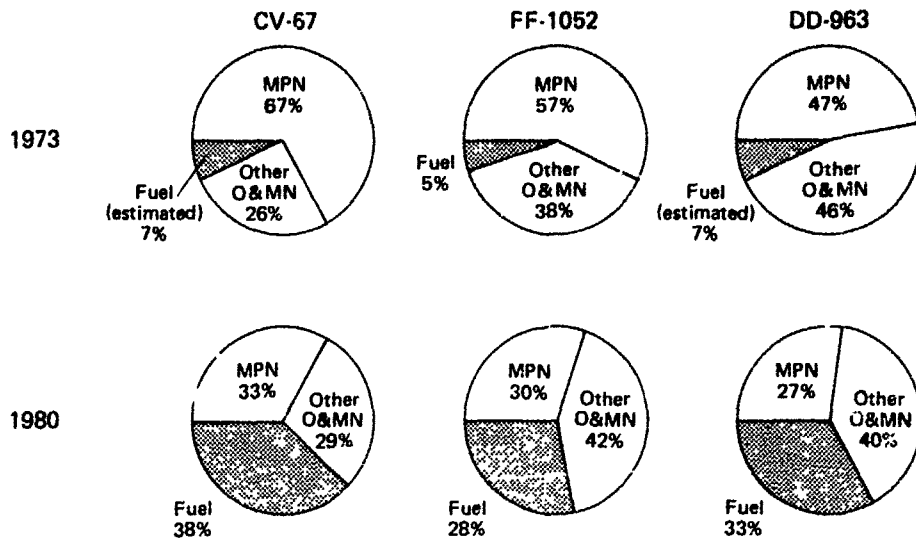
CV·67 FF·1052 DD·963

1973

MPN 67%
Fuel (estimated) 7%
Other O&MN 26%

MPN 57%
Fuel 5%
Other O&MN 38%

MPN 47%
Fuel (estimated) 7%
Other O&MN 46%

1980

MPN 33%
Other O&MN 29%
Fuel 38%

MPN 30%
Other O&MN 42%
Fuel 28%

MPN 27%
Other O&MN 40%
Fuel 33%

**FIG. III: FUEL PORTION OF DIRECT O&S COSTS — SHIPS**

F-14 P-3C

1973

MPN 33%
56%
Fuel (estimated) 11%

MPN 54%
Fuel 10%
36%

Other O&MN and spares

Other O&MN and spares

1980

MPN 21%
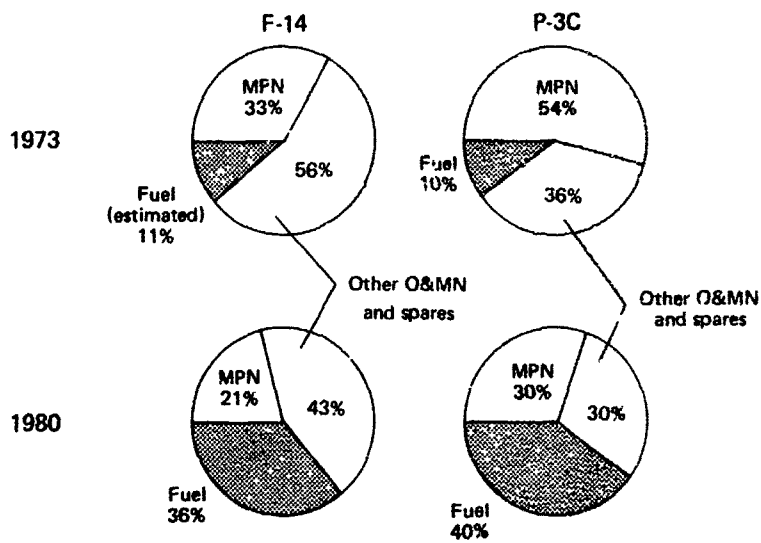43%
Fuel 36%

MPN 30%
30%
Fuel 40%
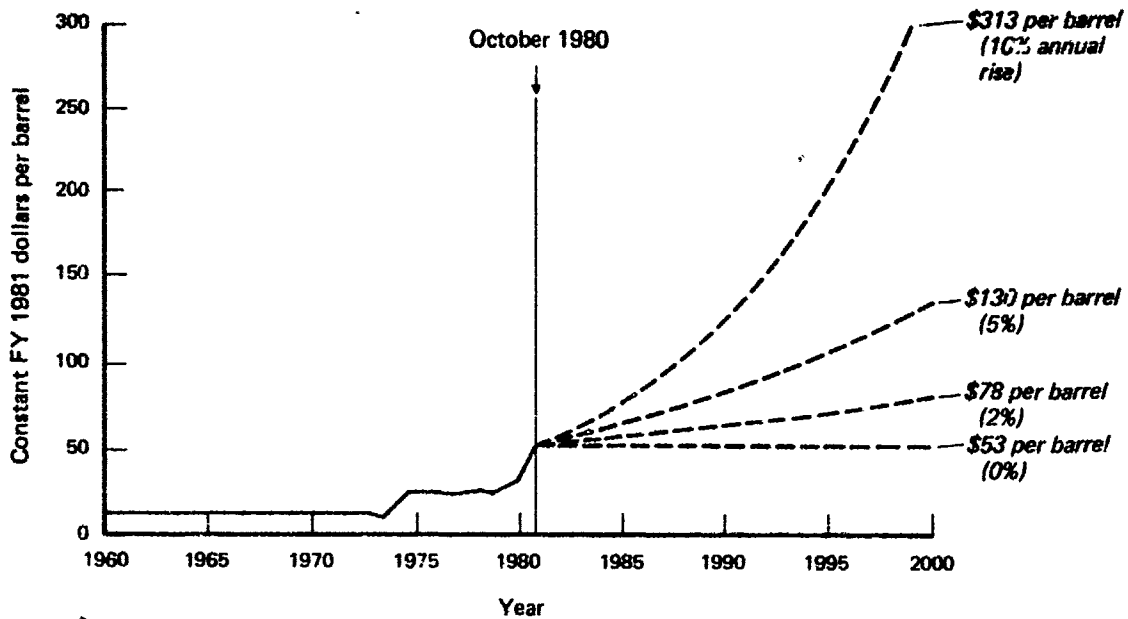
**FIG IV: FUEL PORTION OF DIRECT O&S COSTS — AIRCRAFT**

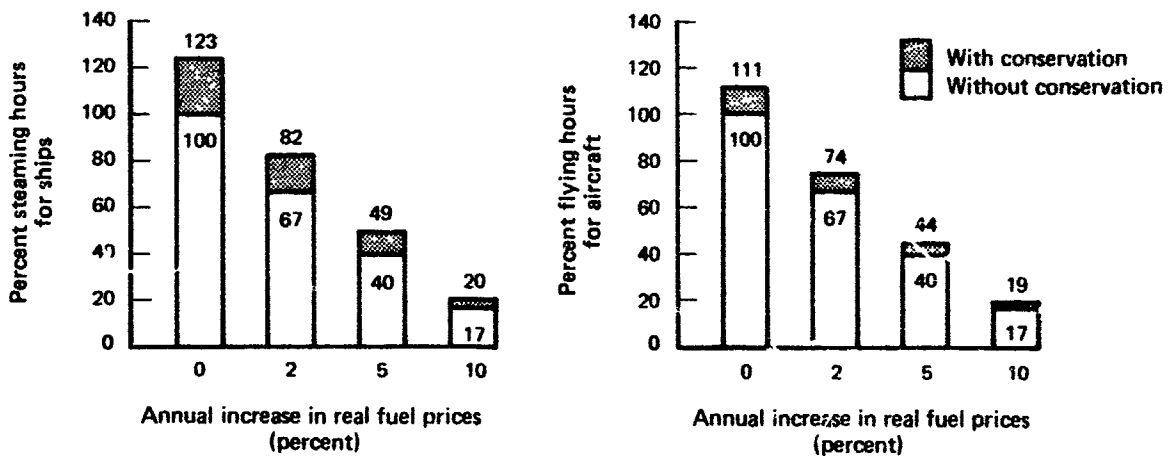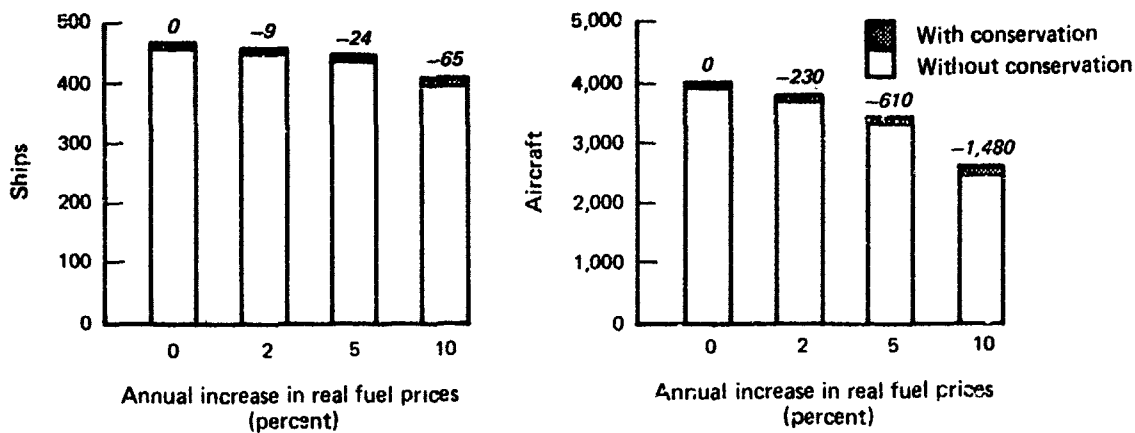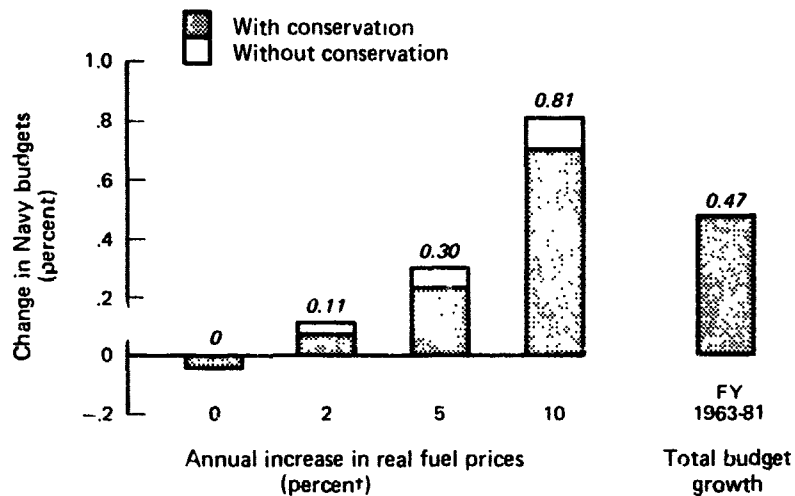**FIG. V: NAVY FUEL-PRICE HISTORY AND PROJECTIONS**



**FIG. VI: YEAR 2000 OPERATING TEMPO: EFFECT OF FUEL PRICE INCREASES**

**FIG. VII: YEAR 2000 FORCE LEVELS: CUMULATIVE REDUCTIONS
DUE TO FUEL PRICE INCREASES FROM 1981 TO 2000**



**FIG. VIII: NAVY BUDGET: ANNUAL INCREASES REQUIRED
TO OFFSET FUEL PRICE RISES**

Figure VI shows how increases in the real price of fuel could reduce the steaming and flying hours of the fleet by the year 2000. It illustrates the erosion as a percentage drop from the 1980 level of operations, assuming that the budget for operations is fixed. The intermediate case of a 5-percent annual increase in price would cut steaming and flying hours to less than half of their 1980 levels. The benefits of conservation are shown if the goals for fuel efficiency are met.

Figure VII shows the possible erosion of future force levels caused by increases in the price of fuel. In this example, the tempo of operations is assumed to stay at 1980 levels. Increases in the fuel price then cause fuel costs to rise above the October 1980 level. These excess fuel costs are assumed to be paid for from the procurement budgets for new ships (SCN) and new aircraft (APN). Under these assumptions, the cumulative effect by the year 2000 of an annual 5-percent real increase in the price of fuel would be a loss of 24 new, average combat ships and 610 combat aircraft. Successful conservation might avert the loss of 7 ships and 90 airplanes under the 5-percent case.

Figure VIII is an illustration of how much the 1981 Navy budget would have to grow each year to offset hypothetical annual increases in the price of fuel. The percentage increases required annually in the Navy's total obligational authority (TOA) are small. However, the 0.11-, 0.30-, and 0.81-percent increments accumulate by the year 2000 to about $10 billion, $28 billion, and $78 billion, respectively. Effective conservation would reduce the need for additional funding.

An additional perspective on the size of the annual increases in figure VIII can be obtained by comparing them with the history of the Navy's budget growth. Including the Vietnam years, real growth in the Navy budget averaged 0.47 percent annually. An intermediate fuel price hike of 5 percent would offset about two-thirds of that total increase.

FUTURE FUELS AND FUEL QUALITY

Other considerations closely related to the cost of fuel are the type and quality of fuel. Although exotic alternatives to petroleum-derived fuels, such as hydrogen and alcohol, may eventually help meet the Navy's energy needs, liquid hydrocarbons will remain the mainstay of Navy mobility fuels through at least the next few decades. Liquid hydrocarbons, including synthetics, are superior to the alternatives because of their energy density by volume, availability, ease of storage and handling, and adaptability to engines designed for petroleum products.

However, many of the future synthetic and petroleum crude products will be of lower quality than those derived from the light, low-sulphur crudes currently available. Because these products require more

processing and additives, they are expected to be both higher in price and lower in quality.

Fuel of low quality causes maintenance and reliability problems, particularly in gas turbine engines. The Navy has already encountered aspects of this problem with both JP-5 for aircraft and DFM for ships. Unless engines are modified, using fuel of degraded quality could cut the life of some expensive components in half. Fuel quality is likely to become one of the important considerations in managing the Navy's fuel. It will almost certainly contribute further to the problem of fuel costs.

NAVY RESPONSES

There are a number of measures available to contend with future price rises, interruptions in supplies, and a decline in fuel quality. They are classified below as actions to reduce petroleum consumption or actions to increase access to whatever petroleum is available.

Measures to reduce consumption:

- Make existing and planned systems more fuel efficient.

- Reduce the operating tempo of the fleet.

- Reduce force levels.

- Rely more on substitute systems that are less fuel intensive.

- Develop alternative fuels.

Measures to increase access:

- Obtain larger Defense budgets.

- Obtain a larger share of the available Defense budget.

- Change fuel specifications.

- Design engines to accept lower quality fuel.

- Increase petroleum reserves.

Most of the Navy's efforts are concentrated on getting more efficiency from existing and programmed systems. Fuel can also be saved by operating less or by reducing the size of the Navy. Large fuel savings could come as a byproduct of changing the mix of naval weapons. For example, relying more on missiles and remotely piloted vehicles (RPVs) as complements to manned aircraft and on nuclear

propulsion for conventionally powered ships could yield large direct savings in petroleum. A long-term possibility is to develop nonnuclear fuels that are alternatives to petroleum.

There are a number of possibilities for the Navy to get more of whatever fuel is available. One is to get larger budgets for all the Services to offset higher fuel prices—as has been done. Another is to demonstrate the comparative advantages of seapower to get a larger share of whatever resources are available to Defense. The Navy might also reduce its fuel specifications and design engines so that they are less sensitive to variations in the quality of fuel. Finally, the Navy's leaders can use their influence to increase the nation's Strategic Petroleum Reserve and military stocks of petroleum products.

Most of the measures in the above list are getting attention within the Navy, the Department of Defense, or the Department of Energy. However, some merit more management attention.

Conservation

Conservation within the Navy yielded about $200 million in fuel savings in 1980. If the goals for 1985 are reached, savings of about $1 billion will be realized for that year. For ships and aircraft, meeting these goals will require a reduction in fuel consumption from 1975 levels of 20 percent per underway steaming hour and 5 percent per flight hour.

However, three problems face any management of energy-related issues in the Navy, including the implementation of conservation programs. They are:

- How to organize to manage a problem as pervasive as energy

- Need for more meaningful incentives to foster conservation

- Scarcity of planning information on the nuclear portion of the Navy's energy consumption.

Substitution Measures for Aircraft and Ships

Additional ways to save fuel involve substitution measures for the major users of mobility fuels—ships and aircraft.

For aircraft, some additional fuel savings will result from efficiency improvements and increased use of flight simulators. However, large reductions in aviation fuel consumption can only come from reduced operations or as a byproduct of some long-term changes in the mix of naval weapons. Examples of such changes would involve less

dependence on manned aviation and more use of cruise missiles, surface-to-air missiles, artillery, and unmanned surveillance systems. This last measure includes systems such as satellites and RPVs.

In contrast to the relatively small efficiency improvements possible with gas turbines in aircraft, ship prime movers offer a wider range of possibilities. Diesel engines consume less fuel than gas turbines for the same power output. Savings can be in the range of 40 to 50 percent during cruise operation and 0 to 10 percent at full power. Steam plants can also provide fuel savings of perhaps 20 percent at low-power settings. Thus, combinations of a gas turbine for high-power operations with another system that displays greater part-load efficiencies can be attractive. Furthermore, low-speed diesels and steam plants display greater tolerance than gas turbines for fuels of lowered quality.

## Nuclear Propulsion

Large savings in petroleum could come from making more ships nuclear powered. Today's fleet of nuclear ships and submarines uses an amount of energy equivalent to over 8 million barrels of oil-equivalent (mmboe) per year, or about one-third the fuel consumed by current conventional ships.

One of the major arguments against nuclear-powered ships has been their higher costs of acquisition. However, as the price of petroleum outstrips other prices, the operating costs and, thus, the total costs of conventional ships will rise relative to their nuclear-powered alternatives. Figure IX shows the life-cycle costs of nuclear and nonnuclear aircraft carriers as if they were new construction. Costs are calculated for both their undiscounted and discounted values.

The life-cycle costs of the two carriers cross in the undiscounted case at an average fuel price of $58 per barrel—very close to the current price of $52.50 per barrel. Discounting places a greater weight on the nuclear carrier's higher procurement costs than on the conventional carrier's higher operating costs because the latter occurs later in time. The point of equal life-cycle costs in the discounted case is at an average fuel price of about $220 per barrel. This corresponds to an increase in the price of fuel of about 6 percent per year over the lifetime of the ship. It should also be noted that the difference in discounted costs between these two ships becomes small well before the breakeven point.

The life-cycle costs of two Aegis cruisers—one nuclear, the other conventional—for varying fuel prices were also considered. The points of equal cost for the nuclear and the nonnuclear cruisers occur at a fuel price of about $270 per barrel in the undiscounted case and at about $550 per barrel in the discounted case. Such high fuel prices

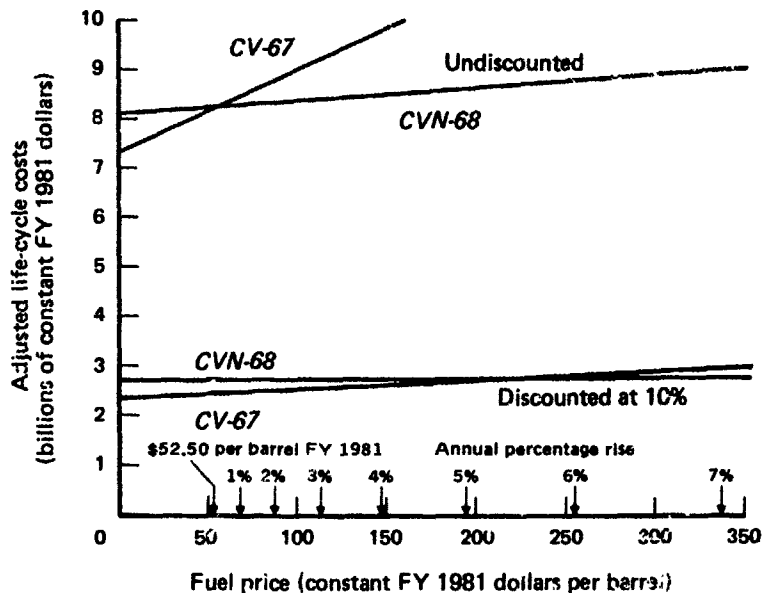would result from average annual increases of about 6 and 9 percent, respectively.



**FIG. IX: CARRIER LIFE-CYCLE COSTS (IOC 1992)**

Nuclear propulsion also offers a number of tactical advantages for surface ships, such as sustained high speeds and reduced support requirements. Along with the consideration of comparative life-cycle costs, these advantages increase the attractiveness of nuclear power for ships above about 10,000 tons.

EFFECTS ON THE NAVY OF CHANGES IN THE PETROLEUM MARKET

On Warfare

One important effect of rising fuel costs on naval warfare will be on the size and the readiness of the Navy. The Navy's capabilities at the outbreak of a future conflict could well be less than they would have been with stable fuel costs.

Another aspect of the problem of petroleum availability is that the Middle East has up to two-thirds of the non-Communist world's reserves of petroleum. Access to that region will therefore be essential to the U.S. and its allies. To insure that access, the Navy must be able to keep the sea lanes open.

The level of both civil and military reserves will affect the availability of military fuels during supply disruptions. In addition, these stock levels could be a major determinant of the nation's response to conflicts that reduce petroleum imports. Because oil shortages impair the economy, pressures for quick resolution of conflicts--either through escalation or by submission--are apt to be greater in an environment where petroleum stocks are critical.

Fuel rationing could produce similar responses. Wars that fail to engage the support of the American public could be more difficult to prosecute when accompanied by fuel shortages and rationing. As in the case of critical oil stocks, the pressure would be in the direction of quick resolution of the conflict.

## On Weapons

The effect on the choice of weapons will be similar to other situations in which resource costs rise appreciably. Substitutes and different ways of performing missions will become increasingly attractive as the economic burden of higher priced fuel becomes clearer to planners. In the acquisition of new weapons, fuel efficiency will become a more important factor, provided likely increases in fuel prices are treated realistically in estimates of life-cycle costs. The problem of uncertain supplies of fuel in a crisis will also make fuel-efficient alternatives more attractive.

As fuel of lower quality becomes more prevalent, there will be corresponding decreases in reliability and increases in maintenance requirements for ships and aircraft. Engine modifications could reduce these effects somewhat.

The advantages of designing future ship and aircraft engines to be less sensitive to variations in fuel specifications will become apparent. In addition, there will be pressures to move toward fuel that is more widely used by other military and civilian users. These changes could lower costs and increase supplies.

In manned aviation, conservation efficiencies and simulators will provide added fuel savings. However, very large savings could only result from reduced operations or as a byproduct of some long-term changes in the mix of naval weapon systems.

## On Mobility

Diesel engines are more fuel efficient than gas turbines. At low-power settings, steam powerplants are also more fuel efficient than gas turbines. Low-speed diesels and steam engines are also less sensitive than gas turbines to variations in the quality of fuel.

Nuclear power provides the greatest freedom from reliance on petroleum. The higher procurement costs of large nuclear ships can be offset by their lower operating costs as the real price of petroleum increases in the future. Oil prices have risen enough already so that the undiscounted life-cycle costs of nuclear-powered carriers are nearly equal to those of conventionally powered carriers. For smaller ships, fuel prices will have to rise significantly before the life-cycle costs of nuclear and nonnuclear ships are equal.

The prospect of higher fuel costs also adds to the comparative advantages of sealift over airlift.

RECOMMENDATIONS

The study concludes with the following recommendations:

● The Navy needs strong management of energy-related matters to implement conservation and to help it adjust to the constraints imposed by the higher costs, lower availability, and poorer quality of fuel. All relevant energy information—including the nuclear aspects—should be available to Navy planners for a complete management perspective on the Navy's energy problems and options.

● A strong and comprehensive research and development (R&D) program should be maintained to increase fuel efficiencies and to prepare for problems of degraded fuel.

● The life-cycle costs of nuclear ships are higher tnan those of conventionally powered ships at the October 1980 fuel price. However, the prospect of even higher petroleum prices and interrupted fuel supplies, combined with the effectiveness advantages of nuclear power, argues that all large ships of the future be much stronger candidates for nuclear propulsion than they are now.

● Because of their efficiency and tolerance for varying fuel quality, diesel engines should be used more widely on smaller ships.

● Large civilian and military reserves of petroleum give significant protection against disruptions in the market and curtailed supplies of fuel. They should be vigorously supported.

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# CHAPTER 1

## INTRODUCTION

This study evaluates petroleum issues facing the Navy over the next 20 to 30 years. It responds to concerns expressed by the Chief of Naval Operations (CNO) for the adequacy of the Navy's fuel supply. The work was sponsored by the Navy's Long Range Planning Group, Op-00X.

## OBJECTIVES

The study has two main objectives:

- To evaluate the likely availability of petroleum products for the fleet to the year 2010

- To identify the probable effects of the availability of petroleum on the conduct of naval warfare, the selection of weapons, and mobility.

## SCOPE AND ASSUMPTIONS

To present a CNO-level perspective on such a pervasive problem, several key issues were selected and analyzed to support the inferences drawn. A mix of empirical, statistical, and heuristic arguments were made. Although the arguments may not be equally compelling, they are all relevant to Navy planning. Quantitative analyses were used where appropriate.

The scope of the study was reduced in several ways. One way was to focus on the fuel derived from conventional oil and synthetic petroleum liquids. Other energy forms, such as uranium or hydrogen, were introduced to make some comparisons but were not analyzed in detail. Another way was to limit the study to the direct consumption of petroleum by the major fuel users--the ships and aircraft of the fleet. Although there are significant quantities involved, the energy consumed by the industries supporting the Navy and the direct use of petroleum by the Navy's shore establishment were excluded from the analysis. Finally, it was assumed that the fleet would evolve along the lines of its current composition of aviation, surface ships, and submarines. Radically different fleets were not examined, even though they could have large effects on fuel usage.

Most of the projections by industry and government used in the study do not extend beyond the year 2000. However the trends and major inferences drawn are expected to continue as dominant considerations in planning through the year 2010.

## ORGANIZATION AND SOURCES

There are four distinct areas of investigation: background, forecasts, supply interruptions, and options.

Chapter 2, background, emphasizes the changes that have taken place in the oil market since the embargo of 1973 and how they have affected the Navy. The principal sources for this part of the evaluation include oil-price data from industry and government; Navy fuel-consumption data from the Chief of Naval Operations (Op-413); and published, energy-related reports from the Navy, the Department of Defense (DoD), the Department of Energy, the Congress, and academia.

Chapter 3 evaluates the forecasts of petroleum supply and demand. The forecasts are from published sources and are summarized in the study to characterize the problems the Navy is likely to face. The petroleum industry is the source of the basic drilling and production data on which most assessments are based. A broader segment of private and public organizations provides estimates of both proven reserves and ultimately recoverable resources. A still larger number of organizations get involved in estimating future levels of supply and demand for petroleum products. This study examined over 15 forecasts and analyses of petroleum availability, but relied mostly on analyses from the oil industry and the U.S. Geological Survey (USGS) and on reports from the Department of Energy.

Chapter 4 examines the problems stemming from interruptions of the oil supply. Both government and private analyses are used, which include: econometric studies of past and potential gross national product (GNP) losses from petroleum interruptions, testimony before the Congress by Defense officials on the problems experienced in procuring and managing stocks during crises, and evaluations of the Strategic Petroleum Reserve (SPR).

Chapter 5 summarizes the problem of the future availability of petroleum and introduces the range of options available to the Navy to manage its petroleum consumption efficiently.

Chapters 6 through 9 analyze aspects of the major options for their potential to receive more or less management emphasis. The cognizant offices in the Office of the Chief of Naval Operations, the Naval Material Command, and the Department of Energy provided much of the data used in these mini-analyses.

The conclusions and recommendations of the study are contained in chapter 10.

Additional information supporting parts of the study are in the appendices and in a separate, classified memorandum, cited in [1].

# CHAPTER 2

## BACKGROUND

During the 1970s, changes in the world petroleum market were wide-spread if not revolutionary. The decade ended an era of inexpensive oil and introduced a new period of greater scarcity and higher real prices. In addition, the U.S. became vulnerable to supply interruptions, increasingly interdependent with other industrial economies, and vitally concerned with access to the oil resources in the Persian Gulf. These changes were strategic in character and worldwide in scope. This chapter examines evidence of the changes and their effect on the Navy.

### PETROLEUM CONSUMPTION

The amount of petroleum consumed directly by the Navy and the other military services has varied substantially with differences in the size and composition of the forces, the tempo of operations and, in recent years, with the price of fuel.

### Defense Consumption

The amount of fuel consumed directly by all the armed forces reached a post-World War II peak in 1969 during the Vietnam War. As shown in table 2-1, the average consumption of 1.090 million barrels per day (mmb/d) nearly matched the World War II peak in 1945 of 1.110 mmb/d. However, when viewed as a percentage of total U.S. petroleum consumption, the Vietnam peak was only 8 percent, whereas the World War II peak was 23 percent. Since World War II, the average for the Department of Defense (DoD) has been 5 percent of the nation's total fuel consumption. In recent years, however, record-high petroleum prices and smaller forces have reduced defense consumption substantially below 5 percent.

Figure 2-1 provides an additional perspective on Defense and Navy consumption in 1980. The Navy now directly consumes about 1 percent of the petroleum used in the U.S.

### Nuclear Energy Usage

The Navy is unique among the military services because it does not completely depend on petroleum products for its mobility fuels. Twelve surface ships and 123 submarines are nuclear powered. Nuclear propulsion provides an amount of energy equivalent to about 23,000 barrels of oil daily, or 8.4 million barrels of oil-equivalent (mmboe) annually at 1980 operating levels. This corresponds to about one-third the amount of petroleum consumed by Navy ships in 1980. The derivation of this estimate is published separately [1].

TABLE 2-1

## HISTORY OF PETROLEUM CONSUMPTION FROM 1940 TO 1980

| Year | U.S. (mmb/d) | All military Mmb/d | Percent of U.S. consumption | Navy Mmb/d | Percent of military consumption |
|------|------|------|------|------|------|
| 1940 | 3.7 | 0.045 | 1.2 | 0.037 | 82 |
| 1941 | 4.0 | 0.066 | 1.7 | 0.061 | 92 |
| 1942 | 3.8 | 0.175 | 4.6 | 0.086 | 49 |
| 1943 | 4.1 | 0.591 | 14.4 | 0.376 | 63 |
| 1944 | 4.6 | 0.915 | 20.0 | 0.469 | 51 |
| 1945 | 4.8 | 1.110 | 23.0 | 0.549 | 49 |
| 1946 | 5.0 | 0.673 | 13.0 | 0.451 | 67 |
| 1947 | 5.4 | 0.287 | 5.3 | 0.157 | 55 |
| 1948 | 5.9 | 0.299 | 5.0 | 0.159 | 53 |
| 1949 | 5.7 | 0.328 | 5.7 | 0.158[a] | 48 |
| 1950 | 6.4 | 0.350 | 5.5 | 0.157[a] | 45 |
| 1951 | 7.0 | 0.395 | 5.6 | 0.171[a] | 43 |
| 1952 | 7.3 | 0.397 | 5.4 | 0.166[a] | 42 |
| 1953 | 7.6 | 0.496 | 6.5 | 0.200[a] | 40 |
| 1954 | 7.8 | 0.530 | 6.8 | 0.205[a] | 39 |
| 1955 | 8.5 | 0.568 | 6.6 | 0.210[a] | 37 |
| 1956 | 8.8 | 0.591[b] | 6.7 | 0.216[a] | 37 |
| 1957 | 8.8 | 0.660[b] | 7.5 | 0.239[a] | 36 |
| 1958 | 9.1 | 0.598[b] | 6.6 | 0.214[a] | 36 |
| 1959 | 9.5 | 0.739[b] | 7.8 | 0.262[a] | 35 |
| 1960 | 9.8 | 0.692 | 7.1 | 0.242[a] | 35 |
| 1961 | 10.0 | 0.760[b] | 7.6 | 0.266[a] | 35 |
| 1962 | 10.4 | 0.865[b] | 8.3 | 0.303[a] | 35 |
| 1963 | 10.7 | 0.844[b] | 7.9 | 0.295[a] | 35 |
| 1964 | 11.0 | 0.826[b] | 7.5 | 0.289[a] | 35 |
| 1965 | 11.5 | 0.801 | 7.0 | 0.280[a] | 35 |
| 1966 | 12.1 | 0.873 | 7.2 | 0.305[a] | 35 |
| 1967 | 12.6 | 0.994 | 7.9 | 0.348[a] | 35 |
| 1968 | 13.4 | 1.075 | 8.0 | 0.376[a] | 35 |
| 1969 | 14.1 | 1.090 | 7.7 | 0.381[a] | 35 |
| 1970 | 14.7 | 0.919 | 6.3 | 0.296 | 32 |
| 1971 | 15.2 | 0.825 | 5.4 | 0.258 | 31 |
| 1972 | 16.4 | 0.797 | 4.9 | 0.253 | 32 |
| 1973 | 17.3 | 0.748 | 4.3 | 0.247 | 33 |
| 1974 | 16.7 | 0.578 | 3.5 | 0.216 | 37 |
| 1975 | 16.3 | 0.508 | 3.2 | 0.184 | 36 |
| 1976 | 17.5 | 0.482 | 2.8 | 0.166 | 34 |
| 1977 | 18.4 | 0.473 | 2.6 | 0.165 | 35 |
| 1978 | 18.9 | 0.454 | 2.4 | 0.160 | 35 |
| 1979 | 18.5 | 0.470 | 2.5 | 0.161 | 34 |
| 1980 | 17.5[c] | 0.463 | 2.6 | 0.158 | 34 |

Sources: [2 through 5].

[a] Estimates of Navy consumption are based on partial information for these years.
[b] Based on military purchases of major petroleum products in U.S. and foreign countries.
[c] Preliminary.

Total U.S.

DoD
2 6%

17 5 million barrels
per day

Total DoD

Air Force
55%

Navy
34%

Army
11%

0.463 million barrels
per day

Total Navy

Ships
45%

Aircraft
40%

Shore
establishment
15%

0.158 million barrels
per day

*Source. [3].*
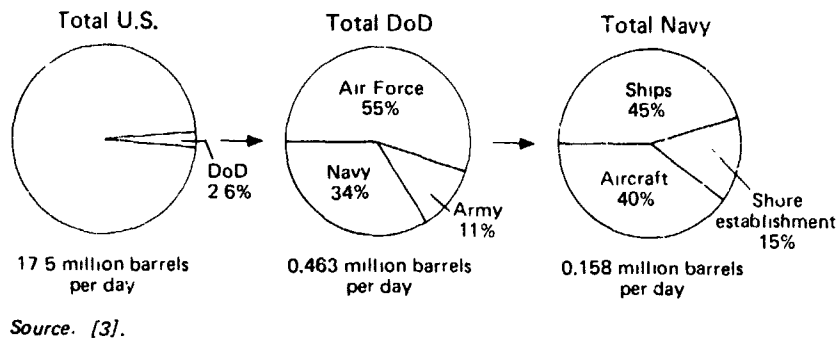
**FIG. 2-1: DEFENSE PETROLEUM ENERGY CONSUMPTION IN 1980**

## FUEL COSTS

### Soaring Prices

One of the changes with strategic significance has been the burden of sharply higher fuel prices. Shortly before the oil embargo of October 1973, the price for a barrel of fuel--an average of the price for the distillate fuels JP-5 (aviation fuel) and DFM (marine diesel fuel)--was $12.57 in constant FY 1981 dollars. In October 1980, the price had risen to about $52.00 per barrel--over a fourfold increase above the rate of inflation. Figure 2-2 illustrates this price history taken from the data in table 2-2. The table shows the prices paid by the Navy to the Defense Fuel Supply Center (DFSC) stock fund.

As shown in figure 2-2, Navy fuel prices increased dramatically in response to the market turbulence experienced in 1973 and 1974 and, again, in 1979 and 1980. The equivalent average annual increase, measured from 1973 to October 1980, was 23 percent above the rate of inflation. From 1960 to 1980, the price increased at an annual average of 8 percent.
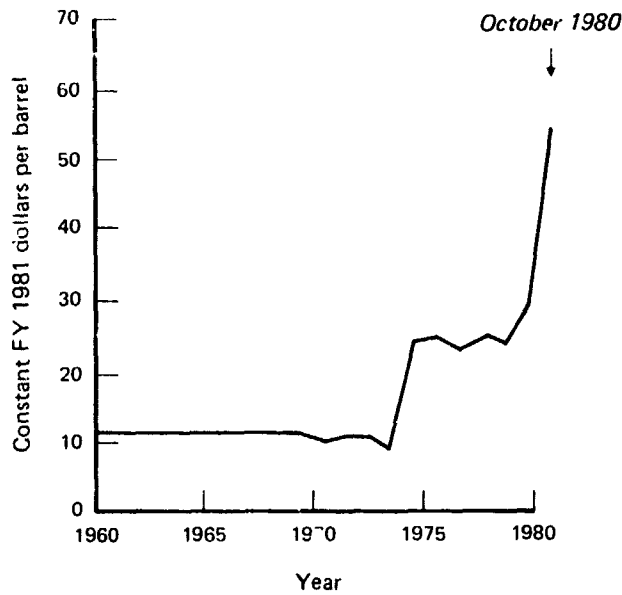
*Source [6].*

**FIG. 2-2: NAVY FUEL PRICES**
**(AVERAGE OF JP-5 AND DFM)**

## Operating and Support Costs

One measure of the changing burden is the fuel portion of the direct operating and support (O&S) costs* of naval weapons. Figures 2-3 and 2-4 show these changes for representative ships and aircraft since 1973. The data have been adjusted to reflect the higher steaming and flying hours in 1973.

As both figures show, fuel--a relatively minor cost consideration in 1973--is now a major claimant for resources. It is in the same range as manpower. Although fuel prices have had the largest effect on changing O&S costs, other support prices contributed also. For example, expenditures for manpower have not kept pace with inflation and have dropped in relative importance between 1973 and 1980.

## Larger Budgets

Higher prices for fuel required larger Navy budgets and, in some cases, reductions in Navy programs. For example, the Navy required

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* O&S costs consist of expenditures for these two categories: military personnel, Navy (MPN), and operations and maintenance, Navy (O&MN). For aircraft, costs of replenishment spares are also included. Fuel costs are contained in the O&MN account.

supplemental appropriations for fuel of $135 million and $807 million in FY 1974 and FY 1980, respectively. In addition, the Navy budget for FY 1981 was amended to add $1 billion for fuel [9 and 10].

TABLE 2-2

HISTORY OF STANDARD NAVY PRICES FOR JP-5 AND DFM
(Dollars per Barrel)

|  | Then-year dollars | | Constant FY 1981 dollars | | | Constant FY 1981 dollars (average of JP-5 and DFM) |
|---|---|---|---|---|---|---|
|  | JP-5 | DFM | JP-5 | DFM | | |
| Jul 1960[a] | $5.10 | $4.70 | $13.32 | $12.28 | | $12.80 |
| Jul 1968 | 5.33 | 5.04 | 12.89 | 12.10 | | 12.49 |
| Jul 1969 | 5.33 | 5.04 | 12.41 | 11.73 | | 12.07 |
| Oct 1970 | 4.96 | 4.45 | 12.76 | 11.44 | | 12.10 |
| Jul 1971 | 5.17 | 4.91 | 12.79 | 12.14 | | 12.46 |
| Jul 1972 | 5.21 | 4.87 | 12.42 | 11.61 | | 12.01 |
| Jul 1973 | 6.80 | 6.85 | 12.52 | 12.61 | Embargo | 12.57 |
| Jul 1974 | 14.28 | 24.57 | 22.13 | 22.57 | | 22.35 |
| Jul 1975 | 17.14 | 16.38 | 24.30 | 23.21 | | 23.76 |
| Oct 1976 | 16.17 | 16.17 | 21.91 | 21.91 | | 21.91 |
| Oct 1977 | 18.52 | 18.52 | 23.65 | 23.65 | | 23.65 |
| Oct 1978 | 18.90 | 18.90 | 22.43 | 22.43 | Iranian | 22.43 |
| Oct 1979 | 26.46 | 25.62 | 28.84 | 27.92 | Revolution | 28.38 |
| Oct 1980 | 53.34 | 51.24 | 53.34 | 51.24 | | 52.30 |

Source:  [6].

[a]In 1960, JP-5 and DFM were not separately identified. The closest comparable fuels in that year were "Jet Fuels" and "Diesel."

Program Reductions

Increased funding has not always been sufficient to cover the added costs of fuel. This was the case in the spring of 1980 when about $1 billion of previously authorized and appropriated Navy programs were reduced or cancelled to help meet the combined costs of fuel, inflation, and operations in the Indian Ocean [9].

Along with a winding down of the Vietnam level of operations, rising fuel prices have contributed to reduced steaming and flying hours. Tables 2-3 and 2-4 show that in 1980, the underway steaming and flying hours for the average ship and aircraft were below 1973 levels by

CV-67          FF-1052          DD-963
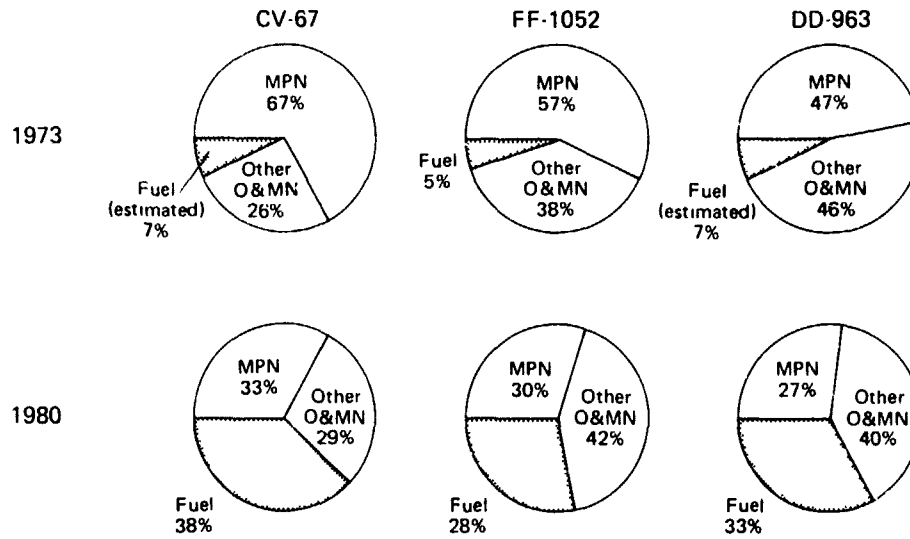
1973

Source. [7 & 8].

**FIG. 2-3: FUEL PORTION OF DIRECT O&S COSTS — SHIPS**



F-14          P-3C
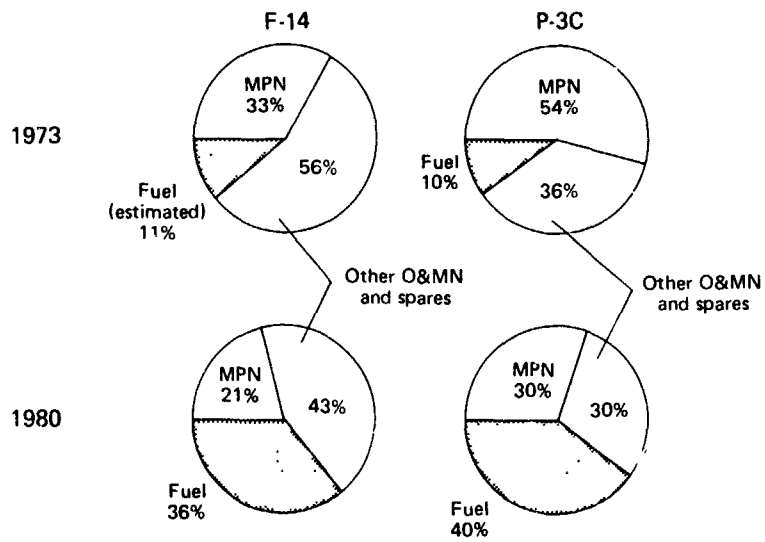
1973

1980

Source: [7 & 8]

**FIG. 2-4: FUEL PORTION OF DIRECT O&S COSTS — AIRCRAFT**

2-6

TABLE 2-3

STEAMING-HOUR HISTORY OF OPERATIONAL SURFACE SHIPS FROM 1973 TO 1980

| Year | Average number of ships[a] | Underway steaming hours | Hours per ship-year | Year-to-year change (percent) |
|------|---------------------------|-------------------------|---------------------|-------------------------------|
| 1973 | 517 | 1,221,700 | 2,363 | -- |
| 1974 | 459 | 839,600 | 1,829 | -22 |
| 1975 | 449 | 900,000 | 2,005 | +10 |
| 1976 | 430 | 798,300 | 1,857 | -7 |
| 1977 | 412 | 736,800 | 1,788 | -4 |
| 1978 | 394 | 732,800 | 1,869 | +4 |
| 1979 | 393 | 719,200 | 1,830 | -2 |
| 1980 | 391 | 756,100 | 1,934 | +6 |
| Percent change: 1973-1980 | -24 | -38 | -18 | -- |

Source: [11 and 12].

[a]Excludes nuclear-powered and Military Sealift Command (MSC) ships.

TABLE 2-4

FLIGHT ACTIVITY OF OPERATIONAL NAVY AIRCRAFT FROM 1973 TO 1980

| Year | Average number of aircraft | Total flight hours (thousands) | Average flight hours per month per operational aircraft | Year-to-year change (percent) |
|------|---------------------------|--------------------------------|---------------------------------------------------------|-------------------------------|
| 1973 | 5,500 | 2,548 | 38.6 | -- |
| 1974 | 5,260 | 2,184 | 34.6 | -10 |
| 1975 | 5,016 | 2,142 | 35.6 | +3 |
| 1976 | 4,877 | 2,042 | 34.9 | -2 |
| 1977 | 4,762 | 1,998 | 35.0 | 0 |
| 1978 | 4,419 | 1,925 | 36.3 | +4 |
| 1979 | 4,316 | 1,899 | 36.7 | +1 |
| 1980 | 4,313 | 1,947 | 35.7 | -3 |
| Percent change: 1973-1980 | -22 | -24 | -8 | -- |

Source: [13].

18 and 8 percent, respectively. However, most of the reductions occurred in 1974. Since then, the steaming and flying hours of the average ship and aircraft have varied only slightly from year to year.

In contrast, the fleet's aggregate steaming and flying hours are down sharply, which mainly reflect the decline in force levels. The reduced hours have resulted in substantial petroleum savings, shown in table 2-5.

TABLE 2-5

TOTAL FLEET STEAMING AND FLYING HOURS IN 1973 AND 1980

| Total fleet | 1973 | 1980 | Percent change: 1973 to 1980 |
|---|---|---|---|
| Underway steaming hours[a] (thousands) | 1,221 | 756 | -38 |
| Flying hours (thousands) | 2,548 | 1,947 | -24 |
| Petroleum fuel consumed[b] (millions of barrels) | 72 | 46 | -36 |

Source: [11, 12, and 13].

[a]Includes only conventionally powered surface ships in the active fleet.
[b]Petroleum fuel used by naval ships and aircraft; total Department of Navy consumption was 93 and 58 million barrels, respectively.

VULNERABILITY TO SUPPLY INTERRUPTIONS

Another change of strategic significance and with implications for the Navy is the vulnerability of the U.S. to interruptions in the supply of oil. The embargo in 1973 and the Iranian Revolution in 1978 and 1979 disrupted the world petroleum market with economic effects in the U.S. and in the other Western industrial economies. Sharply higher prices for oil contributed to a slowdown in the economy in the U.S., to higher rates of inflation, and to shortages in Defense fuel stocks.

Effects on the U.S. Economy

During the past 8 years, interruptions of supplies to the world market have resulted in higher prices that, in turn, have affected the

nation's economy. Several econometric studies have estimated those effects. One estimate [14] placed the loss in real gross national product (GNP) at $30 billion in 1974 and at an additional $66 billion in 1975. Significant losses are thought to have been incurred as a result of the market turmoil stemming from the Iranian Revolution and the war between Iran and Iraq. The Congressional Budget Office [15] estimated that the $4-per-barrel rise in the price of crude oil imposed by the Organization of Petroleum Exporting Countries (OPEC) in 1980 (a 12-percent price increase) added about 1 percent to the nation's rate of inflation.

## Effects on the Navy

U.S. vulnerability to import interruptions has serious consequences for both the Department of Defense and the Navy. When the economy's output is smaller, fewer real resources are available for either Defense or the civil sector. In addition, inflation complicates managing the Navy. For example, inflation has been a major factor in difficult contract negotiations for new ships. Furthermore, inflation is often cited as a reason for both lower morale and difficulty in keeping personnel due to the erosion of benefits and pay.

Oil-supply interruptions also affected military operations. As a result of the embargo in 1973, naval operations were curtailed because of the uncertainty about the length of the interruption. However, petroleum stocks held by Defense reportedly were not seriously affected during that crisis [16].

In contrast with the earlier crisis, operations in 1979 and 1980 were not significantly curtailed, but Defense fuel stocks fell 6 percent below acceptable levels. To maintain the level of operations, war reserve stocks were used. This shortage was caused by the inability of the DFSC to contract for all of its requirements. Cumbersome government procurement practices and the inability of some of the refiners to obtain crude oil in the regulated market all contributed to the problem [17].

## INTERDEPENDENCE

A third change with strategic implications and with potential to affect Navy fuel supplies is the added emphasis on the interdependent relationship among Western industrial economies.

Volatile petroleum markets had adverse effects on Western Europe and Japan similar to those experienced in the U.S. Economic growth rates fell and unemployment and inflation rates rose. Although the reasons for the worldwide recessions in 1975 and, again, in 1979 and 1980 are debated, several estimates consider oil price increases to be a major culprit—responsible for about half the inflation rates and the decline in economic growth rates [18].

The economic health of allies matters to the security of the U.S. As a consequence, even if petroleum self-sufficiency for the U.S. were attainable, it would not solve energy-related threats to U.S. global interests. Compared with the U.S., Western Europe and Japan depend even more on imported oil (see table 2-6). They are expected to continue to rely heavily on production from the Middle East. Finally, the U.S. participates in the International Energy Agency (IEA) and has agreed to share petroleum supplies in the event of serious interruptions [19]. Thus, the vulnerability of these important allies will be a continuing concern with potential to influence the allocation of available petroleum stocks.

TABLE 2-6

PETROLEUM IMPORTS--PERCENTAGE OF TOTAL CONSUMPTION IN 1978

|  | U.S. | Western Europe | Japan |
|---|---|---|---|
| Percentage of petroleum imported | 45 | 87 | 100 |
| Percentage imported from Middle East | 12 | 59 | 72 |

Source: [20].

STRATEGIC IMPORTANCE OF THE PERSIAN GULF

A fourth major change in the strategic environment that affects Navy planning is the added significance of the Persian Gulf in world politics. Its importance has risen steadily as the world's demand for petroleum has increased. During the 1970s, the region accounted for about one-third of the world's entire production of crude oil and for about 60 percent of the crude oil in the world's export trade [20]. The importance of this region is further emphasized by its ability to significantly increase or decrease its petroleum output to respond to world market conditions.

Access to the petroleum in the Persian Gulf has become an added national priority that affects U.S. defense capabilities. That priority has been a major rationale for forming the Rapid Deployment Force. Implementing this priority will continue to require adjustments in forces, commands, and war plans that are predominantly oriented to the forward defense of Western Europe and Japan.

CHAPTER 3

PETROLEUM FORECASTS

There are two broad threats to the continued availability of petro-
leum. One is the problem of inadequate production rates. The other
threat arises from interruptions in the supply of oil stemming from
political, economic, or military causes. This chapter examines the
evidence for inadequate production of petroleum because of geological
limitations.

The future of petroleum production is important to the Navy because
the Navy depends on the civil sector for oil and because of the long
planning horizon of 20 to 40 years for aircraft and ships. However,
assumptions for planning have been inconsistent because of disagreements
in the forecasts. Two representative analyses exemplify the divergence
in views. One, by the Air Force Systems Command [21], sees a
"Malthusian" ceiling on oil production. It projects continued high
rates of demand against a declining supply of petroleum. The result is
an ever-widening "gap" within a decade between the quantity of oil that
could be supplied and the quantity of oil that will be demanded.

A far more optimistic viewpoint has been taken by Professor S. Fred
Singer at the University of Virginia's Energy Policy Studies Center
[22]. He sees the demand for conventional oil falling rapidly as both
price and price-induced substitutes for petroleum alleviate the pressure
on the available reserves. In contrast to the doomsday view, his
opinion anticipates the world abundant with excess petroleum within a
decade.

This chapter addresses the differences between the two divergent
views and, using published forecasts, suggests an alternative long-term
outlook.

FORECASTS--METHODS AND UNCERTAINTIES

Estimates of future oil production must consider both the quantity
of petroleum thought to be ultimately recoverable--already discovered or
undiscovered--and the future demand that will determine the rate of
depletion.

Ultimately Recoverable Resources

The quantities of the world's petroleum that are ultimately
recoverable include oil that has been or can be economically produced
using existing technologies--both primary and enhanced recovery methods.
Sources of this oil include known reservoirs, extensions of known
fields, and undiscovered fields. A number of complementary methods are

used to estimate amounts of oil from undiscovered fields, including:

- Projections from empirically derived finding rates of new oil [23]

- Geophysical studies of likely and known oil-bearing formations [24]

- Analyses of the distribution of large and giant oil fields, including the likelihood of finding additional ones [25].

Table 3-1 lists six estimates of the world's crude-oil resources that used some or all the above techniques. The highest estimate, attributable to Bernardo Grossling, is based on his premise of insufficient exploration in underdeveloped countries and offshore areas. However, this premise is not generally shared by the oil companies, which claim that most of the world's sedimentary basins have been adequately assessed by geophysical methods [26].

TABLE 3-1

ESTIMATES OF ULTIMATELY RECOVERABLE WORLD CRUDE-OIL RESOURCE

| Organization and source | Date of estimate | Quantity (billions of bbl) |
|---|---|---|
| British Petroleum Ltd. (H.R. Warman) | 1973 | 1,915 |
| Mobil Oil Corporation (J.D. Moody and R.W. Esser) | 1974 | 2,000 |
| U.S. Geological Survey (M. King Hubbert) | 1974 | 2,000 |
| U.S. Geological Survey (B. Grossling) | 1974 | 2,600-6,500 |
| World Energy Conference (Delphi approach) | 1977 | 2,230 (average of 28 estimates) |
| Rand Corporation (R. Nehring) | 1979 | 1,600-2,000 |

Source: [26].

As table 3-1 shows, most of the estimates of the world's ultimately recoverable resource indicate a total of about 2 trillion barrels. About 0.4 trillion of that figure had already been consumed by 1980, with 1.6 trillion still to be produced. Of the 1.6 trillion, about 0.6 trillion is considered to be discovered reserves that can be produced by primary or enhanced recovery techniques.

The data in table 3-1 do not include natural gas liquids (NGL). NGL are usually produced separately from crude oil and then added to petroleum stocks in the refining process. Their production might augment total liquid petroleum output by 5 to 15 percent.

The recoverable resource represents less than half the total resource. If prices are high enough and the technology for more advanced recovery exists, more than 1.6 trillion barrels might be ultimately recoverable.

## Finding Rates

One of the most important techniques for estimating oil reserves is to extrapolate from the history of crude-oil discoveries. This history, well documented for the U.S., is shown in figure 3-1. The figure shows the relationship between the discovery of new oil and the total amount of exploratory drilling. Figure 3-1 also shows the approximate dates when the drilling occurred. The area under each bar represents a quantity of crude oil added to reserves. This quantity accumulates as more wells are drilled until eventually the ultimately recoverable resource is established. In this way, the ultimately recoverable resource can be estimated by extending the falling trend in the finding rate. This was the technique that M. King Hubbert used in his pioneer work [23]. He noticed that the behavior of the finding rate is matched fairly well by an exponential curve fit.

Before 1945, the larger oil deposits constituted the primary finds, because they were the easiest to discover. With discovery rates of about 250 barrels per foot of exploratory drilling, additions to already proven reserves stayed well above the usage or production rates. The supply of domestic oil could be easily tapped to meet the country's growing needs.

In later years, however, finding rates dropped. They are now about 10 barrels per foot of exploratory drilling, primarily because additional discoveries are coming from smaller fields. As more and more resources are needed to locate and to extract petroleum, first additions to reserves and then levels of production have fallen below the nation's rate of consumption.

Figure 3-1 strongly suggests that this trend will continue. Additional large finds will be at best infrequent. Even the great increases

in drilling activity existing today will not significantly alter the fact that new reserves of oil are not keeping pace with production.
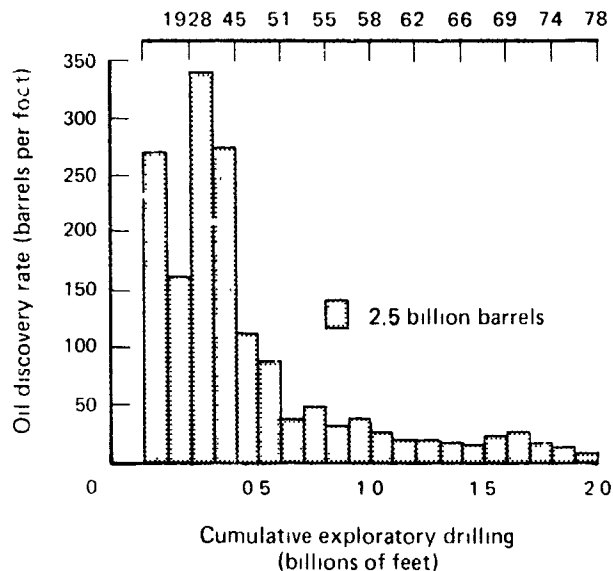


Source  [27 and 28]

FIG., 3-1: CRUDE-OIL DISCOVERY RATE IN
LOWER 48 STATES

The phenomena of declining rates are not confined to the U.S. Exxon reports [29] that world production rates have exceeded the additions to new reserves since 1970. The resulting pattern of declining reserves is expected to continue, even though drilling activities have increased and Exxon's projections of the world demand for oil are lower—less than 1 percent annually. The Exxon report reaches the following conclusion about the possible upper limit on world production through the year 2000:

> Consequently, even with a very active exploration effort, the average discovery rate for the outlook period is likely to be well below the expected production rate of about 20 billion barrels per year. The unavoidable result will be further decline in the world's inventory of discovered reserves. Production cannot continue growing under these circumstances, and it is reasonable to expect it to plateau around the turn of the century.

Additional evidence that the finding rate is a valid measure of the rate of depletion is taken from the locations of drilling sites of the major oil companies. If oil were still plentiful and easy to find, then the oil companies would not have to drill in geographically remote and

difficult frontier areas—including offshore—where the costs are
several times higher.

## Future Demand

The future demand for petroleum is a major uncertainty. Price, a
key determinant, affects not only the incentives to conserve energy, but
also the incentives to replace oil with alternative forms of energy
where possible. The effects of higher prices on consumption again
became apparent early in 1981: U.S. and world demand was expected to
drop below 1980 levels by about 6 and 3 percent, respectively.

Table 3-2 shows past and projected levels of demand for both the
U.S. and the world. Most of the estimates show a growing demand for
petroleum products in the less-developed nations and in the oil-
producing nations, but not in the Western industrial states. The Com-
munist states are expected to become net importers by the year 2000
[30].

TABLE 3-2

PAST AND FUTURE PETROLEUM CONSUMPTION

| Year | U.S. Size (mmb/d) | U.S. Percent annual increase over the decades[a] | World Size (mmb/d) | World Percent annual increase over the decades |
|------|------|------|------|------|
| 1960 | 10 | — | 22 | — |
| 1970 | 15 | 4.1 | 46 | 7.7 |
| 1980 | 17 | 1.3 | 63[b] | 3.2 |
| Projected: | | | | |
| 1990 | 13–16[b] | (2.7)-(0.6) | 70[c] | 1.1 |
| 2000 | 13–15[b] | 0 -(0.6) | 77[c] | 1.0 |

Source: [20 and 29].

[a]( ) denotes decrease.
[b]Estimates by the Department of Energy.
[c]Estimates by the Exxon Corporation.

The assumptions made about future rates of demand will largely determine whether a doomsday or a relatively less pessimistic view of the petroleum market is reached. High energy prices, recessionary economies, and less-expensive substitutes for petroleum will clearly slow the rate of depletion. However, Exxon and the Congress' Office of Technology Assessment [26] do not project a sufficient drop in world demand to sustain an optimistic view of world oil supplies.

As potential substitutes for conventional oil, petroleum-like liquids from shale, coal, and heavy oils could reduce the demand for oil. The higher petroleum prices become, the greater is the potential for synthetics. Within the U.S., the question is not so much whether there will be a synthetic-fuel industry, but when and at what levels of production. The Exxon Corporation projects that synthetics from shale, coal, and heavy oils will meet up to 8 percent of the world's demand for petroleum liquids by the year 2000 [29]. Texaco and others, less optimistic than Exxon, foresee a more modest contribution from synthetics.

U.S. PRODUCTION

Figure 3-2 illustrates projections of domestic production of conventional crude oil and NGL. It was adapted from USGS data and is an update of M. King Hubbert's work. This and subsequent curves in this chapter have been smoothed for clarity. The graph shows that in 1970, production of conventional oil in the lower 48 states peaked at 11.3 mmb/d and declined gradually thereafter. The estimated course of U.S. production is a continuation of that decline in the form of a bell-shaped curve.

The trend toward declining production was reversed in 1977 with the arrival of oil from the Alaskan North Slope. But this turnaround is thought to be temporary. Alaskan production is also expected to taper off. As shown in figure 3-2, petroleum substitutes—such as heavy oil from enhanced recovery techniques, plus synthetics—are likely to slow the rate of decline, but not stop it. The amounts attributed to synthetics in the figure are at best suggestions. As noted above, there are large uncertainties about the availability and production levels of synthetic fuels.

Alternative Projections

Figure 3-2 shows total domestic production in the year 2000 at about 7 mmb/d, including over 1 mmb/d of synthetics. In comparison, Texaco [31] foresees almost 8 mmb/d, including about 1 mmb/d of synthetics. Exxon [29 and 32] expects about the same conventional production levels as Texaco, but with additions from synthetics of perhaps 4 mmb/d. Exxon's projection is the most optimistic for domestic synfuel production. Whatever the levels of petroleum substitutes, they bring with them problems of fuel quality that are just beginning to appear.
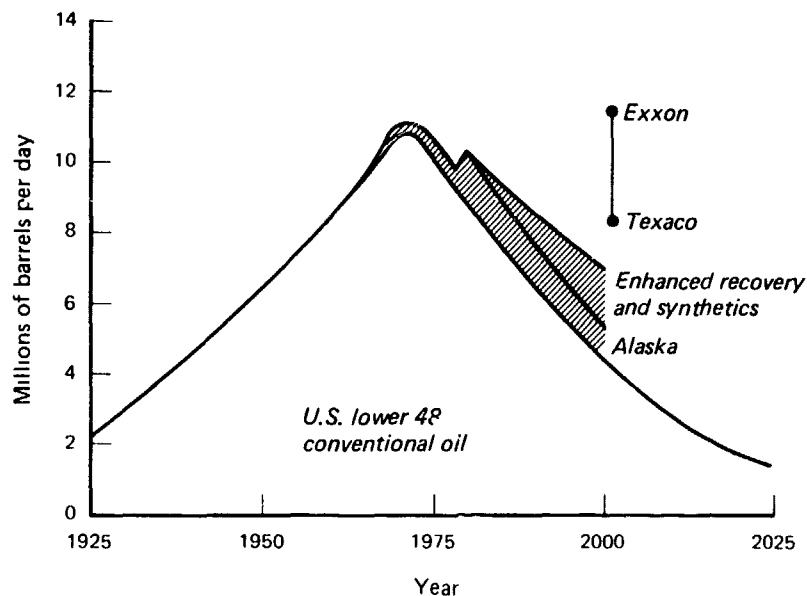
Source: [27, 29, and 31-33]

**FIG. 3-2: PROJECTIONS OF U.S. OIL PRODUCTION**

## Fuel Quality

Fuel quality is associated not only with future synthetic fuels, but also with today's petroleum-derived fuels. Difficulties have already begun to appear from more use of heavy, high-sulphur crude stocks. Products of low quality have a greater prevalence of long-chain hydrocarbons and higher levels of contaminants. The cost of the extra refining needed to upgrade these products to meet current military fuel specifications will be substantial if not prohibitive. Thus, the quality of fuel is expected to deteriorate over the next few decades, with serious implications for the maintenance and reliability of engines. Chapter 8 discusses in detail the problem of fuel quality and its implications.

## U.S. Consumption

Figure 3-3 adds the history of U.S. consumption to the production curve. The graph illustrates that, at a time when production was beginning to drop, domestic consumption continued to grow steadily. Therefore, it was necessary to expand the import levels to cover the shortfall. The sharp peak in consumption in 1977 at 19 mmb/d and the anticipated reduction to levels ranging from 13 to 15 mmb/d by the year 2000 reflect the effect on demand of higher oil prices and slower

economic growth. Exxon and Texaco are forecasting year 2000 consumption at 15 mmb/d, but the Department of Energy's midrange estimate is 13 mmb/d [34]. This picture indicates that consumption will fall, but not as rapidly as the production of conventional oil. Thus, import levels could be reduced only by accelerating the production of synthetics or by cutting consumption even more drastically.
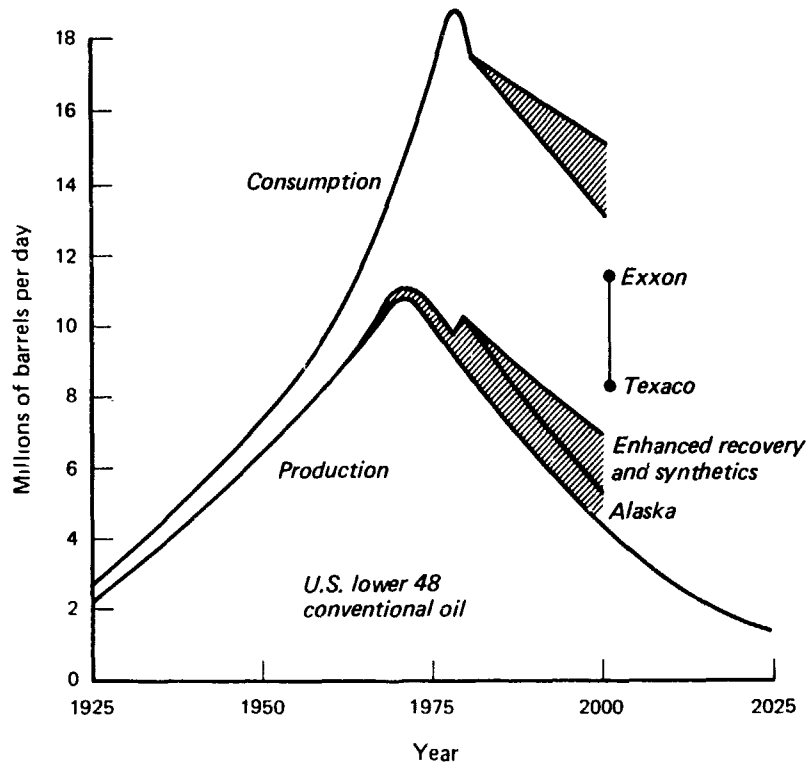


*Source: [27, 29, and 31-34]*

**FIG. 3-3: U.S. OIL PRODUCTION AND CONSUMPTION**

WORLD PRODUCTION

Figure 3-4 depicts two projections of the production of world oil and oil substitutes and gives some perspective on U.S. production. One curve was drawn by the Energy Editor of the Financial Times (London) in 1979 to show the trends of a bell-shaped production curve [35]. As the curve suggests, there are substantial quantities of unproduced oil. In addition to the estimate of 1.6 trillion barrels for the remaining conventional oil, heavy oil from enhanced recovery and synthetics from shale and coal will greatly increase the total quantities of liquid petroleum that will be eventually produced [36]. However, these additional resources will be more difficult to refine and to use.

Note
The U S curve is from
figure 3-2.

Exxon

Synthetics

Conventional oil

Heavy

Consumed

U.S. lower 48
conventional oil

Millions of barrels per day
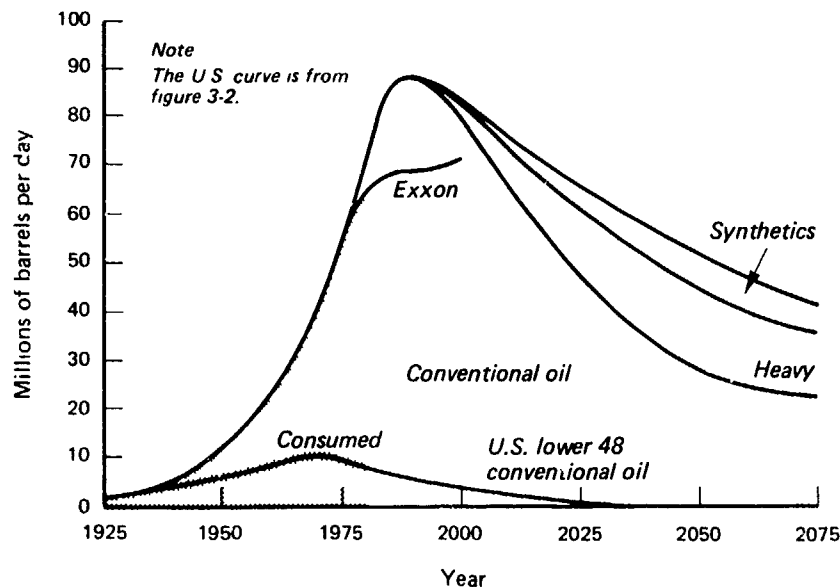
Year

Source. [29, 32, and 35].

FIG. 3-4: PROJECTIONS OF WORLD OIL PRODUCTION

## Alternative Production Peaks

In contrast to the peak in world oil production in the 1990s suggested by one curve, Exxon projects a lower, flatter plateau extending to the year 2000. This view reflects the effect of higher prices and slower economic growth.

A family of production curves, each having its own peak, could be drawn that would allow for different patterns of future oil demand and exploratory drilling rates. Assuming the world will not experience widespread economic stagnation, the Exxon projection of 1-percent-per-year growth in demand will not force world oil production against a physical ceiling until after the year 2000. However, if demand growth rates are 3 percent or more per year, world production of conventional oil is likely to peak and begin a decline before the year 2000 [37].

## Distribution of Reserves

One of the important features of world oil production is its unequal distribution. The world's significant reserves are concentrated in a small number of countries, with current world production dominated by a few giant fields out of hundreds of producing fields. For example, in 1975, 42 percent of the world's production of oil came from 33 giant

3-9

fields—25 are in the Middle East, 2 each in the U.S. and the USSR, and 1 each in Algeria, China, Libya, and Venezuela [37]. Future discoveries are unlikely to significantly alter this dominance of a few producers. For example, studies by Richard Nehring of the Rand Corporation estimate that the Persian Gulf region contains over 50 percent of the world's ultimately recoverable conventional oil [25].

FORECAST FINDINGS

The gap between the pessimistic and optimistic views of the energy future has been reduced by this analysis. A drop in demand will alleviate the pressures on production. However, demand is unlikely to drop so rapidly that a peak in the world production of conventional oil can be postponed much beyond the year 2000. Using more petroleum substitutes will help delay the time of peak production, but will bring additional problems of quality and cost.

The following points summarize this study of the forecasts:

- The production of conventional oil in the U.S. is estimated to have peaked in 1970. Petroleum-like liquids from shale, coal, and heavy oil are expected to slow, but not reverse, the overall decline in U.S. production of petroleum products.

- The production of conventional oil worldwide is expected to reach a ceiling around the year 2000.

- The U.S. and other Western industrialized nations will continue to import large quantities of petroleum for the foreseeable future.

- Because of estimates that from 50 to 60 percent of the remaining ultimately recoverable conventional oil is in the Persian Gulf region, that area will be just as important in the year 2000 as it is today.

- For the next few decades, major nonnuclear mobility fuels will be produced from petroleum, heavy oil from enhanced recovery techniques, and synthetic liquids from shale and coal. Because these primary products will vary widely in quality, fuel of low quality will be more prevalent.

- With 1.6 trillion barrels of recoverable, conventional oil remaining, plus synthetics and heavy oils, the world is not going to run out of oil suddenly. However, the conditions of that availability will require significant changes in the way hydrocarbon fuels are produced and used.

CHAPTER 4

OIL SUPPLY INTERRUPTIONS


Interruptions in the supply of petroleum to the world market during
the 1970s demonstrated the extent to which the U.S. and the industrial
West had become vulnerable. The preconditions of that vulnerability
included rapidly growing rates of oil consumption, the concentration of
the remaining petroleum resources among a few key producers, heavy
reliance on imports, and, in the case of the U.S., the loss of its
earlier capacity to expand domestic oil production significantly.

Future import interruptions are a near certainty. This chapter
provides a perspective on that problem by describing the ways interrup-
tions of oil supplies can affect the Navy and possible measures that
might be taken by the Navy's leadership.

DETERMINANTS OF SEVERITY

As in the past, future disruptions in the supply of oil will stem
from economic warfare or from some circumstances within a producer
state. Some historic examples are cited below:

Economic warfare

Anglo-American embargo against Japan--1941
Destruction of tankers--World Wars I and II
Attacks on refineries--World War II, Iran-Iraq War 1980
Arab oil embargoes--1946, 1957, 1967, 1973.

Other causes

Nigerian civil war--1967-70
Iranian Revolution--1978 and 1979
Terrorist attacks on pipelines--Trans-Arabian Pipeline, 1971
Reduced production for conservation--Saudi Arabia, Kuwait,
and others
Reduced production for price increases--OPEC and others.

Worldwide Effects of Interruptions

In contrast to the relatively small effects of oil supply disrup-
tions in the 1950s and 1960s, interruptions in the 1970s had serious
worldwide effects. The emphasis is on worldwide because the "oil
weapon" has turned out to have very low selectivity with respect to
specific targets. Whether arising from embargoes, revolutions, or
production quotas, oil shortages in the 1970s have indiscriminately
damaged most of the world's petroleum importers by destabilizing prices.

With the world's largest economy and as the largest user of petroleum, the U.S. has been hit particularly hard. The U.S. has lost its capacity to expand domestic production of petroleum [38]. A decade earlier, a Cabinet-level task force had estimated this excess capacity at 3 mmb/d [39]. Additional evidence from the previous chapter (see figure 3-2) supports the view that U.S. production had peaked by 1970 and is now in decline.

The implications are clear. The U.S. and other industrial nations will continue to be vulnerable as long as they require substantial imports from a market dominated by a few producers. By increasing or decreasing the quantities of petroleum they produce, the exporting countries can influence, if not manipulate, market prices and national policies.

Even when world stocks of petroleum are at high levels, as in mid-1981, the underlying conditions for U.S. vulnerability still remain. Lower fuel prices can even increase the nation's vulnerability by reducing the urgency to implement conservation and substitution measures.

## Size and Length of Disruptions

Judging from the history of disruptions and the importance of imported petroleum to the industrial nations, future disruptions are a near certainty. It is the size and the length of the disruptions that are highly uncertain and will be major determinants of severity.

One planning paper of the Department of Energy presented alternative probabilities of interruptions by size and duration. Their mid-range scenario, established for purposes of contingency planning, used the numbers in table 4-1.

When both recent experience and the volatile conditions in the Middle East are considered, the numbers in table 4-1 may be reasonable. The 3-, 10-, and 20-mmb/d levels correspond to the loss of production from Iraq, Saudi Arabia, and the Persian Gulf, respectively. In comparison, table 4-2 shows the magnitude of the past two disruptions. The shortages and associated percentages shown are measured from data on world production for the month before the crisis.

In both historic cases, the excess productive capacity of other suppliers and their willingness to use that capacity determined the net loss to world markets. Saudi Arabia and other producers stepped up production and made up most of the deficit caused by Iran in 1979. In the 1973 and 1974 embargo, however, Iran and others were unable to offset the Arab-induced shortages.

TABLE 4-1

SIZE OF DISRUPTION LASTING 1 YEAR
VERSUS PROBABILITY OF OCCURRENCE IN 10-YEAR PERIOD

| Size (mmb/d) | Probability (percent) |
|---|---|
| 3 | 75 |
| 10 | 30 |
| 20 | 5 |

Source: [40].


TABLE 4-2

DURATION AND SIZE OF DISRUPTIONS TO THE WORLD PETROLEUM MARKET

| Event | Duration (mo) | Maximum monthly shortage[a] | | Average net shortage | |
|---|---|---|---|---|---|
| | | Size (mmb/d) | Percent of world | Size (mmb/d) | Percent of world |
| Embargo 1973 and 1974 | 5 | 4 | 8 | 2 | 4 |
| Iranian Revolution 1978 and 1979 | 6[b] | 2 | 4 | 1 | 2 |

Source: [38 and 41].

[a]See appendix A for tabular data on world production during the two crises.
[b]Iranian Revolution has continued longer, but significant shortages in oil supplies occurred in the first 6 months.

Table 4-2 also shows how small the actual net reductions were on average; yet, the economic effects in the non-Communist world were very large.

The effects of interruptions on the future economy could surpass the past adversities discussed in chapter 2. If 3 mmb/d were removed from the world market of the 1980s, U.S. imports might be cut by 0.5 mmb/d with an annual GNP loss estimated at $85 billion [40]. If 10 mmb/d were lost--the equivalent of Saudi production--the U.S. share might be about 2 mmb/d. The Congressional Budget Office estimated that a 2-mmb/d loss in U.S. imports would reduce the GNP for 1984 by $146 billion in that one year [42].

## DETERMINANTS OF PETROLEUM AVAILABILITY FOR THE NAVY

Disruptions in the world's petroleum supply will inevitably affect the Navy's supply of fuel. The evidence and some of the effects on the Navy of past disruptions were presented in chapter 2. The remainder of this chapter develops some of the determinants of future availability and their effects on the Navy.

Disruptions in petroleum supplies can affect both the early availability of fuel and long-term cost to the Navy. Investigating petroleum interruptions in the 1970s failed to identify any significant examples of a complete cut off of military fuels. Nevertheless, early in a crisis, fuel could be cut off or at reduced levels of availability for a number of reasons. As noted earlier, commanders may reduce their operations because they are uncertain about the length of the interruption and they anticipate higher priority missions. Fuel levels may also be reduced because suppliers are either unwilling or unable to provide military products. Currently, the Department of Defense has contracts with about 20 suppliers overseas and 60 in the U.S. [43]. Fuel may also be unavailable because of the failure of either the user service or the Defense Fuel Supply Center (DFSC) to anticipate military requirements. Foreseeing such requirements, arranging for timely tanker support, and positioning stocks where needed are enduring management problems.

Although fuel may be unavailable for short periods and in specific locations, it is difficult to envision situations in which it would be unavailable for any significant period during a crisis. The reasons for this judgment include: the high levels of domestic production relative to DoD requirements, the existence and planned expansion of military and civilian petroleum stocks, governmental powers both to acquire and to allocate the resources it needs, and the high priority usually extended to national security activities.

## Domestic Production

The U.S. has and will continue to have for several decades the domestic productive capacity to provide the Department of Defense with

its fuel requirements during a severe crisis or a war. However, it is apparent that the burden on the civil sector would be heavy and could not be sustained for long without substantial imports and domestic stockpiles.

Table 4-3 shows Defense and Navy levels of petroleum consumption for peacetime, crisis, and wartime operations. These estimates assume that crisis-level operations are 133 percent of 1980 operating levels and that wartime operations are 300 to 400 percent of the 1980 levels.

TABLE 4-3

ALTERNATIVE DEFENSE FUEL CONSUMPTION
(Millions of Barrels per Day)

| Consumption by a 1980 force | DoD | Navy |
|---|---|---|
| Routine peacetime | 0.46 | 0.16 |
| Crisis level[a] | 0.61 | 0.21 |
| Wartime[a] | 1.38-1.84 | 0.48-0.64 |

[a]Source: [44].

The U.S. production of liquid petroleum in 1980 was 10 mmb/d, but it is projected to drop to about 6 to 8 mmb/d by the year 2000. Even if all imports of oil were somehow lost, domestic production could still meet defense needs. Table 4-4 shows year 2000 estimates of the direct defense burden on U.S. petroleum supplies under different assumptions about import interruptions and the availability of reserve stocks. Under these scenarios, defense needs are expressed as a percentage of the available supply in the U.S. They range from 3.8 to 7 percent in peacetime and from 15 to 29 percent in wartime.

Reserve Stocks

In addition to domestic production, both the Government and the private sector hold reserve stocks of crude oil and products that would be available to help offset an import interruption. Table 4-5 sho . the approximate U.S. holdings of petroleum in mid-1981. Although comme cial stocks are the largest quantity in this table, only about 25 perce1 . of the 1 billion barrels is considered usable by industry standards because

4-5

TABLE 4-4

DEFENSE PETROLEUM CONSUMPTION IN YEAR 2000
RELATIVE TO U.S. SUPPLIES

| Scenario | Supplies (mmb/d) | | | | DoD usage as a percent of U.S. supplies | |
| --- | --- | --- | --- | --- | --- | --- |
| | U.S. production | Imports | Reserve drawdown | Total | Peacetime[a] | Wartime[b] |
| Best case[c] | 7 | 6 | 0 | 13.0 | 3.8 | 15 |
| Partial interruption | 7 | 3 | 1.5[d] | 11.5 | 4.3 | 17 |
| Complete interruption | 7 | 0 | 1.5 | 8.5 | 5.8 | 24 |
| Worst case[e] | 7 | 0 | 0 | 7.0 | 7.1 | 29 |

[a] DoD consumption of 0.5 mmb/d.
[b] DoD consumption of 2.0 mmb/d.
[c] Best case assumes no interruption of imports and a peacetime demand of 13 mmb/d.
[d] Average rate of drawdown to empty a reserve of 550 million barrels in 1 year.
[e] Assumes exhausted reserves and complete interruption of imports.

of the need to maintain pipelines and feedstocks at minimum levels
[45]. In the case of the Strategic Petroleum Reserve (SPR) and holdings
by the Department of Defense, 95 percent or more may be usable [43].

TABLE 4-5

U.S. PETROLEUM STOCKS[a]
(Millions of Barrels)

|  | Total | Probably usable |
|---|---|---|
| Commercial stocks (crude and product) | 1,000 | 250 |
| SPR (crude) | 160 | 150 |
| Defense stocks (product) | 100 | 95 |

Source: [45 through 47].

[a]Holdings in June 1981.

Endurance of reserves. In the unlikely event that 6 mmb/d of U.S.
imports are interrupted, the usable stocks shown in table 4-5 could
offset the import losses for about 3 months. However, import inter-
ruptions are more likely to be smaller--perhaps in the 0.5- to 3-mmb/d
range--so that stocks would last longer. Figure 4-1 estimates endurance
at alternative stock levels for the year 2000.

When coupled with estimates of U.S. domestic production, these data
suggest that U.S. stocks could meet both defense and civilian needs for
a few months and alleviate the upward pressure on oil prices. If import
crises were frequent and stock levels were low, however, both the eco-
nomic effects and the constraints on military operations could be far
greater. Also, the possible demands of international sharing agree-
ments, such as the one mentioned earlier under the International
Emergency Agency (IEA), add uncertainty about the duration of U.S.
stocks. During an import interruption, the SPR would be important under
any circumstances.

Strategic Petroleum Reserve. The Congress established the SPR to
help offset the severe economic effects of import interruptions [42].
Its authorized capacity is 1 billion barrels, but the program has been
plagued by intermittent funding shortages, and there is some uncertainty
about its reaching the authorized goal.

4-7

Millions of barrels

| Stocks | High | Low |
|---|---|---|
| DoD | 140 | 100 |
| Industry | 500 | 200 |
| SPR | 750 | 250 |
| Total | 1,390 | 550 |

U.S. stocks
1,390 million barrels
550 million barrels

Shortfall (millions of barrel per day)

6 months    15 months

Endurance (months)
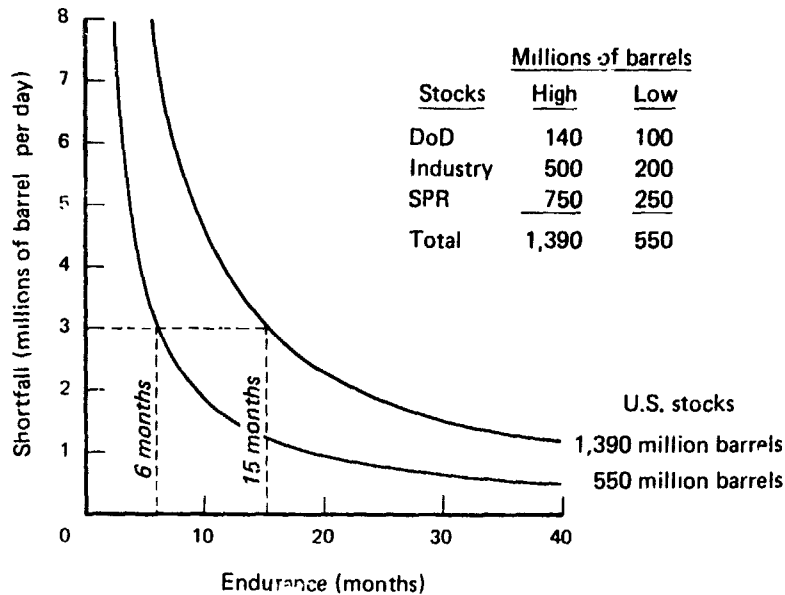
**FIG. 4-1. ENDURANCE OF U.S. OIL STOCKS DURING AN IMPORT INTERRUPTION IN YEAR 2000**

To be effective, the SPR must contain sufficient reserves so that the Government is willing to use them early in a crisis of uncertain length. It must also be able to withdraw the reserves at an adequate rate to offset losses from an import interruption. The withdrawal rate is the distinguishing advantage of the SPR over the earlier concept of reserving oil fields and keeping the oil in the ground. The current withdrawal capability of the SPR is about 1 mmb/d. The planned capability, associated with a 750-million-barrel capacity, is about 4 mmb/d [48].

As shown in table 4-6, a reserve of 750 million barrels could offset a 3-mmb/d interruption for up to 8 months. Once depleted, however, the SPR could take years to refill. Thus, the U.S. economy would become more vulnerable.

Allocation Powers

The general concern of Defense managers over the future availability of fuel was intensified in 1979 when the DFSC was unable to contract for all of its requirements. As noted earlier, Defense fuel stocks fell below acceptable levels as war reserve stocks were used to keep up an adequate level of operations. Most of the problems of inadequate government procurement practices reportedly have been corrected.

4-8

The Government can take certain measures to meet defense needs, such as allocating petroleum products by invoking the Defense Production Act of 1950. Although this Act was criticized as ineffective in 1974 [43], it has been improved. Domestic refiners can be required to make prompt delivery of petroleum products to Defense users [49]. In addition, the Congress could legislate new measures to ensure that the military services get the petroleum products they need.

TABLE 4-6

STRATEGIC PETROLEUM RESERVE
(Total:   750 Million Barrels)

| Fill rate (b/d) | Time to fill (yr) | Drawdown rate (mmb/d) | Time to deplete (mo) |
|---|---|---|---|
| 100,000 | 20 | 4 | 6 |
| 200,000 | 10 | 3 | 8 |
| 300,000 | 7 | 1 | 25 |

In brief, the Department of Defense has access to a range of market and nonmarket mechanisms for procuring fuel under a variety of shortage conditions. These measures are set forth in the Defense Energy Emergency Management System (DEEMS) [49].

The uncertainty deals not so much with the measures for acquiring fuel, but with the timely and effective administration of these measures. During a minor interruption comparable to the two crises in the 1970s, political reluctance to employ the acquisition powers available and the uncertainty about the length of the crisis may lead Defense managers to cut their own operations to conserve fuel—as has been done in the past [17].

National Priorities

National security has a priority claim on the nation's resources. In the face of a clear threat, the necessary resources, including petroleum, would be made available—by mobilization if necessary. The problems arise when the threat is ambiguous and there is a lack of national consensus on the appropriate level of support for the nation's defenses. Two examples are cited below in which an equivocal popular support could result in reduced availability of petroleum and other resources important to Navy operations.

One arises from the adverse effects of oil shortages on the economy. With fewer total goods and services produced, it would be more difficult for Defense to obtain resources. In this indirect way,

petroleum shortages would continue to affect adversely both the size and the operation of naval forces.

Petroleum shortages might also constrain a foreign-policy initiative or the conduct of warfare. The tolerance of the American people for possible fuel rationing--whether by substantially higher prices or by administrative allocations--is uncertain and depends on the circumstances. In contrast with the public support of rationing in World War II, fuel rationing in the future could become an additional pressure on the Government if coincident with an unpopular foreign-policy initiative or an unpopular war. At the height of the Vietnam War, less than 1 percent of the adult population was affected by conscription. In contrast, the "conscription" of fuel would affect virtually every citizen.

Under these hypothetical circumstances, the Government would most likely attempt to resolve the conflict quickly, either through escalation or by submission. Either outcome would have significant implications for the conduct of warfare, the associated naval operations, and the availability of military fuels.

EFFECTS ON THE NAVY

The effects of future import interruptions on the Navy are likely to be similar to those experienced in the 1970s. Fuel may be temporarily at reduced levels of availability. However, even with a cutoff of all imports, the nation's domestic production, planned reserve stocks, and allocation mechanisms are adequate to provide the military forces with petroleum products if the nation's leaders give them the priority normally extended national security activities. Less urgent and training missions may be particularly vulnerable to severe market disruptions.

Because of the potentially severe consequences of petroleum shortages on the civil economy and on the tolerance of the public for fuel rationing, the pressures on the Government for decisive actions during an import interruption are apt to be great. Under these circumstances, the Navy could be called on to increase its level of operations to support political or military objectives, thus using more fuel for very important operations.

The Navy can help protect itself from some of the short-term, adverse effects of interruptions by ensuring that the mechanisms for Defense to acquire fuel are effective and by supporting larger civil and military reserves of both crude oil and refined products.

Recent history indicates that the more enduring problem of future disruptions will be the higher cost of fuel. At planning and programming levels in the Navy, the requirement to conserve and to manage fuel efficiently is likely to be viewed as a problem of affordability. The

same problem may be seen by the operators in the fleet as being one of
reduced availability. Whether from the standpoint of affordability or
availability, coping with the long-term effects of the fuel constraint
will require every management technique to deal with a scarce resource—
including effective conservation programs. These measures are addressed
in chapters 6 through 9.

CHAPTER 5

FUEL AVAILABILITY AND NAVY OPTIONS


Navy planning and programming can be significantly influenced by what decisionmakers see as their prospects for fuel supplies. This chapter briefly summarizes these prospects, suggests the urgency for additional management action, and lists a range of Navy measures for dealing with the problems arising from greater scarcity of petroleum. These measures are developed further in chapters 6 through 9.

THE FUTURE OF PETROLEUM FUELS: AN INTERPRETATION

The availability of petroleum has been evaluated from geologic and economic perspectives and from the viewpoint of import interruptions. From those evaluations, three problems facing the Navy have been identified--the cost, availability, and quality of petroleum products. Over the next 20 years, all three problems will become more severe.

The cost of fuel has been discussed as that of a higher priced resource. Some of the past effects of higher real prices were described in chapters 2 and 4. Petroleum fuels are expected to cost even more in the future as world production of conventional oil reaches a peak and as substitutes for conventional products enter the market. As a consequence, the day-to-day management of expensive fuel is likely to be one of the more enduring and challenging problems fac.ng the Navy's leadership over the long term.

The discussion of the availability of fuel nas depended on the context but generally refers to access to fuel as if price were not a factor. Some of the circumstances leading to reduced availability or to the absence of supplies were treated in chapter 4. In future interruptions, delivery of fuel to military forces could be curtailed whether fuel is allocated by the government or by market prices. While the reduced availability of petroleum is unlikely to impair important military operations for any extended period, routine operations and training may suffer more. The long-term effects of interruptions can make the problem of cost even worse.

The quality of fuel determines how well a petroleum-derived fuel burns relative to a well-retined product from conventional crude oil. The quality of fuel available to the Navy is expected to decline as more high-sulphur crudes and synthetics derived from coal and shale are processed. This decline will add further to the cost problem.

OPTIONS

The above assessment of future petroleum supplies identifies a problem that will be enduring, pervasive, and serious. The problem will

endure until petroleum-like substitutes or completely different fuels
are commonplace. The problem is pervasive because it affects nearly all
aspects of energy-dependent naval operations. It is serious because of
its demonstrated and potential costs.

Three possible levels of emphasis for the Navy's leadership to deal
with petroleum and other energy-related issues are business as usual,
accelerated adjustments, and crash programs.

If the optimistic view of rapid and drastic reductions in world
demand for petroleum suggested by some in chapter 3 proved to be
correct, a business-as-usual response would be appropriate. A crash
program would be the appropriate response if the doomsday view of near-
term depletion were correct. Our interpretation of the petroleum prob-
lem argues for a level of management attention that clearly transcends a
business-as-usual attitude, but considers an extensive crash program to
be unnecessary at this time.

The specific measures available to the Navy to manage its energy
future fall into two broad categories. Emphasis can be placed on those
measures that reduce the consumption of petroleum, and/or effort can be
directed at increasing the Navy's access to the available petroleum
fuels. Specific measures under each approach are listed below. They
address different aspects of the triple threat of cost, availability,
and quality.

Reduce Consumption of Petroleum

- Make existing and planned systems more fuel efficient.

- Reduce the operating tempo of the fleet.

- Reduce force levels.

- Rely more on substitute systems that are less fuel
  intensive.

- Develop alternative fuels.

Increase Access to Available Petroleum

- Obtain larger Defense budgets.

- Obtain a larger share of the total Defense budget.

- Change fuel specifications.

- Design engines to accept lower quality fuel.

- Increase petroleum reserves.

Most of the above measures have received attention within the Navy, the Office of the Secretary of Defense, or the Department of Energy. Chapters 6 through 9 evaluate aspects of the above measures for their potential to receive more emphasis from management.

CHAPTER 6

MEASURES TO REDUCE PETROLEUM CONSUMPTION:
CONSERVATION AND PROGRAM REDUCTIONS


This chapter addresses the first three of the measures that can contribute to the reduction of fuel consumed by the Navy. They are conservation efficiencies and program reductions in both operations and force levels. The purpose is to describe briefly the measures and their potential for management action in the future.

CONSERVATION

Conservation is the wise use of fuel. It reduces the amount of fuel normally consumed while keeping to a minimum interference with the structure, size, or tempo of operations of naval forces.

The Navy used 36 percent less petroleum in 1980 than in 1973, the year of the embargo. However, most of that reduction, which amounted to 35 million barrels, was the result of smaller forces and a winding down of the Vietnam War--not efficiency improvements. In 1980, a reduction of about 3.3 million barrels, worth about $200 million, could be attributed to the more efficient use of fuel by ships, aircraft, and the shore establishment [3].

Goals

Further savings from conservation are expected. Using consumption in 1975 as the base year for calculating conservation, the Navy has established goals for 1985. If reached, current Navy goals for 1985 should yield a total annual savings of 13 million barrels of fuel, worth about $1 billion in 1981 constant dollars. These planned savings are expected to come mainly from [3]:

- Aircraft--1.3 million barrels

- Ships--4.0 million barrels

- Shore establishment--7.4 million barrels of oil-equivalent (mmboe).

Aircraft

Conservation in aviation is measured by the reduction in fuel consumed per flight hour. The 1985 goal is a 5-percent reduction below 1975 levels. It was attained in 1980 with savings mainly from improved flight planning and from more efficient refueling operations. Further savings are expected from engine and airframe modifications and greater use of simulators [3].

## Ships

Conservation in ships is measured by the reduction in fuel used per underway steaming hour. By 1980, little progress had been made toward the 1985 goal of a 20-percent reduction for ships. However, as table 6-1 shows, substantial savings are expected from drag reduction methods and more efficient fuel combustion. Other modifications with energy-saving potential under study are waste heat recovery systems and smaller propulsion plants for cruise [50].

TABLE 6-1

PROJECTED FY 1985 UNDERWAY FUEL SAVINGS
FOR THE EXISTING FLEET

| Procedure or modification | FY 1975-85 fuel reduction (percent) |
|---|---|
| Underwater hull cleaning | 8.6 |
| Naval boiler combustion optimizer | 5.1 |
| Machinery performance monitoring | 1.6 |
| Standby main feed pump | 1.5 |
| Low-excess air burners | 1.3 |
| Water resource management | 1.0 |
| Improved economizer | 0.9 |
| Total | 20.0 |

Source: [3].

## Shore Establishment

Shore facilities yielded fuel savings of about 1.7 mmboe in 1980. Greater use of alternative solid fuels, more energy-efficient designs for new buildings, and waste reduction measures in older facilities are expected to meet the 1985 conservation goals. With command attention, the shore establishment can yield substantial savings through conservation and can help redistribute petroleum from consumption ashore to the mobility users.

## Simulators

Using simulators to augment training has great potential for saving fuel. The Navy is just beginning to employ simulators for ships with the introduction of an FFG-7 training simulator, although "fast cruise"* training methods have been used for years.

The Navy now uses aircraft simulators more extensively than it did in the past. In 1980, simulators saved the equivalent of about 8 percent of the fuel used by aircraft in 1975. With operating costs of about 5 to 20 percent that of comparable aircraft [51], simulators are cheaper to operate than aircraft. However, their greatly expanded use in the future is controversial for combat training. Although additional savings with advanced simulators are likely, the minimum number of actual in-flight hours required to maintain pilot readiness must be determined.

## Energy-Management Problems

Figure 6-1 shows the organizations responsible for managing the Navy's energy programs. Alternative organizational arrangements were not addressed in this study. However, three needs confront any management of energy-related issues in the Navy:

- Comprehensive planning information on the Navy's energy consumption, including the nuclear aspects

- Sustained support for a Navy research and development (R&D) program in energy

- Incentives to adopt conservation measures.

The organizations in figure 6-1, charged with managing the Navy's energy programs, are limited to looking only at conventional fuels. This is a direct result of the division between the nonnuclear and nuclear Navy. A consequence is that information is fragmented; it is more difficult for the CNO to get a complete view of his energy problems and options. A more effective structure would have access to all the relevant information for decisionmaking—including the nuclear aspects of the choices.

A second issue is continued support for a Navy R&D program in energy. Leadership support is needed to keep of the current modest program ongoing when fuel is temporarily plentiful and to overcome views that somehow energy R&D is not directly relevant to Navy hardware. Keeping abreast of developments in fuels and related technology and

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* When the crew simulates at-sea operations while the ship is at the pier, it is called a "fast cruise."
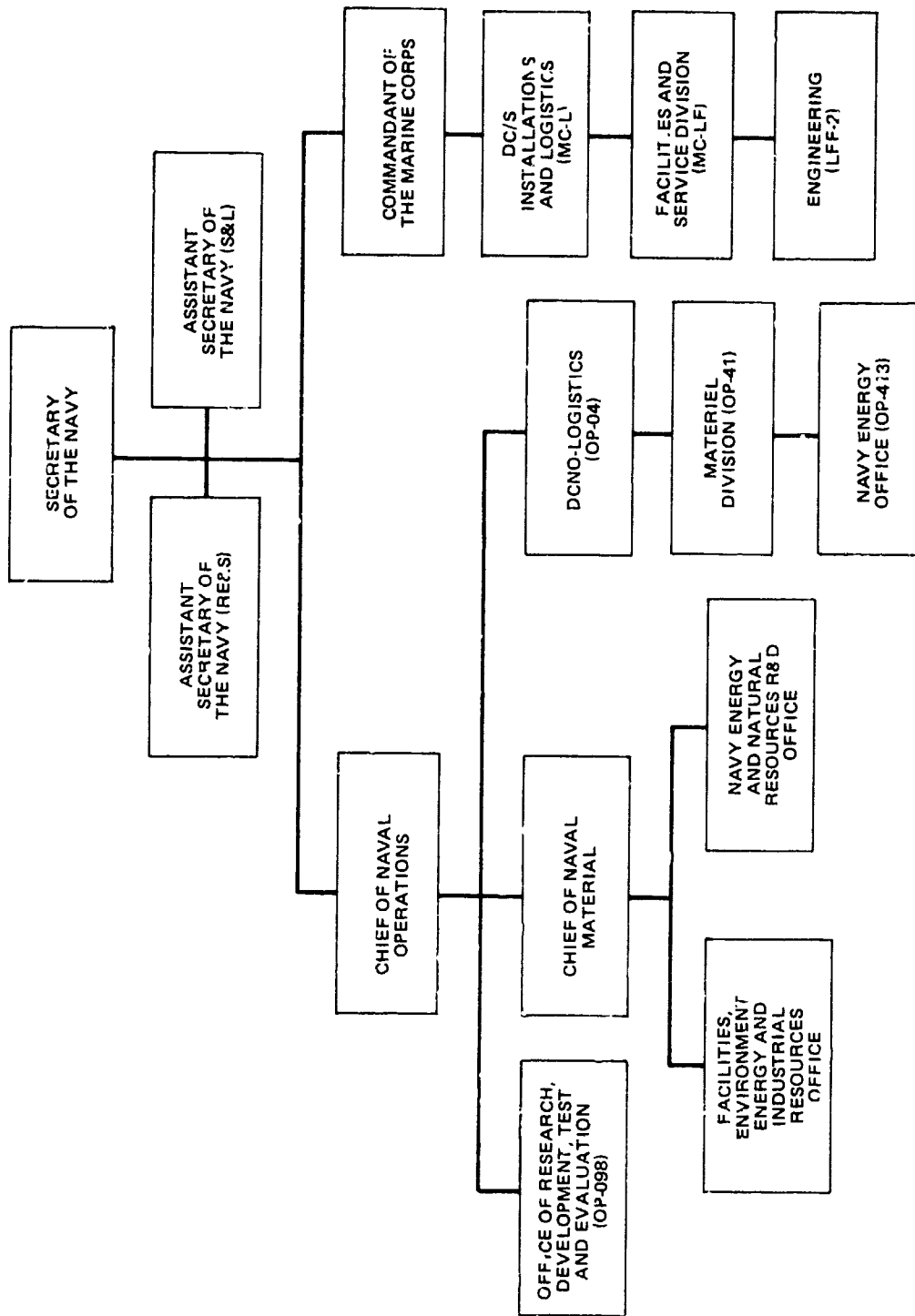
FIG. 6-1: DEPARTMENT OF THE NAVY ENERGY MANAGEMENT ORGANIZATION

Source: [52].

having the technical base to adapt the Navy to changing fuel supplies will become even more important in the future.

A third and related issue is the difficulty of implementing energy initiatives. Long-term energy issues may not seem as important or relevant as today's concerns because of rosy views of future supplies of petroleum. Another and more likely reason is that the structure of incentives is oriented to near-term payoffs, and serious energy conservation is not one of them. The problem is common to most large organizations whose budget is mostly determined by someone else. When managers do not have to pay for the resources they use, such as fuel, and are judged primarily by their output or their level of effectiveness, they have less incentive to conserve resources. Under these circumstances, effective energy management depends on the support of the Navy's leadership.

Through effective conservation, the Navy will realize large potential savings. Equally important, conservation will probably be the least painful way to deal with the constraints of higher priced petroleum in the future.

PROGRAM REDUCTIONS

Two additional ways to reduce fuel consumption are to operate less or to buy a smaller force. Both operations and force levels have been reduced since 1973, with some of the reductions due to higher prices for fuel. The effect of even higher fuel prices on year 2000 operations and force levels was estimated with assumptions about future prices, energy conservation, and fleet consumption set forth below.

Projected Fuel Prices

Lower real prices for fuel could result for a period if recessionary economic conditions prevail. However, the more likely outcome over the long term is for fuel prices to rise.

In this study, three alternative price increases are assumed for the year 2000. They are 50-, 150-, and 500-percent real increases above the October 1980 level for a barrel of a composite of DFM and JP-5. As illustrated in figure 6-2, these equate to about 2-, 5-, and 10-percent real annual increases over 19 years.*

Large price increases in the future are apt to occur as in the past—with sudden jumps or shocks. The smooth curves in figure 6-2 are used for analytic purposes; they do not convey the precise way fuel prices will rise.

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* The precise annual increases are 2.16, 4.94, and 9.89 percent compounded for 19 years from a base of $52.50 per barrel.
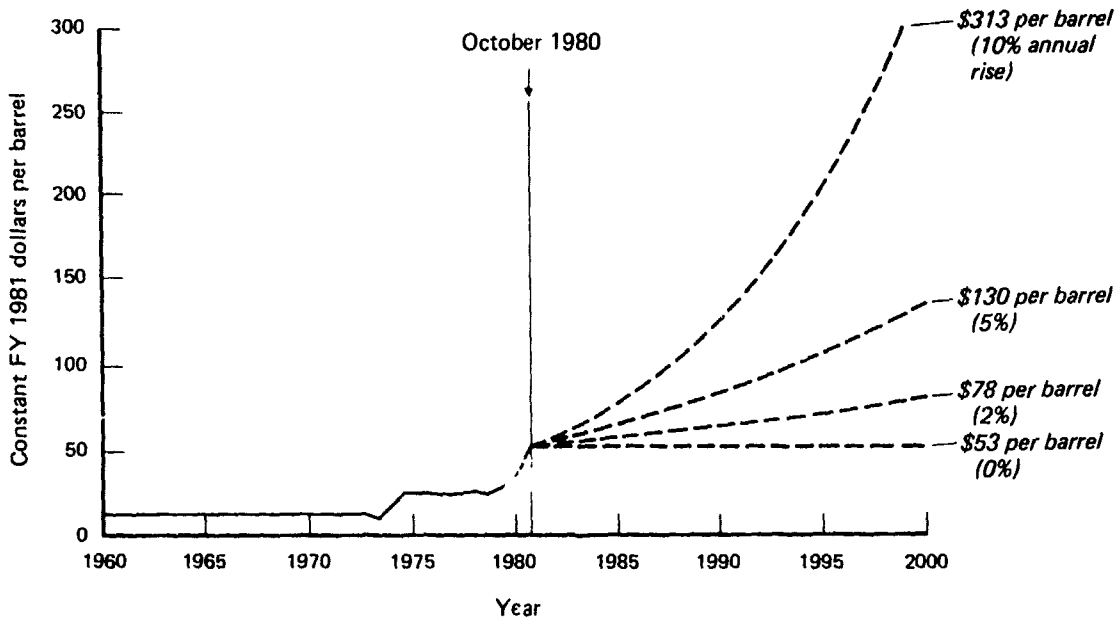
**FIG. 6-2: NAVY FUEL-PRICE HISTORY AND PROJECTIONS**

For comparison purposes, some econometric models used an increase in fuel prices of 5 percent above inflation. The Saudis have urged a steady price rise in the 2- to 3-percent range [15]. Although the 10-percent case may appear unrealistically high, prices actually rose at an equivalent annual rate of 8 percent from 1960 to 1981 and at 23 percent from 1973 to 1981.

## Reduced Operations Due to Price Increases

Figure 6-3 shows what the potentially devastating effects of higher fuel prices on the operating tempo of the fleet in the year 2000 will be if the fuel budget stays at a level to support current operations at current prices. With no price increase, 100 percent of the 1979 steaming and flying hours can be maintained. As the real price of fuel increases, however, the fuel available to sustain that tempo of operations will decrease.

The benefits of conservation are shown by the shaded areas in figure 6-3. The conservation achieved by the year 2000 was assumed to be 20 percent for ships and 17 percent for aircraft below their respective 1975 levels of consumption.
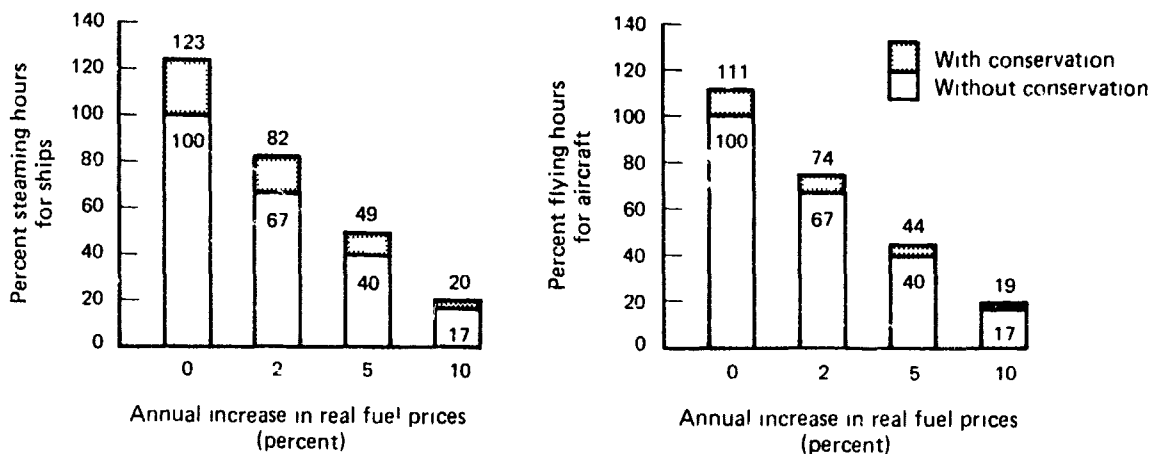
**FIG. 6-3: YEAR 2000 OPERATING TEMPO: EFFECT OF FUEL PRICE INCREASES**

## Fleet Fuel Consumption in Year 2000

Data for figure 6-3 were derived from the 1979 operating tempo and individual consumption rates of existing ships and aircraft [53]. Estimates were made for types that have not yet been added to the fleet. The Extended Planning Annex (EPA) to Program Objective Memorandum (POM)-82 [54] was used for the number of nonnuclear ships in FY 2000. Aircraft force levels were also obtained from EPA guidance, but the anticipated numbers of active squadrons were taken from the 1980 Naval Aviation Plan (NAP) [55].

Table 6-2 summarizes the expected fleet fuel consumption in year 2000 and the corresponding fuel costs. They are based on the October 1980 price of $52.50 per barrel and a force of 460 ships and 3,900 aircraft that individually operated at the same tempo as in 1979.*

The above estimates do not consider the naval expansion planned by the current Administration. It was estimated that by 1986, the augmented force might consume an additional 6 million barrels per year over the consumption in 1980 by ships and aircraft. That is about a 12-percent increase. The amounts in table 6-2 would also be increased.

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* See appendix B for additional details on the calculations. The listings for ships and aircraft are in [1].

TABLE 6-2

TOTAL FUEL CONSUMPTION AND COSTS FOR
FY 2000 SHIPS AND AIRCRAFT

| | Fuel consumption (millions of bbl) | | Fuel cost (millions of constant FY 1981 dollars)[a] | |
|---|---|---|---|---|
| | No conservation | With assumed conservation | No conservation | With assumed conservation |
| USN ships | 24.10 | 19.65 | 1,265 | 1,032 |
| USN aircraft | 13.01 | 11.71 | 683 | 615 |
| USMC aircraft | 4.57 | 4.11 | 240 | 216 |
| Training aircraft | 2.17 | 1.95 | 114 | 102 |
| Total | 43.85 | 37.42 | 2,302 | 1,965 |
| FY 1979 total | 47.6 | | 1,250[b] | |

[a] $52.50-per-barrel base price.
[b] $26.25 per barrel.

Force-Level Reductions Due to Price Increases

Another way to meet higher fuel prices is to buy fewer ships and aircraft. For example, with fixed budgets, procurement funds from ship-building and conversion, Navy (SCN), and aircraft procurement, Navy (APN), accounts could be diverted to maintain the tempo of operations. Figure 6-4 depicts the effect such a decision would have on force levels.

In the intermediate case of a 5-percent annual fuel-price increase, 24 notional ships and 610 average aircraft would be lost to the fleet. If conservation goals were met, they would avert an equivalent loss of about 7 ships and 90 airplanes. The 10-percent case would have even more severe consequences.

The long-term effects on Navy forces of deferring procurement of new systems would be even more severe than shown because new ships and aircraft would be lost. As a consequence, the fleet would have a higher average age.
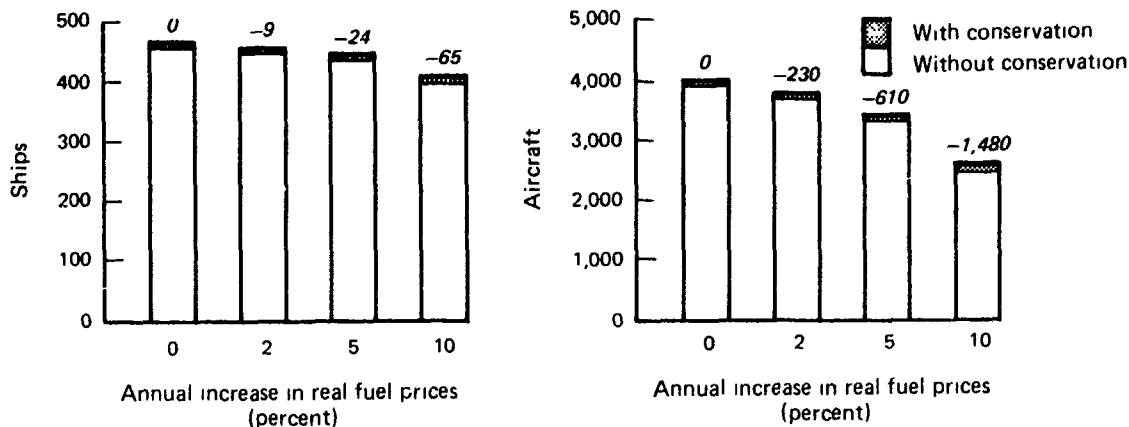
**FIG. 6-4:** YEAR 2000 FORCE LEVELS: CUMULATIVE REDUCTIONS DUE TO FUEL PRICE INCREASES FROM 1981 TO 2000

Figure 6-4 incorporated some additional assumptions. It was assumed that under conditions of no fuel price rises, new construction was just sufficient to offset attrition, so that force levels would remain the same over the period 1981 to 2000. With the active EPA and NAP force levels as the base, excess fuel costs above FY 1981 levels were then charged against the SCN and APN budgets. As new units were deferred for lack of funds, force levels dropped. The reductions each year were computed using the unit procurement cost of an average ship or aircraft, taken from the EPA and the Five-Year Defense Program (FYDP) [56]. Expressed in terms of constant FY 1981 budget dollars, the average ship cost $561 million and the average aircraft cost $18.2 million.

CHAPTER 7

SUBSTITUTION MEASURES:  AIRCRAFT AND SHIPS


Of the total petroleum used by the Navy in 1980, ships and aircraft consumed 45 percent and 40 percent, respectively. Thus, they are primary candidates for measures that reduce fuel usage. As discussed in chapter 6, fuel savings can come from efficiency improvements and from increased use of simulators to substitute for some in-flight and at-sea training. Savings can also come from greater reliance on different engines or completely different weapon systems that use less petroleum than existing ships and aircraft. However, large reductions in aviation fuel consumption can only come from reduced operations or as a byproduct of some long-term changes in the mix of naval weapons. Such changes would be motivated by larger cost-effectiveness considerations than just fuel.

This chapter discusses some of the substitution measures possible in ships and aircraft. Alternatives to perform the missions now covered by tactical aviation are addressed briefly, but most of the analysis is on nuclear propulsion in ships.

COMPLEMENTS AND SUBSTITUTES IN TACTICAL AVIATION

Further advances in cruise missiles could change the composition of the Navy. If missiles and other unmanned systems assume some of the missions now performed by tactical aircraft, substantial direct savings of fuel would be a result.

Although they have not been studied for their potential to save fuel, several possible alternatives to complement or to substitute for tactical air capabilities are listed below:

- Cruise missiles
    - Air launched
    - Surface launched
    - Submarine launched

- Surface-to-air missiles

- Artillery for the Fleet Marine Force

- Unmanned systems in surveillance.

The first two alternatives involve greater use of missiles. Direct fuel savings would be expected from building more performance into a missile system and less performance into the launching platform, assuming no loss of overall effectiveness. For example, a recent study by the Naval Weapons Center at China Lake [57] evaluated the potential

7-1

to substitute for tactical airpower. That study found cruise missiles to be more cost-effective than tactical aviation against heavily defended targets in a campaign using conventional weapons. The submarine, equipped with cruise missiles, was said to offer unique capabilities to initiate the offensive against land-based targets and to complement subsequent strikes by carrier aviation.

Savings might also be obtained by relying more on missiles for air defense and by increasing the proportion of artillery to close air support for direct fire support of the Marine Corps.

Finally, some fuel savings could result from greater reliance on unmanned surveillance systems such as satellites and remotely piloted vehicles (RPVs). For example, the F-4 is reported by Science magazine as using 20 times more fuel than an RPV in a similar surveillance mission [58].

In general, additional fuel savings in naval aviation will result from efficiency improvements, simulators, and reduced operations. However, large reductions in the use of aircraft fuel would result from some long-term changes in the mix of naval weapon systems that diminished the role of tactical aviation.

DIESEL ENGINES AND STEAM POWERPLANTS

Although the recent trend in propulsion has been toward shipboard gas turbines, diesel engines and even steam powerplants offer several advantages over gas turbines.

The advantages of diesel engines and steam powerplants are primarily in the areas of lower fuel consumption and lesser sensitivity to low-quality fuels. Figure 7-1 shows that for part-load operating conditions, diesels and steam plants have higher thermal efficiencies than a gas turbine. They are able to convert a greater percentage of the chemical energy stored in the fuel to useful work than a gas turbine can. This greater fuel efficiency extends for diesels over their entire operating spectrum. Diesels, particularly low-speed diesels, and steam plants can also be made more rugged and less sensitive to future fuels of degraded quality. This last important advantage is discussed more fully in chapter 8.

A disadvantage of diesels relative to gas turbines is their inability to match the great acceleration of gas turbines, which is useful for sprint purposes. Proposals are being considered to combine gas turbines with diesels to exploit the greater fuel efficiencies displayed by diesels during cruise operations (at about 15 to 20 percent of maximum power). Other combinations that pair propulsion systems optimized for different load conditions are also possible.
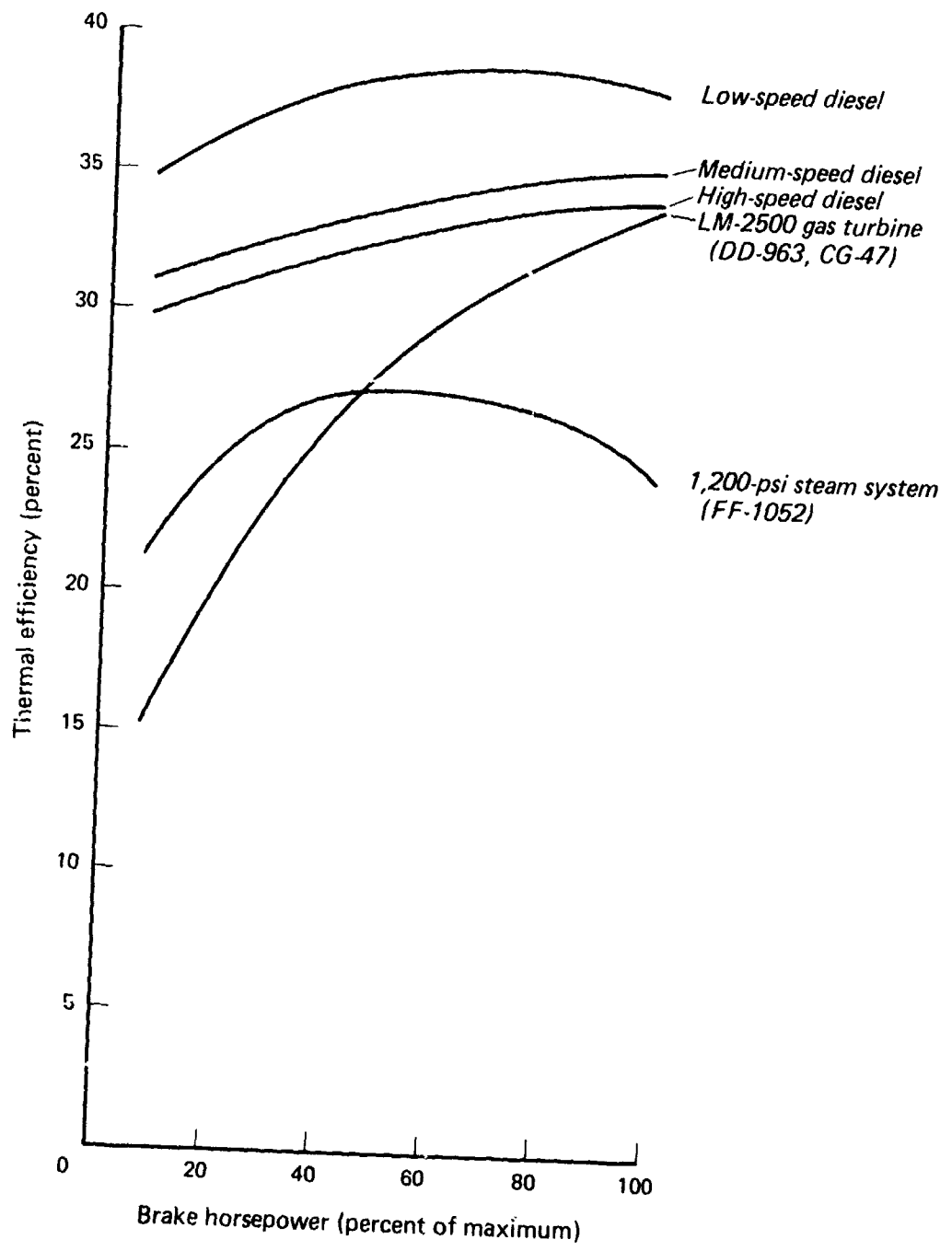
**FIG. 7-1: THERMAL EFFICIENCIES OF PROPULSION SYSTEMS**

Source: [59].

7-3

Another disadvantage of diesels, especially the low-speed variety, lies in their greater noise generation, which is particularly important in antisubmarine warfare. While work is reportedly underway to reduce the noise problem, this study did not examine the extent to which this can be accomplished.

NUCLEAR PROPULSION

Large savings in petroleum could come from making more ships nuclear powered. Today's fleet of nuclear ships uses an amount of energy equivalent to over 8 mmboe annually, or about one-third the fuel consumed by current conventional ships.*

One of the major arguments against nuclear-powered ships has been their higher costs of acquisition. However, the rising price of conventional fuel has made large nuclear ships more attractive by raising the total costs of their conventional alternatives. Future increases in the price of fuel can be expected to favor nuclear ships.

Life-Cycle Costs of Nuclear and Conventional Ships

To show the likely effect of future fuel prices on the choice of nuclear or conventional propulsion, the life-cycle costs were compared. An Op-96 study [60] was adapted and upd     That study examined two aircraft carriers, CV-67 and CVN-68:     Aegis cruisers, CG-47 and CGN-42; and one non-Aegis cruiser, CG. 8. The underway replenishment ships, escorts, consumables, and manpower were all included in the costs. However, the costs of the air wings were excluded because they were assumed to be identical.

Changes to the Op-96 study included using constant FY 1981 dollars, incorporating the October 1980 price of $52.50 paid by the Navy for a barrel of fuel that is a composite of DFM and JP-5, and calculating the life-cycle costs for both their undiscounted and their discounted values. An additional change was the use of an escalation factor for the cost of nuclear fuel. The escalation factor used may be more applicable to the costs in commercial nuclear plants than to the Navy. The actual costs to the taxpayer of nuclear fuel for Navy reactors could not be determined from the available data. However, sensitivity analyses suggest that the costs of nuclear fuel would not be a significant factor because the burnup charges amount to about 0.3 percent of the total, adjusted life-cycle costs of the ships.** The results are in table 7-1, and in figure 7-2 for the carriers and figure 7-3 for the cruisers.

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* The derivation of this estimate is in [1].
** See appendix C for more details on the escalation factor used in costs of nuclear fuel.

TABLE 7-1

ADJUSTED LIFE-CYCLE COSTS OF CARRIERS AND CRUISERS

| | Procurement | Midlife conversion | O&S[a] | Conventional fuel[b] | Total |
|---|---|---|---|---|---|
| Undiscounted costs (millions of FY 1981 dollars) | | | | | |
| CV-67 | 2,782 | 531 | 3,990 | 882 | 8,185 |
| CVN-68 | 3,322 | 495 | 1,320 | 132 | 8,269 |
| CG-47 | 1,026 | 352 | 849 | 153 | 2,380 |
| CGN-42 | 1,213 | 348 | 1,416 | 6 | 2,983 |
| CGN-38 | 906 | 131 | 1,230 | 6 | 2,323 |
| Discounted costs at 10 percent yearly (millions of FY 1981 dollars) | | | | | |
| CV-67 | 1,804 | 49 | 483 | 107 | 2,443 |
| CVN-68 | 2,154 | 46 | 523 | 16 | 2,739 |
| CG-47 | 665 | 32 | 172 | 19 | 819 |
| CGN-42 | 786 | 32 | 172 | 1 | 991 |
| CGN-38 | 587 | 17 | 149 | 1 | 754 |
| Discount factor[c] | 0.6483 | 0.0923 | 0.1211 | 0.1211 | |
| Time stream (yr) | 1982-1991 | 2006 | 1992-2021 | 1992-2021 | |

[a]These O&S costs exclude conventional fuel, but include the costs of nuclear fuel. The cost of nuclear fuel is a burnup charge paid by the Navy to the Department of Energy.
[b]At a fuel price of $52.50 per barrel.
[c]The discount factor is the ratio of discounted-to-undiscounted costs. The details of the computation are in appendix C.
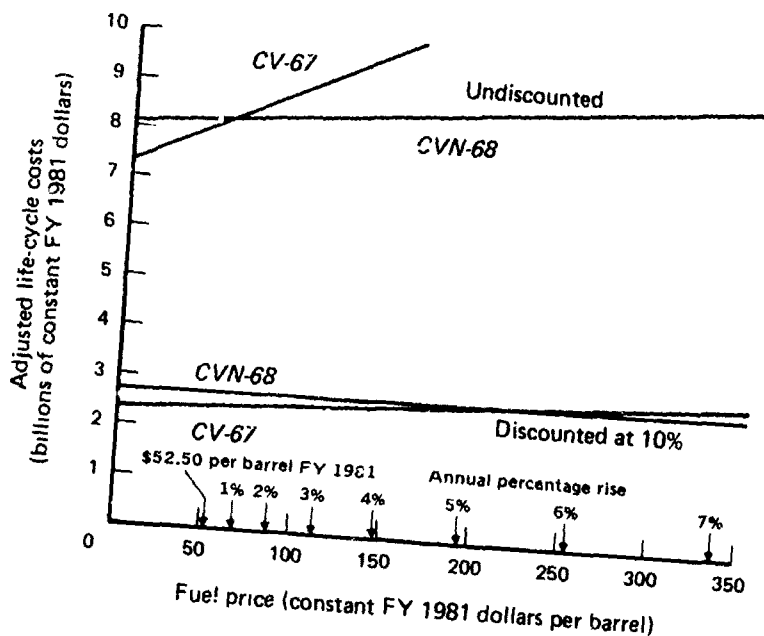
**FIG. 7-2: CARRIER LIFE-CYCLE COSTS (IOC 1992)**
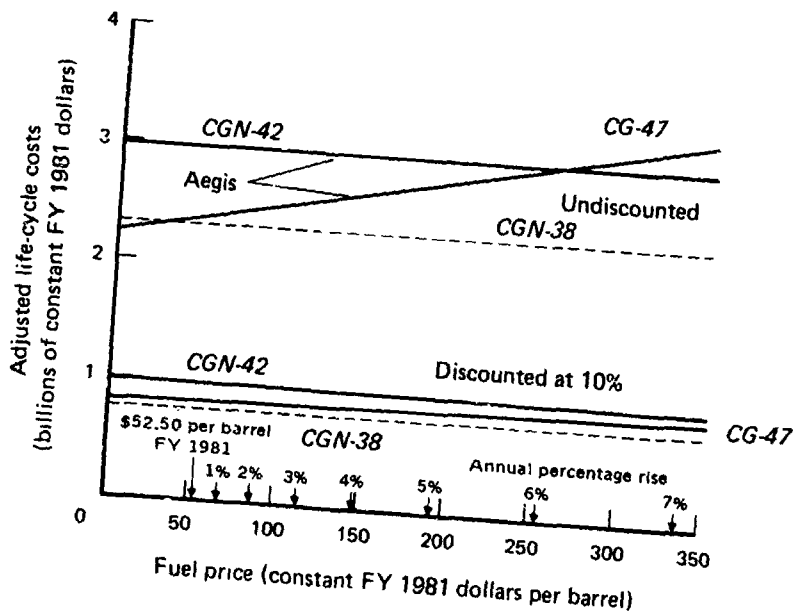


**FIG. 7-3: CRUISER LIFE-CYCLE COSTS (IOC 1992)**

7–6

As fuel prices rise, the costs of conventional ships outstrip those of nuclear ships. The horizontal axis in each graph shows the average teal price of fuel over the ship's operating life. Here, the operating life is 1992--when the ship achieves initial operational capability (IOC)--until 2021. The horizontal axis also includes corresponding annual percentage increases for fuel above inflation, with the FY 1981 price assumed as the base.

The life-cycle costs of the two carriers cross in the undiscounted case at an average fuel price of $58 per barrel--very close to the current price of $52.50 per barrel. This can be reached by only a 1/2-percent annual price increase.

Discounting places a greater weight on the nuclear carrier's higher procurement costs than on the conventional carrier's higher operating costs because the latter occur later in time. The point of equal life-cycle costs in the discounted case is at an average fuel price of about $220 a barrel, which corresponds to an annual increase in the price of fuel of about 6 percent over the lifetime of the ships.

In comparison, earlier studies of conventional and nuclear aircraft carriers, done in the 1960s, used fuel prices of about $12 per barrel (in constant FY 1981 dollars) instead of about $52 per barrel.

Figure 7-3 shows the life-cycle costs of two Aegis cruisers--one nuclear, the other conventional. These smaller ships are more affected than the carriers by the greater weight and acquisition costs of existing nuclear powerplants. The points of equal cost for the nuclear and conventional cruisers occur at a higher average fuel price of about $270 per barrel in the undiscounted case and about $550 per barrel in the discounted case at 10 percent annually. Such high fuel prices would result from average annual increases of about 6 and 9 percent, respectively.

This analysis shows that the higher procurement costs of nuclear ships are offset only by the greater operating costs of conventional ships if fuel prices rise sufficiently. Recent history attests to such large price increases. As previously noted, the prices of distillate fuels used by the Navy have jumped by a factor of over 4 in real terms since 1973, equalling a 23-percent annual increase above inflation. When spread over 20 years, that still corresponds to an annual rise of about 8 percent. This is close to the increase required to reach points of equal cost for the cruisers in the discounted case. On the other hand, the cost differences in the discounted cases become quite small well before the crossover points. Because the choices are not simply a question of the less costly of two equally effective alternatives, these cost differentials might not be that important.

## Other Considerations in Nuclear Propulsion

In addition to the possibility that nuclear ships may cost less than their conventional counterparts, there are other less quantifiable advantages and disadvantages to nuclear power mentioned only briefly here.

Nuclear ships have several advantages over conventional ships. They are able to sustain high speeds over prolonged periods that offer tactical advantages and reduce their vulnerability. High speed can also boost morale, particularly when the speed is used to shorten the transit times to and from deployments. Finally, nuclear-powered ships require fewer support ships and fewer underway replenishments.

Among the cited disadvantages of a larger nuclear program are increased waste disposal, the limited nuclear shipbuilding capacity in the U.S., and the shortage of nuclear-trained manpower. Although the Government's reprocessing facility at Idaho Falls is reportedly adequate for present and anticipated waste quantities [61], this study did not evaluate these areas for their potential to constrain nuclear propulsion systems.

Both the costs and the benefits of nuclear and conventional ships are unequal. With due recognition of the uncertainties noted above, on balance, the Navy's acquisition of more nuclear ships would be a far-sighted move to cope with a future of higher cost petroleum. All large surface ships, above about 10,000 tons, should become more serious contenders for nuclear propulsion than they are presently. The possibility of extending nuclear power to smaller ships will depend on the development of lighter, smaller powerplants.

## Prospects of Nuclear Power for Smaller Combatants

Smaller surface combatants, such as escorts, require a greater ratio of power to overall tonnage than larger combatants such as aircraft carriers. Because of this requirement, the current pressurized-water reactors (PWRs) are not economical for combatants below 8,000 tons. However, smaller ships might eventually benefit from the development of lightweight nuclear powerplants (LWNPPs). This would entail reducing the size and weight of the propulsion system—the reactor and the power conversion system.

Figure 7-4 illustrates the relationship between a ship's specific power (horsepower per ship ton) and the specific weight of its propulsion system (pounds per horsepower of the system). It shows that surface combatants require a greater specific power than larger carriers. Also, conventionally powered ships weighing 8,000 tons have propulsion systems in the range of 60 pounds per horsepower; existing nuclear-powered ships have propulsion systems limited to 100 pounds per horsepower or higher. Thus, an LWNPP would be required in a nuclear

combatant t~ match the light weight of the propulsion system in a comparable conventional ship. Smaller high-speed escorts would need even lighter nuclear propulsion systems.
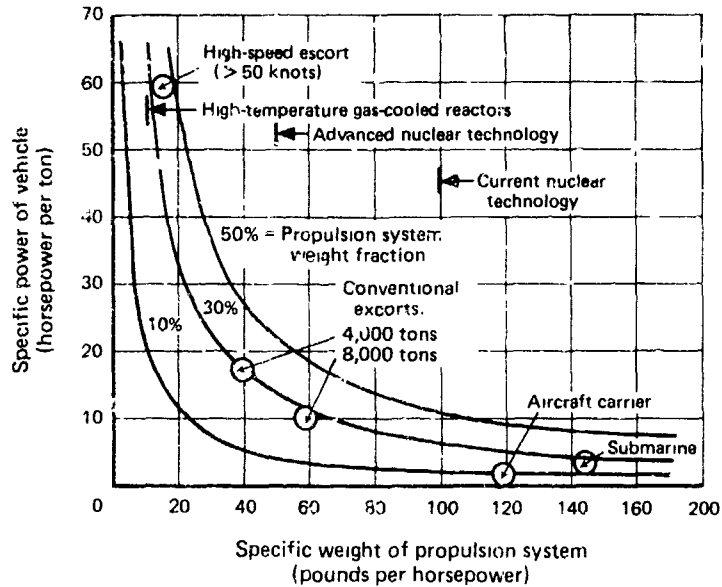


Source [62].

FIG. 7-4: COMPATIBILITY BETWEEN NUCLEAR PROPULSION
SYSTEMS AND SHIPS

Several approaches to attain such an LWNPP were examined at a work-shop conducted by the Office of Naval Research (ONR) in 1975 [63]. It was suggested during the workshop that a propulsion system having a specific weight near 50 pounds per horsepower could be constructed.

Westinghouse has proposed a design for a gas-cooled LWNPP [64]. That design has been advanced as a possible alternative to the LM-2500 gas turbine--the engine being installed in DD-963- and CG-47-class escorts. The LM-2500 is also being considered for the DDGX.

However, as the ONR workshop and others have later noted, there are a number of problems with the LWNPP concept. They include the lack of designs that would permit maintenance work at sea and fears for the loss of coolant.

Apparently little has been done to advance the state of the art in LWNPP in recent years. A large R&D effort probably would be required to implement the concept.

In the absence of a significant R&D effort, the benefits of LWNPP for smaller ships appear to be postponed to a more distant future.

Pending future developments of LWNPP, diesels offer significant petroleum savings and should be considered for expanded use in smaller Navy ships.

CHAPTER 8

MOBILITY FUELS:  ALTERNATIVES AND QUALITY CONSIDERATIONS

Conventional crude oil of generally high quality has been the dominant source for the production of petroleum fuels used in existing ships and aircraft.  However, the supply of such high-quality crude—of low density and containing low levels of sulphur and other contaminants—is becoming scarce.  Refiners are preparing for crude stocks of lower quality and for the production of synthetic, petroleum-like liquids from heavy oils, shale, and coal.  This development will affect the quantity and quality of fuel available to the Navy.

Planners have limited choices to cope with the changing types of fuel.  One possibility is to rely on fuels other than petroleum or uranium, such as hydrogen and alcohol.  Another approach is to change fuel specifications so that a broader range of petroleum fuel types and synthetic substitutes can be used.

This chapter discusses how likely changes in the chemical properties of mobility fuels will affect the Navy.

CANDIDATE NONNUCLEAR MOBILITY FUELS

Petroleum products have been used because of their high energy content, relative abundance, and ease of storage and handling.  However, a wide range of substances can be considered as potential mobility fuels.

Figure 8-1 identifies and arranges potential alternatives according to two major criteria:  energy density by weight and energy density by volume of the substance.  The alternatives to petroleum are evaluated further in terms of their availability, ease of storage and handling, and the inventory of engines that would use the fuels.

Energy Density

The amount of energy that can be released from a given volume of a substance is more important for ships and aircraft than the fuel's energy density by weight.  This is because these vehicles are mostly volume limited instead of weight limited.  Their drag (therefore their rate of fuel consumption) is related more to their volume than to their weight.

Hydrogen has the greatest energy for an equivalent mass, but even in liquefied form, its energy density by volume is far below that of petroleum or the synthetic hydrocarbons (see figure 8-1).  The fuel tank of a liquid-hydrogen system would have to be four times the size of one filled with conventional fuel.  Alternatively, the range of the vehicle

carrying hydrogen would be limited to about one-quarter that of the
conventional system.
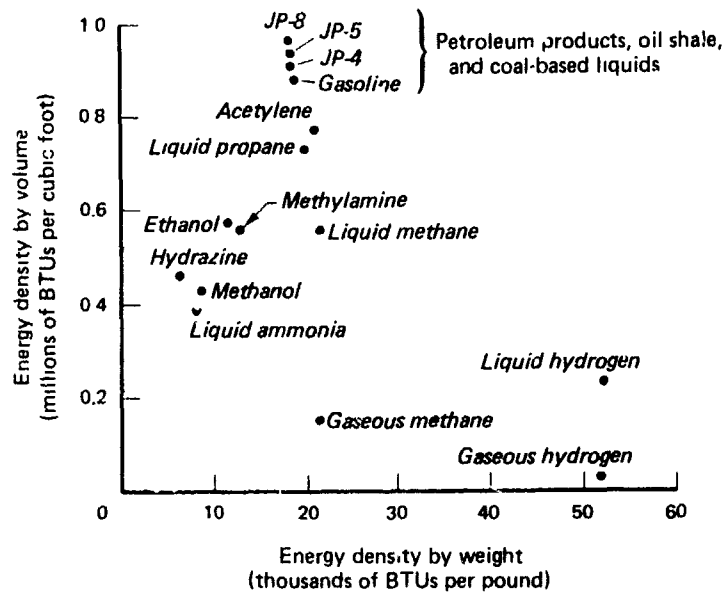


FIG. 8-1: ENERGY DENSITY, PER MASS AND PER VOLUME,
OF VARIOUS CANDIDATE FUELS

None of the other products shown in figure 8-1 compare favorably
with petroleum. Platforms using ethanol (ethyl alcohol), methylamine,
or liquid methane would have their ranges degraded about 40 percent.
Acetylene and liquid propane are similar to the JP fuels, but they have
other unfavorable characteristics, as discussed below.

Resource Abundance

Some candidate fuels, such as hydrogen and alcohol, have poten-
tially abundant resource bases. For example, hydrogen gas can be re-
leased from water; ethanol can be fermented from grain. However, at
present, it is not generally economical to produce large quantities of
these substances, because their production requires a great deal of
energy. For example, hydrogen, now produced by processes associated
with the refining of petroleum or coal gasification, eventually might be
produced in commercial quantities from seawater using a nuclear reactor
for the source of energy. However, that process is not now economically
viable.

Because the production of alcohol is energy intensive, more energy
might be needed to ferment and distill the alcohol than can be obtained
from burning it as fuel. A further problem is the use of grain to

8- 2

provide transportation fuel and as a source of food. The competition for grain would probably drive up prices and effectively reduce the availability of grain for fuel.

Many of the other candidate fuels, such as acetylene, methylamine, and hydrazine, are not readily available in large amounts today by any practical process.

## Handling Problems

A third consideration involves storage and handling problems associated with many of these substances that would seriously interfere with their widespread use. Some compounds are toxic, corrosive, reactive, or explosive. Examples include ammonia, which is both toxic and corrosive; hydrazine, which is very reactive; and acetylene, which becomes explosive when compressed.

Most substances that are gases at room temperature and pressure must be liquefied to raise their energy density by volume to a practical level. This is done either by cooling the gas to form a cryogenic liquid or by keeping it under substantial pressure.

Liquid hydrogen and liquid methane--the latter is essentially liquefied natural gas (LNG)--must be maintained at very low temperatures, which requires large amounts of insulation and energy. A study of very large aircraft by the Rand Corporation [66] revealed that the energy expended to maintain these cryogenic fuels as liquids significantly increased the total energy requirements of these planes relative to petroleum-fueled aircraft. These fuels are also more dangerous to handle than petroleum, due to their low temperatures.

Propane, a major constituent of liquefied petroleum gas (LPG), is heavier than air in its gaseous form and must be pressurized to 60 to 300 pounds per square inch to keep it liquid [67]. Because of these characteristics, propane is also a more dangerous fuel than oil to handle and to store.

## Engines and Infrastructure

A final consideration is the need to adapt or to replace the engines and supporting infrastructure (such as refineries, the supply system, and storage) designed for oil.

Table 8-1 summarizes the findings of a study by the National Academy of Sciences [68] on the compatibility of several energy sources for general maritime use and ship prime movers. Aircraft gas turbines were also examined briefly.

Table 8-1 lists a number of factors that relate to the probabilities of producing commercial quantities of each fuel, of adapting the

# TABLE 8-1

## QUALITATIVE RANKING OF CANDIDATE ALTERNATIVE FUELS AND ENERGY SOURCES

| | Present availability for use as a fuel | Probability of economic production | Marine application of fuel | | | Overall ranking | | Time frame |
|---|---|---|---|---|---|---|---|---|
| | | | Potential market size for marine propulsion systems | Types of propulsion systems readily adaptable to fuel by year 2000[a] | Adaptability to existing fuel storage system | Existing ships by year 2000 | Future ships by year 2000 | |
| Synthetic liquid fuel oil from coal | Low | High | High | 1,2,3,4 | High | High | High | 1990s |
| Synthetic liquid fuels from shale rock | Low | High | High | 1,2,3,4 | High | High | High | 1980s |
| Synthetic liquid fuels from tar sands | Medium | High | High | 1,2,3,4 | High | High | High | 1980s |
| Methyl alcohol | Low | High | Medium | 1,3,4,5 | Medium | Low | Low | 1990s |
| Methanol/coal slurries (40/60) | Low | High | Medium | 4 | Low | Low | Low | 2000+ |
| Ethyl alcohol (ethanol) | Medium | Low | Medium | 1,3,4,5 | Low | Low | Low | Present |
| Gasoline/alcohol blends (90/10) | Medium | Medium | Low | 1,3,4,5 | Low | Low | Low | Present |
| Pulverized coal/oil slurries (40/60) | Low | High | High | 2,4 | High | Medium | High | 1980s |
| Hydrogen | Low | Medium | Low | -- | -- | -- | -- | 2000+ |
| Ammonia | Medium | Medium | Low | -- | -- | -- | -- | 2000+ |
| Hydrazine | Low | Low | Low | -- | -- | -- | -- | 2000+ |
| Methane | High | High | Low | 1,3,4,5 | Low | Low | Low | 1980s |
| Nuclear (direct) | High | High | Low | 1,4 | N.A. | Low | Medium | Present |
| Nuclear (indirect) | Low | Varies | Low | Varies | Varies | Varies | Varies | 2000+ |
| Coal | High | High | High | 4 | Low | Low | High | Present |
| Wood (air dried) | Medium | High | Low | 4 | Low | Low | Low | 1980s |

Source [68].

[a]Propulsion systems:
1 = Gas turbine.
2 = Diesel and free piston.
3 = Internal combustion piston engine.
4 = Steam.
5 = Fuel cell.
N.A. = Not applicable.
-- = Possibility of adoption by year 2000 too remote to consider.

existing storage system to its use, and of using the fuel in existing and future engines. The synthetics, coal-oil slurries, and solid coal will be the most likely alternatives by the year 2000. All are expected to be employed in commercial ships built 20 years from now, and all except for solid coal will be burned by the year 2000 in the fleet of older ships still used by the maritime industry. Steam powerplants and some diesel engines that power those ships will be able to use all these fuels. However, gas turbines are not expected to be able to burn either solid coal or a coal-oil slurry.

Liquid hydrocarbons will remain the mainstay of Navy mobility fuels through at least the next few decades. Besides nuclear power, Navy mobility fuels will be liquids derived from conventional oil, heavy oil, shale, tar sands, or coal. Exotic alternatives, such as hydrogen, alcohol, coal-oil slurries, and solid coal, may eventually help meet the Navy's energy needs. But they cannot become important fuels until the proper infrastructure is built up and new engines are produced or existing engines are modified. They are possible fuels for a more distant future.

LOWER QUALITY FUELS

A conclusion from chapter 3 is that the quality of the crude slate has already begun to change from predominantly sweet (low-sulphur), light crude oil to the sour (high-sulphur), heavy crudes [69 and 70]. In addition, as mentioned above, petroleum substitutes will become more prevalent in the future. As a result, products of high quality will become less available. Both technical and economic forces will be responsible for this development because crudes of poorer quality require more extensive processing. Extra processing, which can include hydrotreating or hydrocracking, puts many of the small refiners that supply the Department of Defense at a competitive disadvantage, because they lack some of the necessary refining capabilities [71 and 72].

Figure 8-2 shows the relative hydrogen content of various fuels and sources. Forming liquids of high quality from shale, tar sands, and coal would require completely different processing techniques from those currently employed for crude oil. The reason is that the hydrogen-to-carbon mole ratios (H/C) of the synthetics are even lower than those of residual oil. This comes from their having a greater number of either long-chain molecules or ring structures (including aromatics). Because these molecules are more difficult to burn in diesel engines or gas turbines, they must be broken up to form distillate fuels. Either extensive hydrogenation (hydrogen addition) or pyrolysis (carbon removal) steps are performed to increase the value of H/C so that these sources can reach distillate levels.

Hydrogen/carbon mole ratio

Hydrogen as percentage by weight of total hydrogen plus carbon
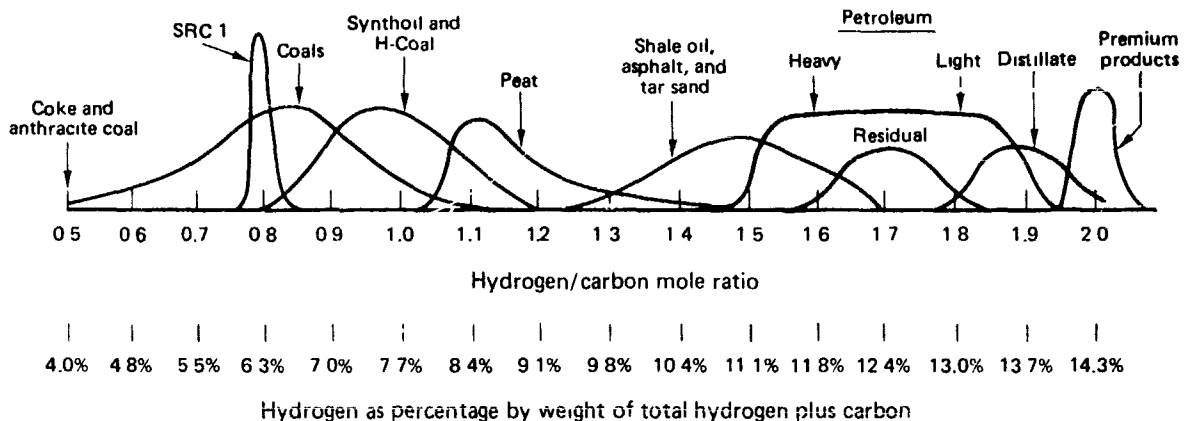
Source [73].

**FIG. 8-2: HYDROGEN CONTENT OF VARIOUS HYDROCARBON FUEL SOURCES AND PRODUCTS**

Many feedstocks of lower quality have severe contaminants that drive up processing costs and damage engines. Contaminants include ash, sulphur, nitrogen, and heavy metals. For example, the high nitrogen content (above 2 percent) and presence of certain trace metals in shale oil will poison catalysts used in refinery operations. Therefore, preliminary distillation and other steps to treat the feedstock become necessary [74].

As mentioned above, more extensive processing and additives will be required to supply petroleum fuels in the future. For this reason, petroleum products are expected to be both higher in price and lower in quality. Both fuel costs and quality have important implications for existing and new engines.

EFFECTS OF LOWER QUALITY FUELS ON ENGINES

Even though fuels derived from heavy oil and synthetic hydrocarbons are basically compatible with existing engines, they are not completely equivalent to petroleum products of high quality. These synthetic fuels introduce a unique set of problems whose scope is not yet well understood.

The Navy has already encountered fuel difficulties with its F-14 operations [75]. Smoking in the F-14's TF-30 turbofan engine and lubrication problems in the afterburner boost fuel pump have been

reported. The high aromatics content of the Alaskan crude used by some refiners plus some deleterious side effects of refining this lower quality product may account for these problems in the F-14.

In general, lower quality fuel causes maintenance and reliability problems for existing engines. The high viscosity of the long-chain hydrocarbons restricts fluid movement and possibly causes clogging within fuel filters or small passages in the engine. Elevated levels of aromatics and other ring structures generate smoke through incomplete burning. Contaminants can increase corrosion or erosion rates.

## Aircraft Engines

Aircraft gas turbines are the most susceptible to lower quality fuel because of the complexity and fine tolerances of their components. Pratt and Whitney Aircraft (P&WA) has estimated the effect of a specific type of fuel of degraded quality on its present and future commercial gas turbine engines [76]. This fuel contained primarily high aromatics levels, but only small quantities of sulphur and heavy metals. The analysis disclosed a number of potential problems associated with using this fuel: reduced combustor-liner life (by about 40 percent), adversely affected ignition characteristics, worsened fuel thermal stability, increased smoke levels, and higher emissions.

In addition to problems with the combustor, P&WA expects to have difficulties with the expensive, high-pressure turbine section. Because of incomplete combustion in the burner, the turbine airfoils will be exposed to higher temperatures and heat loads, along with roughened airfoil surfaces from coating erosion and particle deposits. It is estimated that these factors will reduce the life of those parts by up to 60 percent. Although design modifications could reduce the deleterious effects on the combustor and turbine to a degree, these changes would generally either lower engine efficiency (increase fuel consumption) or reduce engine performance (drop the power level).

Moreover, the P&WA study did not address potential problems that could arise from high sulphur and heavy-metal contaminant levels. They could also be significant, as the study by the National Academy of Sciences [68] indicated.

## Ship Propulsion Systems

Other prime movers are not as sensitive as gas turbines. Marine medium- and high-speed diesel engines are somewhat better able to resist the effects of many fuels of low quality. Low-speed diesel engines provide even greater resistance. Nevertheless, bunker fuels for diesel engines currently in marine use would still require considerable upgrading to prevent excessive maintenance.

Steam powerplants, in particular those ordered since the mid-1960s, are the least sensitive to degraded bunker fuels [68]. Also, these newer plants could probably be adapted to burn coal-oil slurries. Future steam plants could even be designed for solid fuels, such as pulverized coal or stoker coal.

## NAVY RESPONSES

The Navy has initiated a number of research programs designed to both understand and deal with problems caused by future fuels. Their effort is directed toward [77]:

- Assessing the degree to which fuel specifications can be changed without significantly degrading engine performance

- Defining the relationship between fuel chemistry and the behavior of fuel during burning

- Determining the effects of synthetic fuels on the performance and reliability of systems

- Evaluating the fuel requirements of future engines.

This work is directed toward all types of prime movers used by the Navy: gas turbines, diesel engines, and steam plants.

## FUEL SPECIFICATIONS

The Navy's fuel specifications set forth the level of fuel quality desired for each of its fuels. Because the quality may be difficult to maintain for the quantities required, the Navy may consider changing its fuel specifications.

## Reduced Fuel Specifications

The Navy's fuel specifications impose demands on refineries that affect the potential mix of products from a given feedstock. In a recent study [78], Exxon estimated the sensitivity of the maximum theoretical yield of JP-5 to two of its specifications: the freeze and flash points. Table 8-2 lists the properties of the five crude slates considered. The results of this analysis are shown in tables 8-3 and 8-4 for the freeze point and the flash point, respectively. JP-5 production could be boosted about 40 percent by a 10-degree increase in the former and about 25 percent by a 10-degree drop in the latter. Pratt and Whitney has also estimated that a reduction in the smoke point from 19.0 to 17.5 millimeters could be accompanied by a 200-percent increase in JP-5 output [79]. Of course, increasing the yield of JP-5 by changing the specification would reduce other products made from petroleum feedstocks.

TABLE 8-2

PROPERTIES OF CRUDES USED WIDELY BY WESTERN JP-5-PRODUCING REFINERIES

| Property | Type of crude[a] | | | | |
|---|---|---|---|---|---|
| | A | B | C | D | E |
| Gravity (deg API) | 32.8 | 40.3 | 38.1 | 26.2 | 37.1 |
| Pour point (deg F.) | -40 | 25 | 40 | 15 | 15 |
| Total sulfur (wt %) | 1.6 | 0.05 | 0.12 | 1.1 | 0.40 |
| Mercaptan sulfur (ppm) | 71 | 1.3 | 2.0 | 2.0 | 1.0 |

Source: [78].

[a]Crude description:
A = medium-gravity, high-sulfur Mexican crude.
B = light-gravity, low-sulfur, high-aromatics Indonesian crude.
C = light-gravity, low-sulfur, low-aromatics Nigerian crude.
D = heavy-gravity, high-sulfur, high-aromatics Alaskan crude.
E = light-gravity, low-sulfur, California crude.

TABLE 8-3

EFFECT OF RELAXATION OF FREEZE POINT ON
MAXIMUM THEORETICAL YIELD OF JP-5

| Type of crude | Maximum theoretical yield[b] | Percent increase in yield[a] | | |
|---|---|---|---|---|
| | | -45 | -40 | -30 |
| A | 7.0 | 41 | 76 | 144 |
| B | 19.3 | 24 | 44 | 83 |
| C | 14.2 | 23 | 41 | 78 |
| D | 11.5 | 25 | 45 | 86 |
| E | 12.3 | 26 | 50 | 94 |

Source: [78].

[a]Over current specifications at the indicated freeze points (degrees Fahrenheit).
[b]In volume percent, at the current specifications: freeze point of -51 degrees Fahrenheit and flash point of 140 degrees Fahrenheit.

TABLE 8-4

EFFECT OF RELAXATION OF FLASH POINT ON
MAXIMUM THEORETICAL YIELD OF JP-5

| Type of crude | Maximum theoretical yield[b] | Percent increase in yield[a] | |
|---|---|---|---|
| | | 135 | 130 |
| A | 7.0 | 21 | 49 |
| B | 19.3 | 13 | 27 |
| C | 14.2 | 13 | 25 |
| D | 11.5 | 13 | 25 |
| E | 12.3 | 17 | 33 |

Source: [78].

[a]Over current specifications at the indicated
flash points (degrees Fahrenheit).
[b]In volume percent, at the current specifica-
tions: freeze point of -51 degrees Fahrenheit
and flash point of 140 degrees Fahrenheit.

These results highlight the importance of the ongoing efforts by
the Navy to define acceptable limits in fuel-property variations. If
engines with wider fuel tolerances are developed, the greater flexi-
bility that should come from using lesser quality fuels will guard
against future fuel shortages.

## More Common Fuels

Another way to increase the Navy's access to fuel supplies is to
adapt to types of fuel that are more widely used. The two middle dis-
tillates of high quality, DFM and JP-5, accounted for two-thirds of the
consumption of petroleum-derived fuels in 1980 by both the Navy and
Marine Corps. Furthermore, the Navy is by far the world's largest
consumer of these products.

Refiners might find it profitable or necessary to cut back tempo-
rarily on the production of these fuels. This threat could be reduced
or eliminated by using more common fuels, such as No. 2 diesel oil for
DFM and Jet A-1 for JP-5. Research into the possibilities of tailoring
military fuels more along civilian lines could yield significant supply
benefits.

Standardizing aircraft and ship fuels is another possibility. Although blends of aircraft and ship fuels have been examined for emergency use, the day-to-day use of a single fuel would benefit the Navy. Even though ships might have to shift more toward aircraft fuel, this should not greatly increase the Navy's overall fuel bill. In October 1980, the Navy paid to the DFSC $1.22 per gallon for DFM and $1.27 per gallon for JP-5. Cost savings resulting from transporting and storing ship and aircraft fuel together instead of separately might defray this modest differential. In any case, the proposal merits more study.

# CHAPTER 9

## MEASURES TO IMPROVE ACCESS TO PETROLEUM: LARGER BUDGETS

In addition to reducing the quantity of petroleum used, management might place more emphasis on ways to increase the Navy's access to the available petroleum supply. This study has addressed four of these measures. They are:

- Press for larger civilian and military reserve stocks (chapter 4).

- Insure that both the market and nonmarket mechanisms for Defense to acquire petroleum are adequate for a range of world-supply conditions (chapter 4).

- Change fuel specifications for greater fuel commonality (chapter 8).

- Increase engine tolerances, thereby enabling operations with fuel of lower quality (chapter 8).

An additional measure is to obtain larger budgets to offset fuel price increases.

Future increases in the price of fuel may be offset by larger budgets for all the military services. Alternatively, one service may get a larger share of the available budget for fuel on the basis of some comparative advantage. This chapter estimates how much larger Department of Navy budgets might have to be to offset future price increases. In addition, an example of a comparative advantage of seapower is evaluated for its fuel implications.

### EFFECTS OF FUEL PRICE INCREASES ON THE NAVY BUDGET

The relative burden of higher petroleum prices shows up in Navy budgets. In FY 1973, petroleum fuels accounted for 2 percent of the Navy's total obligational authority (TOA). In FY 1980, they were 6 percent of the budget. This change in the relative burden occurred even though there were larger appropriations for fuel and a smaller Navy that consumed 36 percent less petroleum than in 1973.

Historically, larger budgets have not fully covered the added costs of higher priced fuel. However, this study estimated how much larger the Navy's budget would have to be in the future to fully cover real-price increases of 2, 5, and 10 percent annually. This was accomplished by first determining the cumulative budget growth from 1981 to 2000 required to pay excess fuel costs above the FY 1981 level. That growth was then converted into an equivalent yearly percentage increase above

the FY 1981 budget o $50.9 billion. Figure 9-1 shows the results; appendix B gives the details.
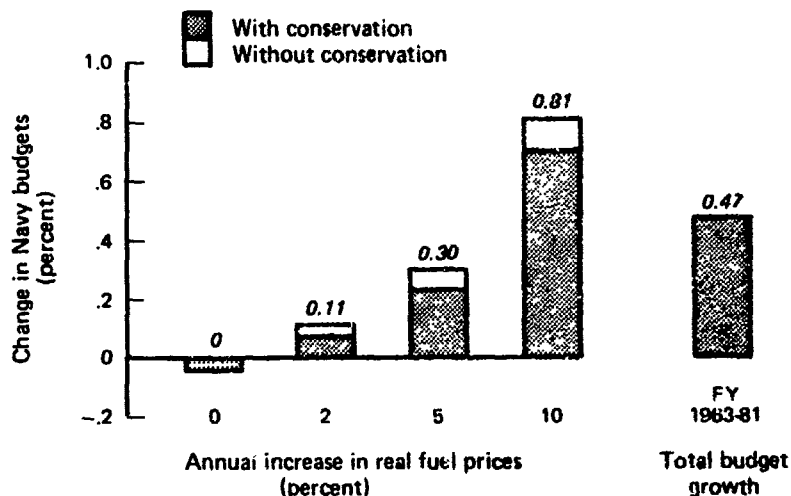


FIG. 9-1: NAVY BUDGET: ANNUAL INCREASES REQUIRED
TO OFFSET FUEL PRICE RISES

The yearly increases in figure 9-1 are small. However, the 0.11-, 0.30-, and 0.81-percent annual rises accumulate by the year 2000 to about $10 billion, $28 billion. and $78 billion, respectively. Effective conservation would reduce the need for additional funding.

An additional perspective on the size of the annual increases in figure 9-1 compares them with the actual history of the Navy's budget growth. Including the Vietnam years, the Navy budget had an average annual increase of 0.47 percent.* The intermediate price increase of 5 percent would cancel about two-thirds of that amount.

A COMPARATIVE ADVANTAGE: SEALIFT VS. AIRLIFT

In addition to a larger budget for Defense to help offset fuel prices facing all the services, the Navy might also obtain a larger share of the budget available for Defense.

_____
* This was computed using data on Navy TOA for 1963 to 1981 taken from [80 and 81], adjusted to constant dollars. The total growth above the FY 1963 level was converted to an average annual increase.

An example in the area of strategic mobility was analyzed for its fuel implications and to demonstrate the potential for redistributing the nation's resources, including petroleum, in response to a comparative advantage.

An estimate was made of the fuel required to lift a notional Marine Amphibious Brigade (MAB) with 15 days of supplies, including POL, from the East Coast around South Africa to the Middle East. Transport by amphibious ships was compared with transport by military aircraft over the same distance.

The sealift of the force would require 24 amphibious ships and a tanker, as shown in table 9-1. The ships would burn about 520,000 barrels of fuel, assuming a round-trip distance of 17,200 n.mi. and an average transit speed of 16 knots. In contrast, an airlift of this MAB would require 4.4 million barrels, with an average speed of 400 knots. Assuming a capability to airlift the POL, the estimates in table 9-2 show that the planes of the Military Airlift Command (MAC) and Civil Reserve Air Fleet (CRAF) would have to fly over 1,800 sorties to complete the mission.

In this comparison, sealift is almost an order of magnitude more efficient in terms of fuel consumption than airlift. Furthermore, positioning the fuel for the four refueling stops needed by the aircraft in each round trip could pose a problem.

There is no doubt that airlift is more responsive than sealift for small, lightly supported forces. However, the capabilities of airlift are overwhelmed by larger, fully supplied forces. Although the initial units of a larger force would arrive sooner by aircraft, the closing times for the MAB considered here would not be much different than if it were transported on ships. Assuming that about 300 aircraft are available continuously for 10 hours per day [85], it would take about 26 days to airlift the entire force. In contrast, the one-way transit time for ships averaging 16 knots is about 22 days.

In brief, sealift offers large potential fuel savings when compared with airlift. Furthermore, when large forces, equipment, and supplies are moved, sealift is the only feasible means for moving them. The advantages of sealift might be stressed more when decisions are made allocating the nation's resources to strategic mobility. It is one example of a comparative advantage of seapower. When appropriately emphasized, a system's comparative advantages should be the basis for a larger share of the available resources for Defense—including the scarce resource of petroleum.

## TABLE 9-1

### CAPACITY OF SHIPS TO TRANSPORT A MARINE AMPHIBIOUS BRIGADE[a]

| Type | Number | Troops[b] | Vehicles[b] (thousands of sq ft) | Supplies[b] (thousands of cu ft) | CH-46 equivalents[b] | Fuel consumption rates[c] (bbl/hr) |
|------|--------|-----------|-----------|-----------|-----------|-----------|
| LHA | 2 | 3,540 | 60.6 | 233.8 | 76 | 88 |
| LPH | 2 | 3,220 | 8.0 | 80.0 | 54 | 39 |
| LPD | 8 | 6,384 | 112.8 | 327.2 | 16 | 186 |
| LST | 7 | 2,513 | 71.8 | 28.7 | -- | 76 |
| LKA equivalent | 5 | 1,050 | 171.5 | 351.5 | -- | 72 |
| AO | 1 | -- | -- | -- | -- | 18 |
| Total | 25 | 16,707 | 424.7 | 1,021.2 | 166 | 479 |

[a]Notional MAB of 14,500 troops weighing 25,000 short tons without supplies; accompanying supplies weighing 5,500 short tons and petroleum, oil, and lubricants (POL) weighing 11,300 short tons.
[b]From [82] with factors included to account for tactical integrity and broken storage.
[c]From [53].

## TABLE 9-2

### AIRCRAFT SORTIES TO TRANSPORT A MARINE AMPHIBIOUS BRIGADE[a]

|  | C-141 | C-5 | CRAF | Total |
|---|---|---|---|---|
| Sorties[b] |  |  |  |  |
| Without supplies | 620 | 194 | 48 | 862 |
| With supplies | 208 | 65 | 16 | 289 |
| POL | 485 | 152 | 38 | 675 |
| Total | 1,313 | 411 | 102 | 1,826 |
| Fuel consumption rate of total sorties (thousands of bbl/hr) | 61.6[c] | 33.9[c] | 7.4[d] | 102.9 |

[a] Same MAB weights as in table 9-1.
[b] Scaled by MAB weights, based on data from [83].
[c] Based on data from [84].
[d] Estimates for civilian aircraft.

# CHAPTER 10

## CONCLUSIONS AND RECOMMENDATIONS

### EVALUATION OF FORECASTS: IMPLICATIONS FOR AVAILABILITY

For the past 10 years, the rate at which petroleum has been produced in the world has exceeded the rate at which new oil has been found. In the non-Communist world, the finding rate of new oil has been declining for about 30 years. These facts support grim geological predictions that a peak will be reached within two or three decades on the production of the world's ultimately recoverable crude oil. U.S. production has already peaked and is in decline.

Economic theory offers some comfort. According to the theory, the unfettered market will compensate for a scarce resource by raising fuel prices. Increased prices in turn will retard demand, thereby stretching the remaining supplies and stimulating the production of substitutes. The theory will probably be valid over the long term; however, the problem is the transition through the next 20 to 30 years. The modern world lacks experience with depletion of a resource as critical as petroleum. In addition, there are large uncertainties about whether substitute products will be available in sufficient quantities and at acceptable levels of quality. Finally, on the issue of quality, it is important to recognize that the chemistry of petroleum-like substitutes and its effect on engines are only partially understood.

Planners can expect fuel to be generally available as products from conventional oil are supplemented by substitutes from heavy oil, shale, and coal. However, the prudent planner should recognize that fuel will cost more and its quality will vary widely because of a greater prevalence of lower quality feedstocks.

### AVAILABILITY IMPLICATIONS OF IMPORT INTERRUPTIONS

The reserves of the world's remaining conventional oil are unequally concentrated in a few producer countries. This condition is expected to perpetuate the vulnerability of the industrial economies to market disruptions at least as severe as those experienced in 1973 and 1974 and, again, in 1979 and 1980. The U.S. will be unable to counteract future supply interruptions by expanding its own domestic production of crude oil. However, by maintaining high stock levels in the SPR, the nation will help reduce its vulnerability. Other measures that can help include conservation, substitution of alternative forms of energy, and possibly the existing international agreements to share shortages among the importing nations.

The nation's domestic fuel production and planned reserve stocks
are adequate to provide products for military use at likely wartime
levels of consumption even with the unlikely cutoff of all imports.
Both market and nonmarket mechanisms exist for the Government to acquire
fuel under a variety of conditions. However, the political will to
allocate fuel to military users may not always exist.

As in the past, oil-supply disruptions will mainly affect the
nation's economy, but the military services will also be affected.
Reductions in supplies to the Navy or even complete unavailability of
fuel may occur for short periods during a crisis. Deliveries of fuel
supplies to military forces could be curtailed as a result of inadequate
logistical planning, command decisions to conserve oil in a crisis of
uncertain length, or the allocation of fuel to other military or
civilian users. Routine naval operations and training may experience
longer periods of curtailed supplies of fuel. The long-term effects of
future interruptions will be an even worse problem of fuel costs.

## PROBABLE EFFECTS ON THE NAVY OF CHANGES IN THE PETROLEUM MARKET

The dominant problem of the future supply of petroleum will be the
day-to-day management of greater costs. The Navy has already exper-
ienced over a fourfold increase in the real price of fuel in less than a
decade. Fuel now constitutes about one-third of the direct O&S costs of
mobile weapon systems--in the same range as manpower.

Future increases in the price of fuel could be even more severe.
In the absence of substantial real growth in Navy budgets, a hypo-
thetical 5-percent, annual real-price increase out to the year 2000
could have one of the following effects:

- A reduction in the operating tempo by more than half the
  current level

- A loss of 24 new, average ships and 610 new, notional
  aircraft

- An offset of two-thirds of the 0.5-percent average real
  growth in the budget experienced by the Navy from 1963
  to 1981.

### On Warfare

One important effect of the rising fuel costs on naval warfare will
be on the size and readiness of the Navy. The Navy's capabilities at
the outbreak of a future conflict will be less than they would have been
with stable fuel costs.

Another aspect of the problem of petroleum availability is the fact
that the Persian Gulf has up to two-thirds of the non-Communist world's

reserves of petroleum. Access to that region will continue to be essential to the U.S. and its allies. To insure that access, the Navy must be able to keep the sea lanes open.

The level of both civil and military reserves will affect the availability of military fuels during supply disruptions. In addition, these stock levels could be a major determinant of the nation's response to conflicts that reduce imports of petroleum. Because oil shortages impair the economy, pressures for quick resolution of conflicts--either through escalation or by submission--are apt to be greater in an environment where petroleum stocks are low.

Fuel rationing could produce similar responses. Wars that fail to engage the support of the American public could be more difficult to prosecute when accompanied by fuel shortages and rationing. As in the case of low oil stocks, the pressure would be in the direction of quick resolution of the conflict.

## On Weapons

The effect on the choice of weapons will be similar to other situations in which resource costs rise appreciably. Substitutes and different ways to perform missions will become increasingly attractive as the economic burden of higher priced fuel becomes clearer to planners. In the acquisition of new weapons, fuel efficiency will become a more important factor, provided likely increases in fuel prices are treated realistically in the estimates of life-cycle costs. The problem of uncertain supplies of fuel in a crisis will also make fuel-efficient alternatives more attractive.

As fuel of lower quality becomes more prevalent, there will be corresponding decreases in reliability and increases in maintenance requirements for ships and aircraft. Engine modifications could reduce these effects somewhat.

The advantages of designing future engines for ships and aircraft to be less sensitive to variations in fuel specifications will become apparent. In addition, there will be pressures to move toward fuel that is more widely used by other military and civilian users. These changes could lower costs and increase supplies.

In manned aviation, conservation efficiencies and simulators will provide added fuel savings. However, very large savings could only result from reduced operations or as a byproduct of some long-term substitutions--such as cruise missiles for manned aviation.

## On Mobility

Diesel engines are more fuel efficient than gas turbines. At low power settings, steam powerplants are even more fuel efficient than gas

turbines. Low-speed diesels and steam engines are also less sensitive than gas turbines to variations in the quality of fuel.

Nuclear power provides the greatest freedom from reliance on petroleum. The higher procurement costs of large nuclear ships can be offset by their lower operating costs as the real price of petroleum increases in the future. Oil prices have risen enough already so that the undiscounted life-cycle costs of nuclear-powered carriers are nearly equal to the conventionally powered carriers. For smaller ships, fuel prices will have to rise further before the life-cycle costs of nuclear and nonnuclear ships are equal. For example, in comparing Aegis cruisers, annual real price rises of about 6 percent in the undiscounted case and 9 percent in the discounted case would yield equal system life-cycle costs.

The prospect of higher fuel costs also adds to the comparative advantages of sealift over airlift. Defense leaders should consider relying more on sealift capabilities to meet the nation's needs for strategic mobility.

RECOMMENDATIONS

The study concludes with the following recommendations:

- The Navy needs strong management of energy-related matters to implement conservation and to help it adjust to the constraints imposed by the higher cost, lower availability, and poorer quality of fuel. All relevant energy information—including the nuclear aspects—should be available to Navy planners for a complete management perspective on the Navy's energy problems and options.

- A strong and comprehensive R&D program should be maintained to increase fuel efficiency and prepare for problems of degraded fuel quality.

- The life-cycle costs of nuclear ships are higher than those of conventionally powered ships at today's fuel prices. In spite of this, the advantages of nuclear power in the projected energy environment make all large ships of the future much stronger candidates for nuclear power than they are now.

- Because of their greater efficiency and tolerance for varying fuel quality, diesel engines should be used more widely on smaller ships.

- Large civilian and military reserves of petroleum give significant protection against disruptions in the petroleum market and curtailed supplies of fuel. Large civil and military reserves should be vigorously supported.

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# GLOSSARY

| | |
|---|---|
| Aromatics | ring hydrocarbons with alternating double bonds; undesirable components of distillate fuels, because they are difficult to burn in gas turbines and diesels |
| Availability of fuel | defined for this study as the accessibility of fuel and often used as if price were not a factor |
| CG | conventionally powered guided-missile cruiser |
| CGN | nuclear-powered guided-missile cruiser |
| Conservation efficiences | reductions in a system's fuel consumption with little or no loss of capability and sometimes resulting in improved capabilities in such areas as noise levels, infrared signatures, endurance, speed, and maneuverability |
| Contaminants | components of fuel other than hydrocarbons; such as ash, sulphur, nitrogen, and heavy metals |
| Conventional oil | crude oil and natural gas liquids |
| Cost, affordability | the economic cost of the fuel resource; usually measured in terms of foregone opportunities or alternatives for spending |
| CV | conventionally powered aircraft carrier |
| CVN | nuclear-powered aircraft carrier |
| DEEMS | Defense Energy Emergency Management System |
| DFM | diesel fuel, marine; distillate fuel used by Navy ships |
| DFSC | Defense Fuel Supply Center |
| Discounting | the process of calculating the present values of future outlays to determine the time value of money assuming a 10-percent discount (interest) rate |

| | |
|---|---|
| Energy density | energy content of a substance per unit of mass or volume |
| Enhanced oil recovery | various methods to produce additional petroleum after natural displacement and waterflooding have been used; such as additions of chemicals to waterflooding, carbon dioxide flooding, steam injection, or in situ combustion |
| EPA | Extended Planning Annex to POM-82 |
| Excess productive capacity | ability of a country to increase it petroleum production above its current output |
| Finding rate | the number of barrels of new petroleum found in relation to the amount of exploratory drilling |
| GNP | gross national product |
| Hydrocracking, hydrotreating | treatment of crude with hydrogen to break down large molecules or to remove various contaminant compounds |
| IEA | International Energy Agency |
| Infrastructure | the pipelines, refineries, storage, and supply system associated with the use of an energy source |
| JP-5 | distillate fuel used by Navy jets and turboprop aircraft |
| Life-cycle cost | the total cost of a system over its projected lifetime |
| LWNPP | lightweight nuclear powerplant |
| mmb/d | millions of barrels per day |
| MPN | military personnel, Navy |
| NAP | Naval Aviation Plan |
| NGL | natural gas liquids |

| | |
|---|---|
| OPEC | Organization of Petroleum Exporting Countries |
| Operating tempo | a measure of the fraction of time (hours or days) that ships or aircraft operate during a given period |
| O&MN | operations and maintenance, Navy |
| O&S | operating and support |
| Proven reserves | the quantity of petroleum in known oil fields that is known with reasonable certainty to be recoverable under prevailing economic and technical conditions |
| Quality of fuel | the characteristics of fuel relative to well-refined petroleum that determine how it burns |
| R&D | research and development |
| SPR | Strategic Petroleum Reserve |
| Synthetic fuel, synfuel | fuel derived from shale oil, oil from tar sands, or coal-based liquids |
| Thermal stability | the degree to which a fuel will form deposits as its temperature is increased |
| TOA | total obligational authority |
| Ultimately recoverable resource | the total quantity of petroleum whose extraction is economically feasible up to a certain price |

APPENDIX A

DISRUPTIONS IN WORLD PETROLEUM SUPPLIES

## APPENDIX A

## DISRUPTIONS IN WORLD PETROLEUM SUPPLIES

The Arab embargo in 1973 and the Iranian Revolution in 1978 and 1979 severely disrupted world petroleum markets. The shortfalls are shown in tables A-1 and A-2 below:

### TABLE A-1

### OPEC OIL PRODUCTION, SEPTEMBER 1973 TO APRIL 1974
(Millions of Barrels per Day)

|  | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr |
|---|---|---|---|---|---|---|---|---|
| **Arab countries** | | | | | | | | |
| Saudi Arabia | 8.5 | 7.8 | 6.3 | 6.6 | 7.5 | 7.8 | 8.1 | 8.7 |
| Kuwait | 3.5 | 3.1 | 2.6 | 2.6 | 2.8 | 2.8 | 2.8 | 2.8 |
| UAE | 1.4 | 1.3 | 1.2 | 1.0 | 1.2 | 1.3 | 1.5 | 1.6 |
| Qatar | 0.6 | 0.6 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Libya | 2.3 | 2.4 | 1.8 | 1.8 | 2.0 | 1.9 | 1.9 | 1.7 |
| Iraq | 2.2 | 1.8 | 2.0 | 2.1 | 1.8 | 1.8 | 1.8 | 1.9 |
| Algeria | 1.1 | 1.0 | 0.9 | 0.9 | 1.0 | 1.0 | 1.0 | 1.0 |
| Total | 19.6 | 18.0 | 15.3 | 15.5 | 16.8 | 17.1 | 17.6 | 18.2 |
| **Non-Arab countries** | | | | | | | | |
| Iran | 5.8 | 6.0 | 6.0 | 6.1 | 6.1 | 6.2 | 6.1 | 6.2 |
| Nigeria | 2.1 | 2.2 | 2.2 | 2.3 | 2.2 | 2.2 | 2.3 | 2.3 |
| Venezuela | 3.4 | 3.4 | 3.4 | 3.3 | 3.3 | 3.2 | 3.2 | 3.0 |
| Indonesia | 1.4 | 1.4 | 1.4 | 1.4 | 1.5 | 1.4 | 1.4 | 1.4 |
| Ecuador | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Gabon | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 |
| Total | 13.1 | 13.4 | 13.4 | 13.5 | 13.5 | 13.4 | 13.4 | 13.3 |
| **Total for OPEC countries** | 32.7 | 31.4 | 28.7 | 29.0 | 30.3 | 30.5 | 31.0 | 31.5 |
| **World production** | 57.5 | 56.0 | 53.1 | 53.7 | 55.5 | 55.7 | 56.3 | 56.9 |

Source: [A-1].

## TABLE A-2

### DEPARTMENT OF ENERGY'S ANALYSIS OF THE EFFECT OF IRANIAN CURTAILMENT ON FREE WORLD OIL PRODUCTION[a]
(Millions of Barrels per Day)

| | 4th quarter 1978 | | | 1st quarter 1979 | | |
|---|---|---|---|---|---|---|
| | Prior project | Actual | Change | Projected before curtailment | Projected after curtailment | Change |
| **OPEC** | | | | | | |
| Iran | 6.2 | 3.8 | -2.4 | 5.9 | 1.1[b] | -4.8 |
| Saudi Arabia | 9.2 | 10.2 | 1.0 | 8.7 | 10.1 | 1.4 |
| Iraq | 2.7 | 3.1 | 0.4 | 2.7 | 3.1 | 0.4 |
| Nigeria | 2.2 | 2.3 | 0.1 | 2.2 | 2.4 | 0.2 |
| Kuwait | 2.3 | 2.4 | 0.1 | 2.0 | 2.6 | 0.6 |
| Libya | 2.1 | 2.1 | — | 2.1 | 2.2 | 0.1 |
| Venezuela | 2.3 | 2.4 | 0.1 | 2.2 | 2.4 | 0.2 |
| Other OPEC | 5.6 | 5.8 | 0.2 | 5.6 | 5.8 | 0.2 |
| Total OPEC | 32.6 | 32.1 | -0.5 | 31.4 | 29.7 | -1.7 |
| **Non-OPEC** | | | | | | |
| United States | 10.3 | 10.3 | — | 10.8 | 10.7 | -0.1 |
| Canada | 1.6 | 1.7 | 0.1 | 1.7 | 1.8 | 0.1 |
| North Sea | 1.7 | 1.7 | — | 1.7 | 1.8 | 0.1 |
| Other developed countries | 0.8 | 0.8 | — | 0.9 | 0.9 | — |
| Mexico | 1.5 | 1.4 | -0.1 | 1.5 | 1.5 | — |
| Other LDC's | 3.5 | 3.5 | — | 3.5 | 3.5 | — |
| Net CPE exports | 1.0 | 1.0 | — | 1.0 | 1.0 | — |
| Total, non-OPEC | 20.4 | 20.4 | — | 21.1 | 21.2 | 0.1 |
| Total production | 53.0 | 52.5 | -0.5 | 52.5 | 50.9 | -1.6 |

Source: [A-2].

[a]Includes NGL and processing gains.
[b]Production at 600,000 barrels per day from January 1 to March 3, rising to 2,500,000 barrels per day by March 13, maintained at 2,500,000 barrels per day for rest of month.

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APPENDIX B

CALCULATION PROCEDURES TO ESTIMATE BUDGET
INCREASES AND PROGRAM REDUCTIONS

## CALCULATION PROCEDURES TO ESTIMATE BUDGET
## INCREASES AND PROGRAM REDUCTIONS

This appendix outlines the computations used to estimate the effects of fuel price rises from 1981 to 2000 on Navy budgets, force levels, and the tempo of operations. It also includes details on the anticipated fuel consumption of Navy ships and aircraft in year 2000.

The effects of price rises determined from these calculations are illustrative. Several simplifying assumptions were made and representative values of parameters were used to facilitate the computations. Forces were initially set to levels planned for FY 2000. The operating tempo was assumed to remain the same on a per ship and per aircraft basis as in FY 1979. Finally, increases in the price of fuel were offset entirely by the budgets for operations and procurement, respectively, instead of allowing for a combination of approaches.

### PARAMETER DEFINITIONS

The fundamental equation employed for this work relates the cost of fuel to both the price and total fuel consumption. This is written simply:

$$C = PF = P \sum_k N_k H_k R_k . \qquad \text{(B-1)}$$

The parameters in this relation are defined by

$C$ $\;=\;$ annual fuel cost (dollars per year)

$P$ $\;=\;$ fuel price (dollars per barrel)

$F = \sum_k N_k H_k R_k$ $\;=\;$ total annual fuel consumption (barrels per year)

$N_k$ $\;=\;$ number of ships or aircraft of type $k$ (units)

$H_k$ $\;=\;$ operating tempo of units of type $k$ (hours per unit-year)

$R_k$ $\;=\;$ unit fuel consumption rate of type $k$ (barrels per hour).

Each  e above variables may either be held constant in time or be varied during a time period. For the current study, this period was set to the years 1981 to 2000. Several different cases are examined in the sections that follow.

## FUEL COSTS PAID FOR FROM AN EXTERNAL BUDGET

In this first simple case, computations are performed for a single year, FY 2000. The total fuel consumption of all ships and aircraft is calculated from estimates of $N_k$, $H_k$, and $R_k$ made for the normal operation of each type. Results of these calculations are summarized in a separate classified publication [B-1]. Fuel savings due to conservation efficiencies are included either by adjusting the value of each $R_k$ or by reducing the total F. Note that these are separate from fuel savings due to reduced operations.

Under these conditions, equation (B-1) shows that the fuel cost is a linear function of the price P. Nonlinearities would result from variations in F as P changes. However, it is assumed that excess fuel costs are paid for from an external budget that does not reduce consumption.

## ANNUAL RISE IN A BUDGET TO NEGATE AN ANNUAL FUEL COST INCREASE

Instead of only treating the case of 1 year, as in the previous section, an analysis can also be made of fuel price rises over time. If, again, annual fuel consumption is kept the same, but the price is allowed to increase at the annual rate $i_c$, cost and price are related by this formula:

$$c^i/c^0 = p^i/p^0 = \left(1 + i_c\right)^i . \tag{B-2}$$

The time step is denoted by i, representing the years 1981 to 2000 by the numbers 0 through 19. The initial fuel cost $c^0$ and price $p^0$ are known.

A budget is designated to pay for all costs above the base level through annual rate increases $i_B$. Starting from the initial amount $B^0$, assumed to be the FY 1981 Navy total obligational authority (TOA) of \$50.9 billion, the budget is allowed to grow according to

$$B^i/B^0 = \left(1 + i_B\right)^i , \tag{B-3}$$

where $i_B$ is a constant to be determined. It can be shown that the discrete relationships of equations B-2 and B-3 are also expressible in terms of continuous relations. The relationships are written as

$$C_t = C_0 \left(1 + i_C\right)^t = C_0 e^{a_C t} \tag{B-4}$$

$$B_t = B_0 \left(1 + i_B\right)^t = B_0 e^{a_B t} . \tag{B-5}$$

The constants $C_0$ and $B_0$ are still the initial fuel cost and budget; $a_C$ and $a_B$ are only the constants

$$a_C = \ln\left(1 + i_C\right) \text{ and } a_B = \ln\left(1 + i_B\right) . \tag{B-6}$$

The time $t$ has units of years and extends over the period from $t = 0$ to $t = t_f$, with $t_f$ set to 19 for this analysis.

Total excess fuel costs above the base level $C_0$ are set equal to the overall rise in budget above $B_0$ during the period $t = 0 - t_f$ to compute the effective annual budget increase $i_B$. Mathematically, this is expressed by

$$\int_0^{t_f} (B_t - B_0)dt = \int_0^{t_f} (C_t - C_0)dt . \tag{B-7}$$

The two integrals written above differ only by their values of constants employed as multipliers and in exponents. Both are easily integrated to yield this result:

$$\frac{\left(1 + i_B\right)^{t_f} - 1}{\ln(1 + i_B)} = t_f + \frac{C_0}{B_0} \left[ \frac{\left(1 + i_C\right)^{t_f} - 1}{\ln(1 + i_C)} - t_f \right] . \tag{B-8}$$

The right-hand side of this equation is completely specified, which enables $i_B$ to be solved for using any of several standard iterative techniques. A first guess for $i_B$ may be generated from an expansion of equation B-8 and a retention of terms to the second power in both $i_B$ and $i_C$, because they are assumed to be small. Equation B-8 then reduces to

$$i_B \approx \frac{C_0}{B_0} i_C \qquad (i_B, i_C \ll 1) . \qquad (B-9)$$

The behavior shown by this expression could have been anticipated for small price increases over short time periods.

Effects of Conservation on Annual Budget Increases

In the previous section, total fuel consumption $F$ was maintained at one level, but price was allowed to vary with time. If fuel savings from conservation measures were also considered, $F$ would fall with time from its initial value $F_0$. The ratio of $F$ to $F_0$, here termed $r$, can then be viewed as the weighted average of the relative consumption curves for all ships and aircraft. Because of the large uncertainties about the actual course conservation will take, this function is assumed to be a straight line. With the value of $r$ at time $t_f$ denoted by $r_f$, this is written

$$r = F/F_0 = 1 - (1 - r_f)t/t_f . \qquad (B-10)$$

Now equation B-4 is modified to read

$$C_t = C_0 \left(1 + i_C\right)^t \left[1 - (1 - r_f)t/t_f\right] . \qquad (B-11)$$

This expression is then substituted into equation B-7. The left-hand side of this equation is not altered; the integral on the right-hand side is not difficult to evaluate, because $r_f$ and $t_f$ are

constants. The result is

$$\frac{\left(1 + i_B\right)^{t_f} - 1}{\ln(1 + i_B)} = t_f + \frac{C_0}{B_0} \left[ \frac{\left(1 + i_C\right)^{t_f} - 1}{\ln(1 + i_C)} - t_f \right] \qquad \text{(B-12)}$$

$$- \frac{C_0}{B_0} \frac{1 - r_f}{t_f \left[\ln(1 + i_C)\right]^2}$$

$$\times \left\{ 1 + \left(1 + i_C\right)^{t_f} \left[ t_f \ln(1 + i_C) - 1 \right] \right\}$$

Equation B-9 indicates that for the case of no conservation, $i_B$ approaches zero as $i_C$ does. However, this is no longer true with conservation being considered. To examine the latter situation, the right-hand side of equation B-12 is first expanded for small $i_C$, and then the limit as $i_C$ approaches zero is taken, which gives

$$\frac{\left(1 + i_B\right)^{t_f} - 1}{\ln(1 + i_B)} = t_f - \frac{1}{2} \frac{C_0}{B_0} t_f (1 - r_f) \qquad (i_C \rightarrow 0) . \qquad \text{(B-13)}$$

The above relation enables the effective annual budget increase with conservation and a constant fuel price to be calculated. It may be realized that $i_B$ is now negative, indicating that the budget actually decreases. Equation B-13 can be approximated by expanding the left-hand side for small values of $i_B$. The result is

$$i_B \approx - \frac{C_0}{B_0} \frac{1 - r_f}{t_f} \qquad (i_C \rightarrow 0, \ |i_B| \ll 1) . \qquad \text{(B-14)}$$

This implies that the annual budget drop is proportional to the slope of the linear conservation function, with no price increase and small $i_B$. Furthermore, it confirms that $i_B$ vanishes when $r_f = 1$, which is the proper result.

## EXCESS FUEL COSTS PAID FROM PROCUREMENT BUDGETS

Another case to be considered involves charging excess fuel costs above a minimum level against procurement accounts. In this case, fewer ships and aircraft can be bought to make up for attrition, thereby causing a drop in force structure with time. It is assumed that forces would have remained at their initial level under the situation of no price increases. In addition, the average annual fuel consumption of a typical unit is presumed to stay the same.

For simplicity, calculations performed in this section are based on characteristics of an average ship or aircraft. Initially, the number of such average units is assumed to equal the total number of ships or aircraft from the first section of this appendix. With the subscript j referring either to all ships (j = S) or to all aircraft (j = A), this is expressed as

$$N_j^0 = \sum_k N_{kj} \qquad (j = S,A) . \qquad (B-15)$$

Now, an average rate of fuel consumption per unit is defined by

$$\overline{HR}_j = \frac{1}{N_j^0} \sum_k N_{kj} H_{kj} R_{kj} = \frac{F_j^0}{N_j^0} \qquad (j = S,A) , \qquad (B-16)$$

which is a constant over the time period. In essence, it represents the annual fuel consumption of all ships (or aircraft) divided by the total number of ships (or aircraft) before changes are made due to price increases.

The effect of these price rises from FY 1981 to FY 2000 is to increase fuel costs above a base level. At time step i, costs are denoted by $c_j^i$, but $c_{*j}^i$ represents the base cost. This last quantity may either be kept equal to the constant $c_j^0$, or be allowed to rise yearly by an amount $i_*$. This is written

$$c_{*j}^{i+1} = c_j^0 \left(1 + i_*\right)^i . \qquad (B-17)$$

For $L_* = 0$, this base remains constant at the initial level. The methodology involves reducing the force structure $N_j^i$ from the previous year by the equivalent number of units that could have been brought from procurement funds, but which instead were used to pay for excess fuel costs above $C_{*j}^{i+1}$. This calculation is then

$$N_j^{i+j} = N_j^i - \frac{C_j^{i+1} - C_{*j}^{i+1}}{b_j} , \qquad (B-18)$$

where $b_j$ is the acquisiton cost of an average unit.

Equation B-1 indicates that fuel costs are computed at step $i + 1$ by the formula

$$C_j^{i+1} = P^{i+1} F_j^{i+1} = P^{i+1} N_j^{i+1} \overline{HR}_j . \qquad (B-19)$$

If equation B-19 is substituted into equation B-18, $N_j^{i+1}$ may be solved for in the form

$$N_j^{i+1} = \frac{N_j^i + C_{*j}^{i+1} / b_j}{1 + P^{i+1} \overline{HR}_j / b_j} . \qquad (B-20)$$

Because at time step $i + 1$ all quantities on the right-hand side of this recursion relation have already been determined, the force structure can also be computed. Equation B-19 is then employed to give the fuel cost.

## Effects of Conservation on Force-Level Reductions

In the derivation of equations B-19 and B-20, it was assumed that $\overline{HR}_j$ did not vary with time. This restriction can be changed to include fuel savings from conservation. If these savings are apportioned over all ships or aircraft in relation to their unit consumption rates, a consumption factor $r_j^i$ is chosen in such a way that

$$R_{kj}^i = r_j^i R_{kj} . \qquad (B-21)$$

B-7

Thus, $r_j^i$ is the same factor for each ship and for each aircraft, depending on the value of $j$. Variable $R_{kj}$ stays equal to the value for each unit assigned in the previous section, but $r_j^i$ registers the drop in consumption as time progresses. In line with equation B-10, this factor is represented by the linear function

$$r_j^i = 1 - (1 - r_{jf}) \, i/i_f \qquad \text{(B-22)}$$

with $r_{jf}$ and $i_f$ replacing $r_f$ and $t_f$, respectively.

Fuel consumption per average unit from equation B-16 is now modified to read

$$\overline{HR}_j^i = \frac{1}{N_j^0} \sum_k N_{kj} H_{kj} r_j^i R_{kj} = r_j^i \overline{HR}_j \, , \qquad \text{(B-23)}$$

which results in the revision of equations B-19 and B-20 to

$$N_j^{i+1} = \frac{N_j^i + C_{*j}^{i+1} / b_j}{1 + P^{i+1} r_j^{i+1} \overline{HR}_j / b_j} \qquad \text{(B-24)}$$

$$C_j^{i+1} = P^{i+1} N_j^{i+1} r_j^{i+1} \overline{HR}_j \, . \qquad \text{(B-25)}$$

Note that by setting $r_{jf} = 1$, these relations reduce to those of the previous case. In this study, the following values were adopted: $i_f = 19$ and $r_{jf}$ was .815 for ships and .900 for aircraft.

CHANGES IN OPERATING TEMPO TO KEEP A CONSTANT FUEL COST WITH RISING PRICES

Instead of paying for excess fuel costs from other sources than normally used, the Navy could choose to hold down the cost of fuel. In this section, the reductions in the Navy's intensity of operations required to keep its fuel costs constant are calculated. It is assumed that forces and consumption rates are held constant. Also, effects of

conservation are included.  At one instant in time, an altered value of the fuel consumption per unit is computed from

$$\overline{HR}'_j = \frac{1}{N^0_j} \sum_k N_{kj} \, h_j \, H_{kj} \, r_j \, R_{kj} = h_j \, r_j \, \overline{HR}_j \, , \qquad (B-26)$$

where:

$$h_j = H'_{kj} / H_{kj} \qquad \text{and} \qquad r_j = R'_{kj} / R_{kj} \, . \qquad (B-27)$$

Both $h_j$ and $r_j$ have been assumed to be the same for each ship and aircraft.  The former represents the relative operating tempo in the modified situation to the original level; conservation is again introduced through the factor $r_j$.

The adjusted cost of fuel is set equal to the original cost $c^0_j$. Equation B-1 may then be employed to yield

$$P' \, N'_j \, \overline{HR}'_j = P^0 \, N^0_j \, \overline{HR}_j \, . \qquad (B-28)$$

Because force levels have been maintained unchanged, they may be cancelled in the above relation.  Substituting equation B-26 into equation B-28 and rearranging them gives the result

$$h_j = \frac{1}{r_j P' / P^0} \, . \qquad (B-29)$$

This indicates that the ratio of altered-to-original operating tempo is inversely proportional to two factors.  The first represents the effects of conservation, and the second gives the relative price change.

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        Wilson and Thomas C. O'Neill, Secret Restricted Data, 1 Sep 1981

**APPENDIX C**

**COST AND ENERGY CONSIDERATIONS
FOR NUCLEAR SHIPS**

# APPENDIX C

## COST AND ENERGY CONSIDERATIONS
## FOR NUCLEAR SHIPS

### NUCLEAR FUEL COSTS

The Navy pays for nuclear fuel in a different manner than it does for conventional fuel. Instead of purchasing it through the Defense Fuel Supply Center (DFSC), the Navy contracts with the Department of Energy for an entire reactor fuel loading, but then pays for only the amount of uranium consumed during each period. This "uranium burnup charge" was included in performing calculations of the annual operating costs of nuclear ships in [C-1]. The nuclear fuel costs were taken from Admiral Rickover's testimony to the Senate [C-2] and then adjusted for future price increases.

The price of nuclear fuel was escalated using projections made by the Electric Power Research Institute (EPRI) [C-3]. With FY 1981 as a base, EPRI expects the price of uranium fuel in the civil sector to increase linearly each year by 3 percent above inflation, under conditions of no reprocessing. Although the Navy is presently reprocessing spent nuclear fuel, this estimate was judged to be the most reasonable of those available.

With a 3-percent rise over the ship's lifetime (40 years, including construction time), the average uranium burnup costs should be about 77 percent greater than FY 1981 levels or 88 percent above FY 1979 costs. This burnup charge represented less than 0.3 percent of the adjusted life-cycle costs of the ships considered in the analysis. Thus, large changes in the burnup charge alter the life-cycle costs only slightly.

A price rise of 3 percent might appear somewhat low. Although the future of uranium costs is uncertain, indirect support for the 3-percent figure comes from [C-4]. This paper anticipates that the U.S. will become dependent on inexpensive foreign sources of uranium within a decade, unless giant domestic uranium deposits can be found soon. The availability of abundant and inexpensive foreign uranium, partially from such giant deposits, is expected to hold down prices.

Although this view is in contrast with recent experience with oil, it reflects to a degree the situation encountered a few decades ago in the petroleum industry. On the other hand, the discovery of huge U.S. uranium supplies would probably also serve to keep prices low.

ENERGY REQUIREMENTS OF NUCLEAR POWERPLANTS

A widely held view is that nuclear power is a net energy deficit
for the nation, because of the large amounts of energy required to
process nuclear fuel. Even if this were true, it might not be a valid
objection to the use of nuclear propulsion by the Navy. This is because
nuclear power still replaces petroleum fuel that the Navy would other-
wise need. This fuel could either be in short supply locally during
crises, or could rise drastically in price, as was already discussed.

Nevertheless, the argument that nuclear powerplants consume more
energy over their life cycle than they produce has been shown to be
incorrect by a study done in the civil sector [C-5]. The results of
this study indicated that the output electrical energy of light water
reactors can be more than 3.5 times the total energy required for its
production. Because some of that input energy is supplied by the
plant's nuclear fuel, the electrical output energy was also shown to be
more than 20 times the amount that could be potentially input by fossil
fuels. The nuclear fuel used by Navy ships is more highly enriched,
however, so that these results would have to be modified to be directly
applicable.

DISCOUNTING THE COSTS OF NUCLEAR AND CONVENTIONAL SHIPS

The discount factors given in table 7-1 for each component of ship
life-cycle costs were used to determine the discounted costs also pre-
sented here. The calculations performed to establish those factors are
outlined below.

A general relation for a discount factor (DF) is given by the
compound interest formula

$$ DF = \sum_{i=i_1}^{i_2} \frac{a_i}{(1 + d)^i} \, , $$

where $d$ is the discount rate (assumed in this study to be 0.10), $a_i$
is a coefficient that varies with index $i$, and $i$ represents the
years 1981 to 2021 by the corresponding numbers 0 to 40. The summation
is carried out from 1 year, which corresponds to $i_1$, through a second
year, represented by $i_2$. The values of $i_1$, $i_2$, and $a_i$ were
determined for each component of the life-cycle costs as follows:

Procurement:

$i_1 = 1$, $i_2 = 10$ .

The coefficients $a_i$ are, from [C-6]:

| $i =$ | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| $a_i =$ | .026 | .134 | .19 | .16 | .15 | .13 | .06 | .06 | .05 | .04 |

<u>Midlife conversion:</u>

$i_1 = i_2 = 25$ .

$a_i$ is a constant;  $a_i = 1$ .

<u>O&S and conventional fuel:</u>

$i_1 = 11$, $i_2 = 40$ .

$a_i$ is a constant; $a_i = 1/30$ .

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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This study evaluates petroleum issues facing the Navy over the next 20 years. It analyzes the threat of reduced availability of petroleum and the probable effects on naval warfare, on the selection of weapons, and on mobility. There are four areas of investigation: the current oil market, production forecasts, the prospect of import interruptions, and Navy options.

The study addresses the changes in the oil market since the embargo of 1973. It explains how those changes in the market have affected Navy budgets and eroded steaming and flying hours. Published forecasts of lowered production of petroleum and the threat of interruptions of imports are

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  evaluated for their potential to disrupt world markets out to the year
2000.  Several aspects of future petroleum supplies are quantified.  The study
concludes by recommending measures the Navy can take to deal with the problems
of reduced fuel availability and quality.