ORNL/TM-9671

OAK RIDGE NATIONAL LABORATORY

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Navy Mobility Fuels Forecasting System Phase I Report

R. M. Davis
G. R. Hadder
S. P. N. Singh
C. Whittle

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ENERGY DIVISION

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AUTHORS: R. M. Davis
G. R. Hadder
S. Singh
C. E. Whittle

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NAVY MOBILITY FUELS FORECASTING SYSTEM PHASE I REPORT

As part of a DOE/Department of the Navy agreement for an interagency program, ORNL developed and tested a modeling system for forecasting the availability and suitability of Navy mobility fuels.

BACKGROUND

Recent declines in the quality of crude oil entering world markets as well as the changing capabilities of domestic and world refineries have increased uncertainty in the future supply of military mobility fuels. Recognizing these trends, the Department of the Navy is developing an improved capability to forecast the availability and quality of fuels that are crucial to Naval operations.

OBJECTIVE

To develop a forecasting system for the Department of the Navy that can be used to analyze and forecast trends in mobility fuel quality and availability. The forecasting system is to be based on publicly available models that represent world energy markets in the years 1990 and 2000 and allow the analysis of fuel availability under business-as-usual and world market disruption scenarios. The system is to be validated against recent history and current world oil market conditions and compared against industry forecasts.

APPROACH

A review of current literature on fuel research was conducted to identify current trends in petroleum production and refinery characteristics and resulting fuel properties. A critical review of available models representing world energy markets was conducted, and three models were selected, modified, and assembled as the basis of the Navy Mobility Fuels Forecasting System. The three models selected were the Oil Market Simulation (OMS) model, the Petroleum Allocation (PAL) model, and the Refinery Evaluation Modeling System (REMS). REMS was modified to represent Navy aviation jet fuel (JP-5) and marine diesel fuel (F-76). The capabilities of the fuel forecasting system to forecast kerosene jet fuel availability was tested for the West Coast Bureau of Mines District 13 for both a business-as-usual and a hypothetical world oil market disruption in the year 1990. Alternative strategies for increasing the availability of jet fuel on the West Coast under the disruption scenario were evaluated.

RESULTS

The West Coast was selected as a test region because it has produced approximately half of the JP-5 required by the Navy in the United States in recent years and because it is a relatively self-contained region. This region has also been identified by other investigators as a critical pinch point in the production of Navy fuels. The modeling system was used to analyze the potential production of kerosene jet fuel (JP-5) from the West Coast refineries under a business-as-usual and disruption scenario in the year 1990. Under the assumptions of this hypothetical evaluation, jet fuel production on the West Coast could reach 45.2 thousand barrels per day under normal market conditions but could decline to 41.8 thousand barrels per day under the disruption case. Several strategies were evaluated with the forecasting system for recovering the lost production. It was found that the lost production could be restored by lowering the smoke point specification or by increasing the refinery gate price for jet fuel. The Navy Mobility Fuels Forecasting System was also exercised in a kerosene jet fuel producibility study of the West Coast region. ORNL's estimates of producibility averaged 10% higher than those published by Exxon and were comparable in magnitude in most cases for simple, moderate, and high complexity refineries.

CONCLUSIONS

The preliminary results indicate that the forecasting system can be used to forecast the availability and quality of specific Navy mobility fuels and to analyze fuel supply strategies and options. A more comprehensive analysis of Navy mobility fuels for the next 20 years is currently being conducted, including all regions in the United States and world refinery regions.

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Energy Division

NAVY MOBILITY FUELS FORECASTING SYSTEM PHASE I REPORT

Authors

R. M. Davis S. P. N. Singh
G. R. Hadder C. Whittle[1]

Contributors

S. Cohn S. B. Hu[2]
R. Curlee D. Dunbar[3]
G. Marland[1] B. Holcomb
A. Turhollow

[1]Oak Ridge Associated Universities
[2]Chinese Petroleum Corporation
[3]Private Consultant

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Navy Energy and Natural Resources R&D Office
Department of the Navy
Program Manager: Wayne Vreatt

Program Coordination with

Naval Air Propulsion Center
Coordinator: Buck Nowack
and
David Taylor Naval Research and Development Center
Coordinator: Richard Strucko

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LIST OF ACRONYMS

AIRA	American Independent Refiners Association
API	American Petroleum Institute
B/CD	barrels per calendar day
B/D	barrels per day
B/SD	barrels per stream day
BAU	business-as-usual
BBO	billion barrels of oil
BOM	Bureau of Mines
CONUS	Continental United States
DOD	Department of Defense
DOE	Department of Energy
DON	Department of the Navy
EIA	Energy Information Administration
GNP	Gross National Product
IEA	International Energy Agency
MB/CD	thousand barrels per calendar day
MB/D	thousand barrels per day
MB/SD	thousand barrels per stream day
MMBOE	million barrels of oil equivalent
NPC	National Petroleum Council
OAPEC	Organization of Arab Petroleum Exporting Countries
OMS	Oil Market Simulation
OPEC	Organization of Petroleum Exporting Countries
ORNL	Oak Ridge National Laboratory
PADD	Petroleum Administration for Defense District
PAL	Petroleum Allocation model
R&D	research and development
REMS	Refinery Evaluation Modeling System
TMA	Turner, Mason & Associates

EXECUTIVE SUMMARY

Recent declines in the quality of crude oil entering world markets as well as shifts in the capabilities of domestic and world refineries have increased uncertainty in the future supply of military fuels. Recognizing this trend, the Department of the Navy (DON) is developing an improved capability to forecast the availability and quality of fuels that are crucial to Navy operations. Changing fuel patterns are important in planning the Navy's Mobility Fuels R&D Program. The Oak Ridge National Laboratory (ORNL) has developed a forecasting system based on DOE Energy Information Administration models for the DON that can be used to analyze these trends. ORNL evaluated available information about past and present quantities and qualities of crude oil produced, investigated the current and expected capabilities of refineries to process crude oil, and assembled a computerized system to analyze those data and forecast future fuel trends.

A review of available literature and current Department of Defense (DOD) fuel research was conducted to identify current trends in petroleum production and fuel properties. This search was supplemented with interviews with industry experts to gain information about unpublished data. This investigation led to the general conclusion that both imported and domestic crude supplies have deteriorated in quality during the past decade. For example, average gravity of crude oils imported into the United States slipped from 33.7 degrees API in 1978 to 31.0 degrees API in 1983 while high-sulfur crudes rose from 5% to 25% of total crude imports during the same period. This trend results from the depletion of high-quality sources of crude oil and the exploitation of fields of lesser quality in recent years. The decline in the quality of crude oil reaching the world marketplace is expected to continue and will require additional downstream refining capability if product quality is to be maintained.

The lower quality crude oil feedstock has forced some refiners to either expand their downstream processing capabilities to process the heavier crudes or to go out of business. The number of operating refineries in the United States declined from 319 in 1980 to 247 in 1984 with most of the decline occurring among small and simple refining operations. The remaining refineries are broadening their capabilities by adding thermal and catalytic cracking, catalytic hydrocracking and hydrorefining, alkylation, isomerization, and other processes to their plants to refine the heavier feedstock crudes. The capital investment required for this industrial conversion is, in large part, eliminating the smaller, marginal refining operations. As of 1984, the United States refining industry had a utilization rate of approximately 72%, indicating that the industry still possessed excess refining capacity. However, the industry's capability appears to be constrained for specific fuel products in selected regions.

The investigations into the trends in crude oil and refinery characteristics served as a necessary background to the assembly of the Navy Mobility Fuels Forecasting System. The system was assembled and tested, based on three publicly available models developed and maintained by the Department of Energy, Energy Information Administration. The three models selected were the Oil Market Simulation (OMS) model, the Petroleum Allocation (PAL) model, and the Refinery Evaluation Modeling System (REMS). REMS was modified to represent Navy aviation jet fuel (JP-5) and Naval distillate (F-76).

The predictive capabilities of the fuels forecasting system were tested for the West Coast (Bureau of Mines Region 13) for both a business-as-usual (BAU) and a hypothetical world oil market disruption scenario. The West Coast was selected as a test region because it has produced approximately half of the JP-5 required by the Navy in the United States in recent years and because it is a relatively self-contained region. A preliminary test of the forecasting system was conducted to analyze potential JP-5 production from West Coast refineries under BAU and a disruption scenario in 1990. In this *hypothetical* study, JP-5 production capability could reach 45.2 thousand barrels per day under normal market conditions but could decline to 41.8 thousand barrels per day under the test oil disruption case. Several strategies for recovering the lost fuel production were evaluated with the forecasting system. It was found that the lost production could be restored by permitting lower smoke point specifications or by increasing market prices for the refined product. These preliminary results demonstrated the forecasting system's ability to predict the availability and quality of specific Navy mobility fuels in the coming decades and to analyze fuel supply strategies and options.

In the full report, an overview of the project appears in Sect. 1, the investigation of the quantity and quality of crude oil supplies is described in Sect. 2, the study of trends in refinery capabilities and flexibilities is presented in Sect. 3, the assembling and testing of the fuel forecasting system is explained in Sect. 4, and additonal helpful information (including a glossary of terms used, specifications for the particular Navy fuels analyzed, experimental details of the model sensitivity testing and a bibliography) is presented in a series of appendices.

ABSTRACT

The Department of the Navy (DON) requires an improved capability to forecast mobility fuel availability and quality. The changing patterns in fuel availability and quality are important in planning the Navy's Mobility Fuels R&D Program. These changes come about primarily because of the decline in the quality of crude oil entering world markets as well as the shifts in refinery capabilities domestically and worldwide. The DON requested ORNL's assistance in assembling and testing a methodology for forecasting mobility fuel trends. ORNL reviewed and analyzed domestic and world oil reserve estimates, production and price trends, and recent refinery trends. Three publicly available models developed by the Department of Energy were selected as the basis of the Navy Mobility Fuels Forecasting System. The system was used to analyze the availability and quality of jet fuel (JP-5) that could be produced on the West Coast of the United States under an illustrative business-as-usual and a world oil disruption scenario in 1990. Various strategies were investigated for replacing the lost JP-5 production. This exercise, which was strictly a test case for the forecasting system, suggested that full recovery of lost fuel production could be achieved by relaxing the smoke point specifications or by increasing the refiners' gate price for the jet fuel. A more complete analysis of military mobility fuel trends is currently under way.

1. INTRODUCTION

1.1. BACKGROUND TO NAVY FUEL USE AND THE NAVY MOBILITY FUELS R&D PROGRAM

The U.S. Navy (and Marine Corps) consumed 84.2 million barrels of oil equivalent (MMBOE) in 1982, and about 69% of the energy used was provided by oil to power aircraft and ships (Fig. 1.1). The Navy's two principal petroleum-based fuels were JP-5 (jet fuel) and F-76 [Naval distillate Fuel (NDF) and diesel fuel maine (DFM)] (Fig. 1.2). Projections of future fuel consumption continue to show heavy dependence on these mobility fuels to the year FY 1990 (Table 1.1).

Navy mobility fuels are essential to the operations of Navy ships, aircraft, and land-based vehicles. Prior to the mid-1970s, the bulk of these military fuels came from generally sweet low-sulfur good-quality domestic or imported crudes that required minimal processing.[2] More recently, however, crude sources with relatively higher sulfur content, such as those from Alaska and Mexico, have become more prominent in the marketplace. As the average quality of crude supplies declines, more extensive processing is required to obtain the required fuel specifications. This more extensive refining may lead to other fuel quality problems. For example, more severely processed fuels may have poor lubricating properties, resulting in more wear of fuel pumps and controls. This overall trend towards poorer quality crudes and more severe processing is expected to continue. Moreover, the introduction of crudes from synthetic sources, such as heavy oils, tar sands, and oil shale in the late 1990s (and possibly coal after the year 2000), may exacerbate this problem.

The Navy is conducting a Mobility Fuels R&D Program to improve its understanding of the relationships among fuel sources, processing, and properties and the effects these properties have on the performance and reliability of Navy propulsion systems. The R&D program is investigating the properties of fuels from new sources and processes, developing new test techniques, and determining

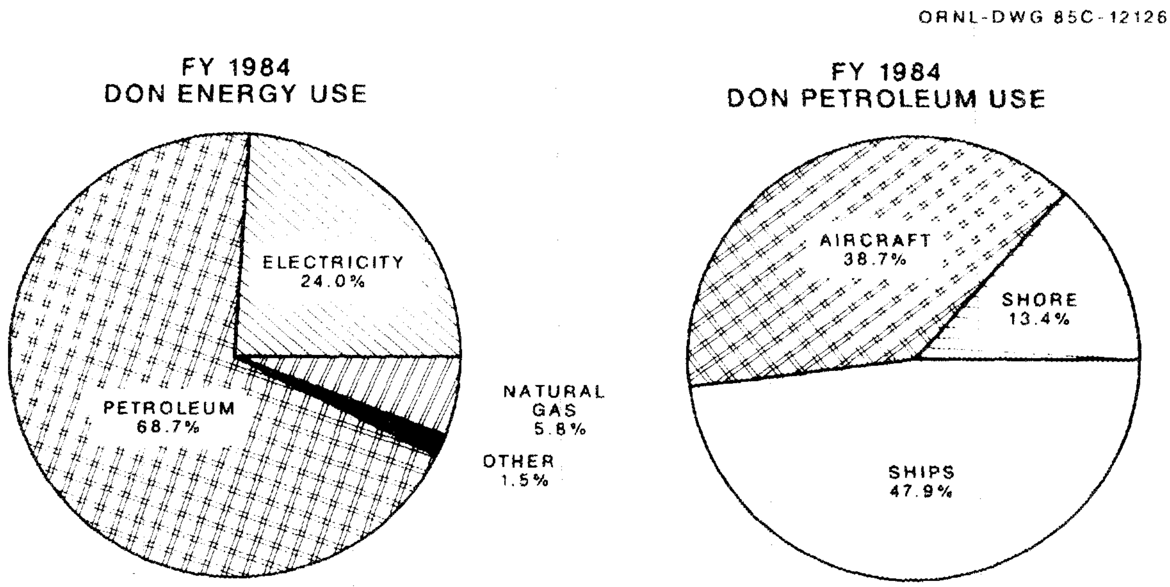

Fig. 1.1. Department of the Navy total energy use by energy source and petroleum use by end use. *Source:* Department of the Navy, *Energy Plan FY 1984–1990,* Washington, D.C., 1983.

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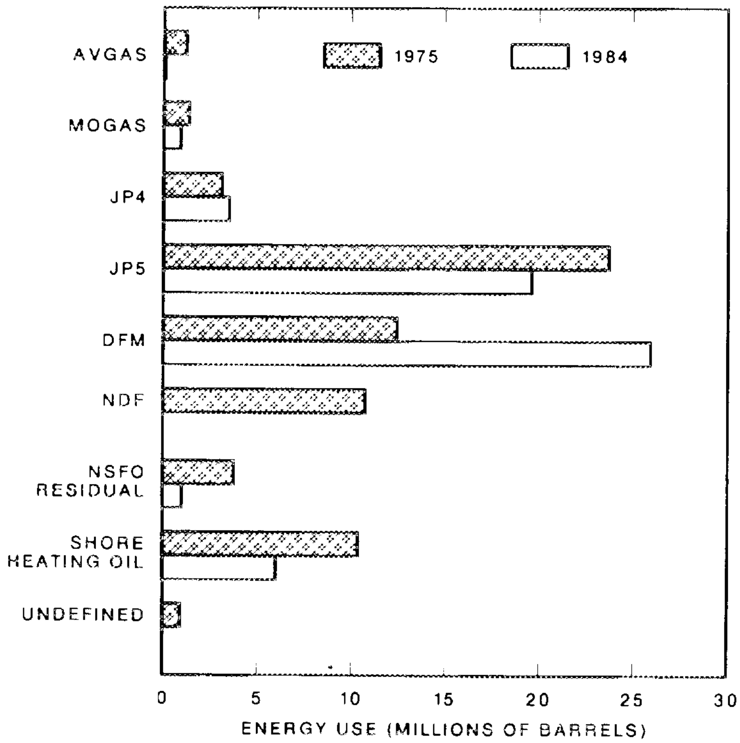

Fig. 1.2. Department of the Navy petroleum use by fuel type, fiscal years 1975 and 1984.

Table 1.1. Projected DON energy consumption (MMBOE) FY 85–FY 90[a]

Consumption	FY 1985	FY 1986	FY 1987	FY 1988	FY 1989	FY 1990
Ships	29.6	29.6	28.7	28.8	29.8	30.3
Aircraft	24.9	26.4	27.7	27.9	29.1	28.1
Shore facilities	26.9	26.7	26.5	26.3	26.2	26.1
Cold iron	3.4	3.5	3.4	3.5	3.7	3.7
Vehicles and ground support	2.0	2.0	2.0	2.0	2.0	2.0
Total	86.8	88.2	88.3	88.5	90.8	90.2

[a]*Source*: W. Vreatt, Navy Energy and Natural Resources R&D Office, Department of Defense, personal communication to R. M. Davis, Oak Ridge National Laboratory, Oak Ridge, Tenn., May 1985.

the tolerance of Navy propulsion systems to fuel property changes. One major objective of the program is to determine the revisions needed in fuel specifications, if any, so that fuels with required performance characteristics can be bought from available sources. DOD goals require specifications to be in place by 1990 that will be independent of crude source and processing except for coal-derived fuels. Specifications that will accommodate coal-derived fuels are to be included by 2000.

ORNL's program is one part of the DON's Mobility Fuels R&D Program. This effort is designed to help DON analyze future trends in mobility fuel availability and quality and to analyze selected technical, economic, and institutional strategies for coping with these trends. This information is needed to help DON plan future mobility fuels research and development.

1.2. STUDY OBJECTIVES AND SCOPE

This report describes work conducted by ORNL for the Navy Energy and Natural Resources R&D Office. The objective of ORNL's assignment was to assemble and implement an improved system for forecasting future trends in liquid fuel availability and quality. A modeling-based approach was selected by ORNL to represent the complex interactions among crude oil supply and quality, changing refinery trends, and the technical characteristics of specific refining operations used to produce Navy fuels. The modeling approach also represents the economic behavior of the commercial market sector in which the Navy must compete with all other users of crude oil and refined products. A two-phase program has been undertaken.

The objectives and scope of Phase I have been to

1. review and assemble available literature on the existing DON mobility fuel research technology base;
2. assemble a modeling system capable of forecasting trends in specific Navy fuel availability, quality, and cost; and
3. test and use the forecasting system to examine future production of selected Navy fuels for a sample U.S. region under 1990 BAU and world oil market disruption conditions.

1.3. PROJECT STATUS

In Phase I, a review was completed of (1) a substantial amount of literature of past or ongoing work in fuel technology research and (2) several models (available from public and private sources), of world energy supply, demand, and prices. Based on this review, publicly available models and data sets developed and maintained by the Department of Energy (DOE) were selected as the foundation of the improved forecasting system. The system consists of the Oil Market Simulation (OMS) model, Petroleum Allocation (PAL) model, and the Refinery Evaluation Modeling System (REMS). REMS was modified and tested to represent specific Navy fuels. The initial test of the forecasting system included a study of the potential production of Navy aviation jet fuel (JP-5) in the West Coast region of the United States under business-as-usual (BAU) and disrupted market conditions in 1990. The West Coast was chosen for the test region because it is a major supplier of JP-5 and is relatively independent of other domestic refining regions. In this test, the loss in JP-5 production from the hypothesized disruption was estimated, and various strategies for recovering the lost production were analyzed. ORNL concluded that the forecasting system could be used to identify specific Navy fuel availability and quality trends and to analyze fuel supply recovery strategies.

In Phase II, the forecast horizon will be expanded from 1990 to 2000, an up-to-date representation of world refineries will be added, and the forecasting system will be used to analyze the production of Navy fuels under a range of world oil disruption scenarios and recovery strategies. Phase II is currently under way and will be documented in a later report.

1.4. OVERVIEW OF NAVY MOBILITY FUELS FORECASTING SYSTEM

The Navy Mobility Fuels Forecasting System is based on a simplified representation of the world liquid fuels market. This system is shown conceptually in Fig. 1.3 and is discussed in detail in Sect. 4. The OMS model is used to forecast general world petroleum supply, demand, and prices. The PAL model is then used to calculate more detailed regional projections of crude and refined product production and consumption. PAL relates (1) the crude production by producing region with (2) refined products from region of processing with (3) region of consumption by using historical worldwide regional flows of crude oils and products. Then the REMS refinery yield model is used to estimate detailed quantities and qualities of refined products from each U.S. refinery region; it provides detailed information on the quantity, quality, and cost of typical refined product slates based on the types of crudes processed by the refinery. Each of the above models was developed under funding from DOE's Energy Information Administration (EIA). They are, therefore, in the public domain and are maintained and updated by the Department of Energy as new information is developed and becomes available.

1.5. LIMITATIONS AND INTENDED USE OF THE SYSTEM

The Navy Mobility Fuels Forecasting System provides a systematic framework for analyzing future fuel trends and strategies. However, the system has certain limitations. First, it is important that the models and data bases be updated and maintained as new information on propulsion

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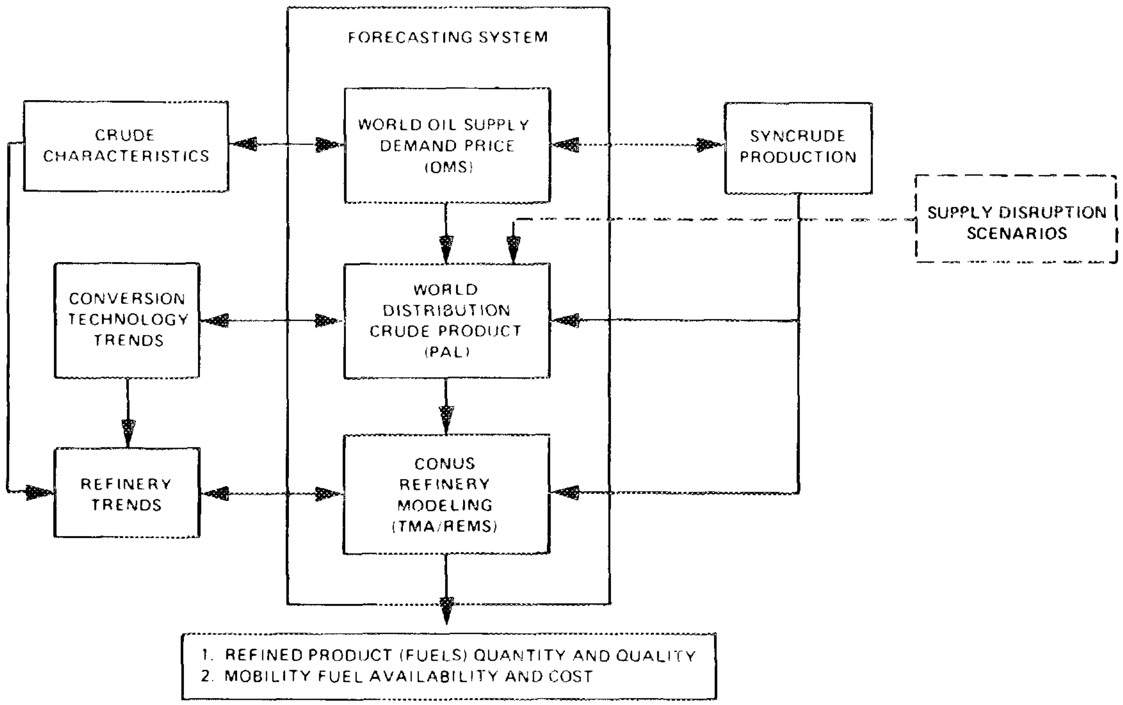

Fig. 1.3. Navy Mobility Fuels Forecasting System and supporting studies.

technologies, world oil markets, refinery trends, and other conditions is developed. Second, the accuracy of model forecasts should be continously cross-checked with history and current conditions as well as with other forecasting work to ensure that the results are reasonable. Although a substantial amount of literature was reviewed, only a limited amount of this information has actually been incorporated or cross-checked with the models to date. Similarily, the three models that make up the system (OMS-PAL-REMS) are currently connected by manual transference of data. The linkages between these models are still being improved. Third, models are only as good as the data and assumptions on which they are based. For example, fuel supply and demand implications from a potential breakthrough in the synthetics fuel industry, new propulsion technologies, fuel storage, the use of the Strategic Petroleum Reserve, or possible institutional strategies such as taxes, allocations, and the like are not accounted for in the forecasting system. These and other related factors may be considered in Phase II. Each of these limitations is important and should be recognized by the users of the system. Every effort has been made to recognize and minimize these limitations in the design of the forecasting system.

The primary purpose of the forecasting system is to help managers analyze fuel availability, quality, and cost trends; to analyze related recovery strategies for coping with fuel shortages; and to plan future fuel research programs. The Navy Mobility Fuels Forecasting System is designed to be used on a periodic basis to analyze trends in fuel availability and quality as new information and assumptions are developed. The system is most suitable for analyzing trends as opposed to making detailed, discrete fuel forecasts. A simplified interactive version of the system to be interactive and used directly by DON or other DOD fuel planners and managers will be developed in later phases of this work.

1.6. REFERENCES

1. Energy Information Administration, U.S. Department of Energy, *Petroleum Supply Monthly*, DOE/EIA-0109 (84/12), Washington, D.C., 1985.

2. Department of the Navy, *Energy Plan FY 1984–1990*, Washington, D.C., 1983.

2. PRELIMINARY REVIEW OF FUTURE CRUDE OIL RESERVE AND PRODUCTION CHARACTERISTICS

2.1. TASK OBJECTIVES

As world petroleum reserves are reduced, the quality of crude oil feedstocks to refineries is expected to decline, affecting the properties of the petroleum-based fuels produced. Problems associated with corrosion, soot, and instability will likely occur with these fuels and become more severe as heavier crudes with higher levels of contaminants are increasingly used as refinery feedstocks.

This task had two objectives. One was to review the available literature for data on obvious trends in the quality and quantity of the crude oil reaching the world market. The second objective was to identify data that could be used to improve or expand the inputs to the computer models used to calculate availability and characteristics of crude oil and petroleum products.

2.2. NEW PATTERNS IN U.S. PETROLEUM IMPORTS

Since 1978, three significant trends have influenced the U.S. petroleum industry: (1) crude oil import levels are down, reflecting lower domestic demand; (2) major shifts are taking place among traditional import sources; and (3) changes in import volumes and sources have changed the mix of crude oil qualities available to U.S. refineries, producing an increase in heavy high-sulfur crude oils.

In the United States the rate of gross imports of crude oil has fallen from 6.4 million barrels per day in 1978 to 3.3 million barrels per day during 1983. Imported oil, which accounted for about 40% of U.S. refinery feedstocks in 1978, made up only 26% of those feedstocks in 1983, despite the fact that imports for the Strategic Petroleum Reserve have remained unchanged at about 0.2 million barrels per day.[1]

The source of imported oil has also changed drastically in recent years. The inflexibility of the Organization of Petroleum Exporting Countries (OPEC) oil prices in the face of the increased worldwide competition and decreasing demand has made OPEC oil more expensive than that from other producers. Figure 2.1 shows the change in gross U.S. imports from OPEC and non-OPEC sources during the past five years. Figure 2.2 shows the changes in the percentages of U.S. imports from selected countries between 1978 and 1983.

Recent data[2] underscore the importance of viewing changes in import levels and sources in the context of the U.S. business cycle and in the context of the interactions among economic activity, seasonal demand for petroleum products, inventory strategies, and the price of oil. With the rally of the U.S. economy, imports from OPEC nations have increased in recent times. In August 1983, imports of OPEC crude oil reached an 18-month high of 2.7 million barrels per day, more than half of the U.S. crude oil imports. This increase reflected stepped-up imports from Algeria, Indonesia, and Saudi Arabia. The rate of importation from OPEC nations increased over that for similar periods the previous year from August 1983 to June 1984. Subsequently, the monthly rate of importation once again declined in comparison with the previous year's.

U.S. imports of petroleum have declined steadily since 1979, reducing U.S. dependence on foreign crude oil and petroleum products. At the same time, there has been a dramatic shift in the sources of U.S. petroleum imports away from members of the Organization of Petroleum Exporting Countries (OPEC) countries. In 1983, 37 percent of U.S. petroleum imports were from OPEC sources, compared with 42 percent in 1982, 55 percent in 1981, 62 percent in 1980, and 67 percent in 1979.

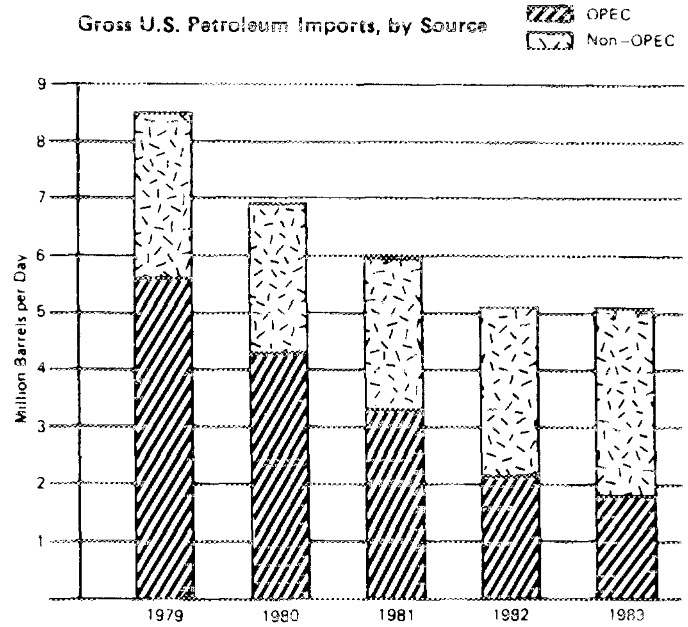

Fig. 2.1. U.S. imports from OPEC and non-OPEC sources. *Source: Petroleum Supply Monthly,* DOE/EIA-0109(84/2), U.S. Department of Energy, Energy Information Administration, February 1984, published April 1984.

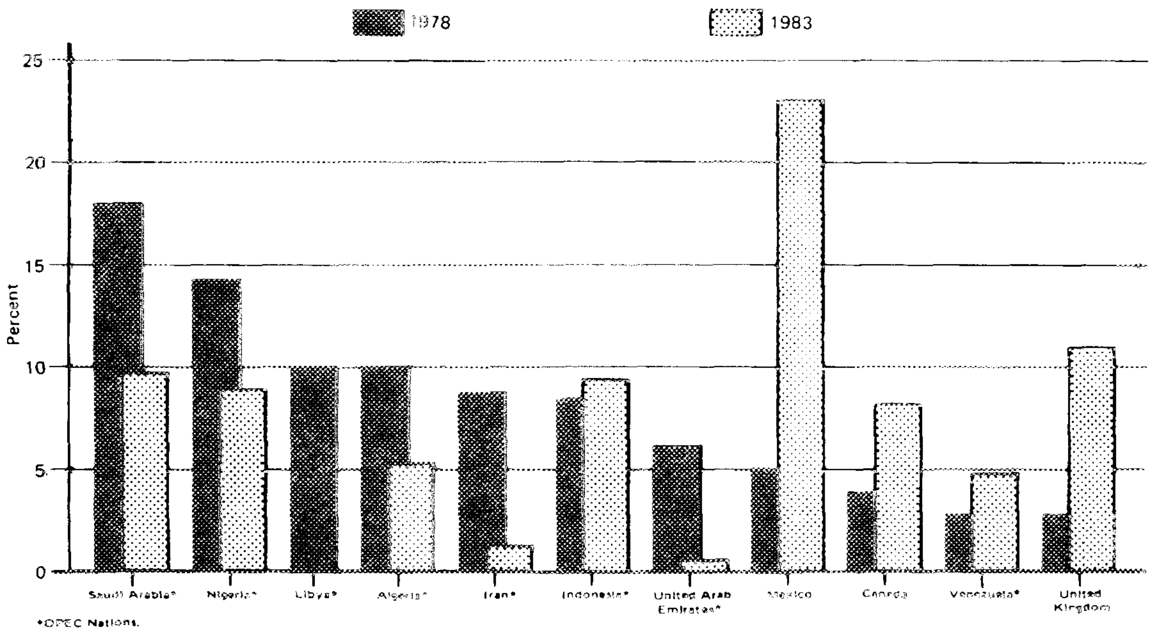

Fig. 2.2. Imports of crude oil from selected countries 1978 and 1983 (percent of total). *Source: Petroleum Supply Monthly* DOE/EIA-0109(84/2), U.S. Department of Energy, Energy Information Administration, February 1984, published April 1984.

2.3. CRUDE OIL CHARACTERISTICS

2.3.1. Overview/Description of Measures

The changes in import volumes and sources since 1978 also represent changes in the quality mix of crude oil available to U.S. refineries with a shift toward heavier crudes and increases in sulfur content.

Crude oils can be classified by several characteristics, such as viscosity, asphalt or paraffin base, and mineral content. The chemical composition of the crude oil fed into a refinery influences the mix of products that can be obtained from that refinery.

One important index of crude oil quality is weight per unit volume or density. A system of density measurement developed by the American Petroleum Institute (API) is the most commonly used measure of the density or specific gravity of crude oil. It uses units of degrees API gravity. As the API gravity increases, the crudes are generally lighter and more preferable. In general, the heavier crudes—those with lower API gravity—contain higher levels of sulfur and other mineral impurities.

2.3.2. Historic Values

Since the rate of U.S. crude production peaked in 1970, the quality of domestic crudes has slipped in terms of API gravity and sulfur content.

The average gravity of crude oils imported into the United States also slipped, from 33.7 degrees API in 1978 to 31.0 in 1983. As the total volume of crude oil imports declined, the percentage of heavy (below 25 degrees API gravity) crude oils imported increased at the expense of the higher priced light (above 37 degrees API gravity) crude oils (see Fig. 2.3).[1]

Between 1978 and 1983, there was also a notable increase in the percentage of high-sulfur crude oils imported. The average sulfur content of crude oil imports rose during the period from 1.0 to 1.3%. High-sulfur crudes (2.5% or more sulfur) accounted for 25% of the imports in 1983, compared with only 5% in 1978. Imported crudes with less than 1.5% sulfur accounted for 60% of the 1983 volumes, down from more than 75% during 1978 (see Fig. 2.4).[1]

Recent OPEC pricing developments have included a shrinkage in the light/heavy crude price premium. This reduction in the premium placed on light vs heavy import crude is related to the additional heavy crude conversion capacity that has been installed in the past three to four years in the United States.[3] Although the $1.00 per barrel (or greater) premium closure may be "significant," it probably will not affect the general trend towards heavier crude imports, but it could conceivably slow that trend.

2.3.3. Projected values

A study by Chase Manhattan estimated that the average crude stream (both import and domestic) used in the United States will slip further from 32.3 degrees gravity in 1984 to 31.7 degrees gravity by 1990.[4] Figure 2.5 gives the distribution by API gravity of the world's original crude oil reserves, and Fig. 2.6 gives a forecast for world crude oil gravity to 1990.[5] Detailed unpublished data on API gravity and sulfur content of crude oils are available by major producing fields.[6]

Chevron economist Tom Burns says that the refinery upgrading trend is a response by the oil industry to long-term trends not short-term markets. He believes that every indication points to a

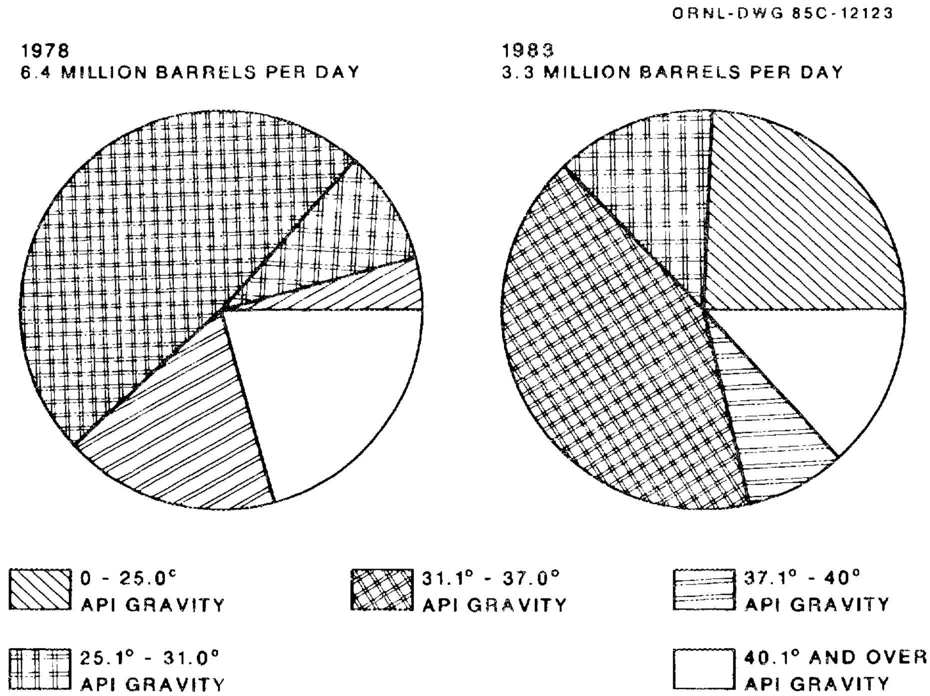

Fig. 2.3. API gravity of imported crude oil, 1978 and 1983. *Source: Petroleum Supply Monthly,* DOE/EIA-0109(84/2), U.S. Department of Energy, Energy Information Administration, February 1984, published April 1984.

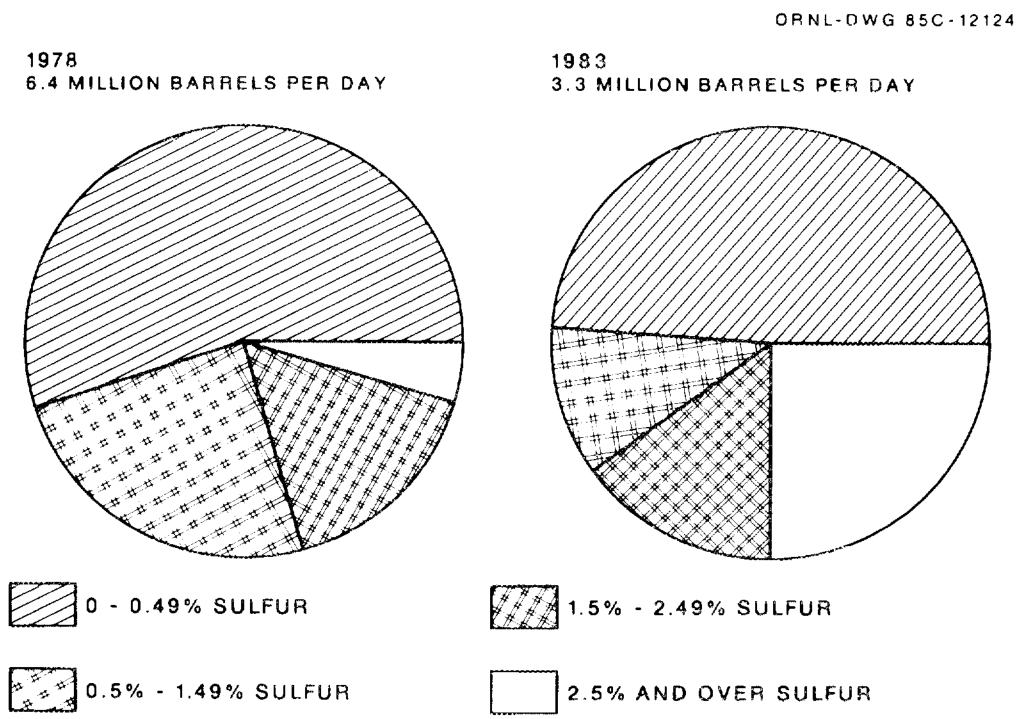

Fig. 2.4. Sulfur content of imported crude oil, 1978 and 1983. *Source: Petroleum Supply Monthly,* DOE/EIA-0109(84/2), U.S. Department of Energy, Energy Information Administration, February 1984, published April 1984.

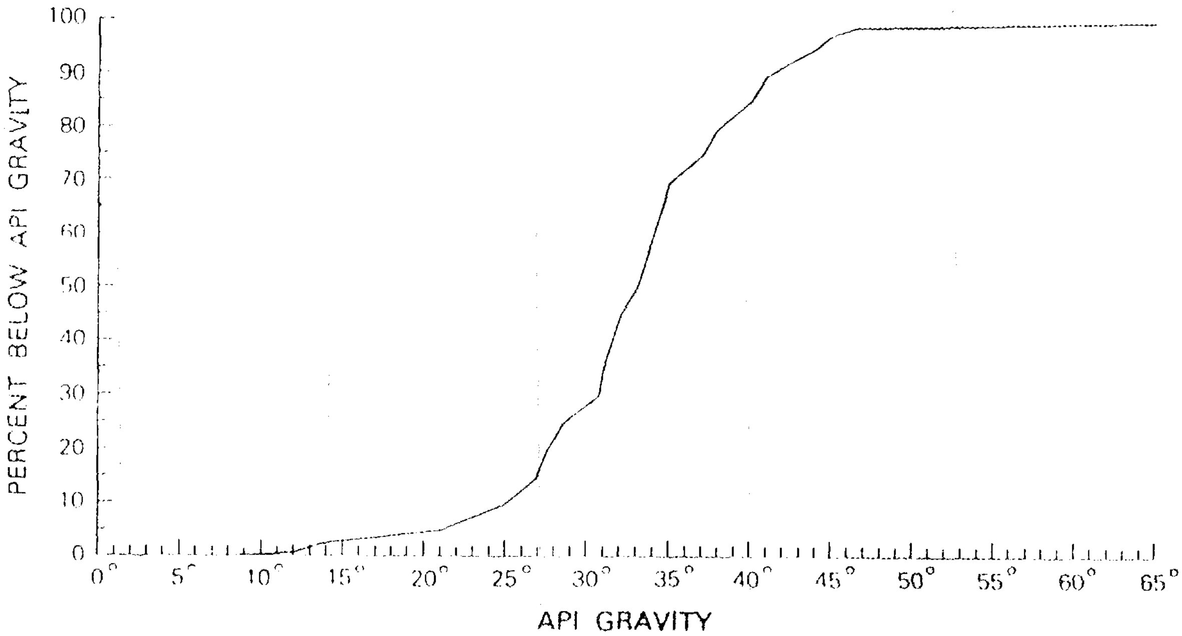

Fig. 2.5. Distribution of API gravity of world's original reserves of crude oil. *Source:* C. D. Masters, D. H. Root, and W. D. Dietzman, "Distribution and Quantitative Assessment of World Crude Oil Reserves and Resources," *U.S. Geological Survey Open-File Report,* USGS-OFR-83-728, 1983.

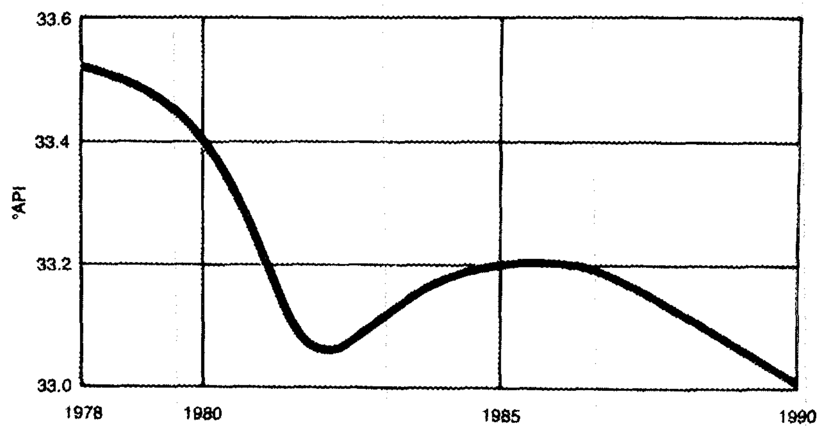

Fig.2.6. World crude gravity. *Source:* "LP Model Simulation Shows How Crude, Product Trends Will Shape U.S. Refining," *Oil and Gas J,* 83–92 (May 30, 1983).

greater proportion of heavy, high-sulfur crude oil in the future and to light oil being in short supply.[4]

2.4. PRODUCTION AND CRUDE OIL RESERVES

2.4.1. 1983 Values

The most complete data set on crude oil reserves and production (for the year 1983) results from a combination of data from publications[3,7,8] of the U.S. Department of Energy/Energy Information Administration (DOE/EIA) and from the *Oil and Gas J.*[9,10] Sixteen regions supplied 87% of the U.S. crude in 1983 (see Table 2.1). Annual data similar to that in Table 2.1 are available from the same sources for the past decade. The list was quite different a decade ago, especially in terms of the major exporting countries. Therefore, it is not surprising that the mix is quite different for the 1990s. The supply region mix can change because of new major discoveries, but is more likely to change for political reasons and because of changing transportation costs.

2.4.2. Projected values

Several studies project world and U.S. oil production and demand to the years 1995 through 2010.[5,11,12] These forecasts in general agree with each other in the aggregate.

The DOE/EIA forecast,[13] for example, projects oil production in the world market economies to increase steadily through 1995, as illustrated in Fig. 2.7. A large proportion of the additional oil is projected to come from OPEC countries. OPEC's share of total marketed production is projected to go from 43% in 1983 to 46% in 1995. The "other" countries group is projected to go from a net importer of oil in the 1980s to a net exporter by the 1990s. The industrialized countries are projected to remain net oil importers. Oil production in the industrialized countries is projected to decline by about 2.3% between 1983 and 1995. The largest percentage gains in production between 1990 and 1995 are projected to come from the "other" countries group. Mexico, currently producing around 3 million barrels per day, including gas liquids, is the largest producer among the "other" countries group and is, indeed, the fourth largest producer of oil in the world today, following the Soviet Union, the United States, and Saudi Arabia.

Although the U.S. domestic production of crude oil and natural gas liquids is now lower than in the peak year of 1970, generally stable production is projected through the 1980s, followed by a slow decline in the early 1990s (see Fig. 2.8). The DOE projects that petroleum consumption will grow at about half the rate of the gross national product (GNP) and that this rising consumption, along with stable or declining domestic production will produce a resurgence in crude oil and refined product imports.[11]

ICF, Inc., on the other hand, forecasts a drop in U.S. petroleum consumption based on an assumed real crude oil price of $47.50 per barrel by the year 2000. ICF also forecasts a lower growth in overall transportation fuel demand and a greater drop in gasoline consumption, which may also reflect the higher assumed price for oil.[14]

The Chevron Corporation studied[15] future supply scenarios in view of the uncertainties of war and the threat of (1) war in the Middle East, (2) the petroleum industry restructuring, and (3) overcapacity of OPEC. Figures 2.9 and 2.10 show the Chevron forecasts for oil consumption for crude oil production in the non-Communist world. Figure 2.11 illustrates Chevron's projection of an OPEC overcapacity, and Fig. 2.12 gives its forecast for expected U.S. oil supply through the year 2000.

Table 2.1. Data on 1983 crude oil reserves and production by 16 major U.S. supply regions

Region (country or state)	Proved reserves[a,b,c] 12/31/83 (millions of barrels)	1983 Current production[a,b] (millions of barrels)	1983 Production or export to U.S.[d] (millions of barrels)	1983 U.S. supply (%)
U.S.-Domestic (1982)	29,459	3,171		
Texas	7,982		903	
Alaska	7,406		626	
Louisiana	3,307		480	
California	5,413		405	
Oklahoma	1,049		159	
Wyoming	979		118	
New Mexico	619		75	
Kansas	380		72	
Total			2,838	65
Major Exporters to U.S.	293,000	5,925		
Mexico	48,000	986	280	
U.K.	13,150	825	133	
Saudi Arabia	166,000	1,778	117	
Indonesia	9,100	472	115	
Nigeria	16,550	450	110	
Canada	6,730	509	100	
Algeria	9,220	251	64	
Venezula	24,850	654	60	
Total			979	22
Worldwide	669,303	19,440		
U.S. Supply			4,386	100

[a]*Source:* "Surge of U.S. Refinery Upgrading Trims Heavy Feed, Boosts Prices," *Oil and Gas J.*, 17–21. April 30, 1984.

[b]*Source:* G. Marland, personal communication to W. D. Dietzman, DOE/EIA, Dallas, Texas, Field Office, September 13, 1984.

[c]*Source: Petroleum Supply Annual 1983,* vol. 1, DOE/EIA-0340(83)1, U.S. Department of Energy, Energy Information Administration, June 1984.

[d]*Source:* C. D. Masters, D. H. Root, and W. D. Dietzman, "Distribution and Quantitative Assessment of World Crude Oil Reserves and Resources," *U.S. Geological Survey Open-File Report*, USGS-OFR-83-728, 1983.

Note: Some of the above data are available for 1984 in the December 31, 1984, issue of the *Oil and Gas J.*, 74–75.

In 1983, the U.S. Geological Survey[4] gave a strong warning that the amount of economically recoverable oil in the world is smaller than some optimists would like to think and may be even smaller than some conservative estimates. It indicates that world demonstrated reserves of crude oil are approximately 725 billion barrels of oil (BBO), that cumulative production is 445 BBO, and that annual production is 20 BBO. Demonstrated reserves have declined during the past 10 years, which is consistent with the fact that discoveries have lagged behind production during the same period. The distribution of ultimate recoverable resources of crude oil is highly skewed toward the

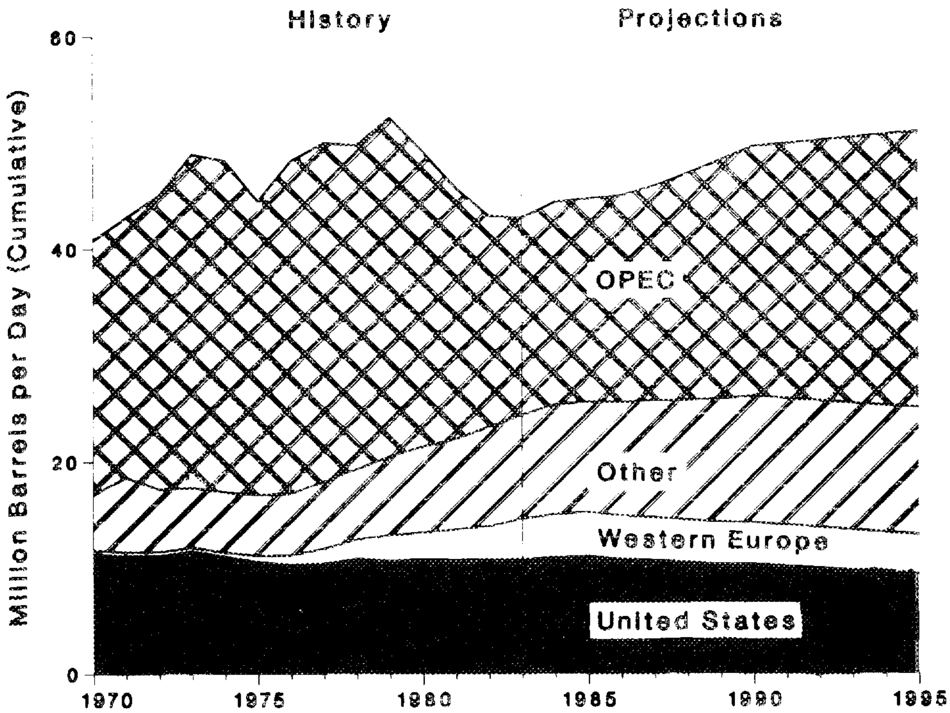

Fig. 2.7. World market economies' oil production, 1970 to 1995. *Source: Annual Energy Outlook 1983 with Projections to 1995,* DOE/EIA-0383(84), U.S. Department of Energy, Energy Information Administration, January 1985.

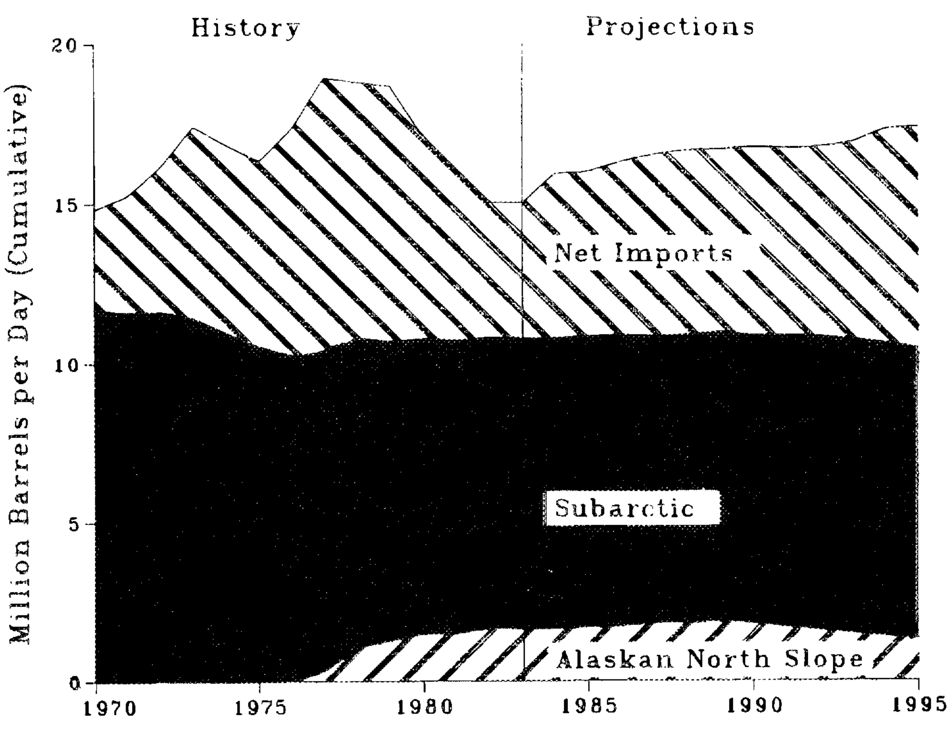

Fig. 2.8. U.S. petroleum supplies by source, 1970 to 1995. *Source: Annual Energy Outlook 1983 with Projections to 1995,* DOE/EIA-0384(83), U.S. Department of Energy, Energy Information Administration, May 1984.

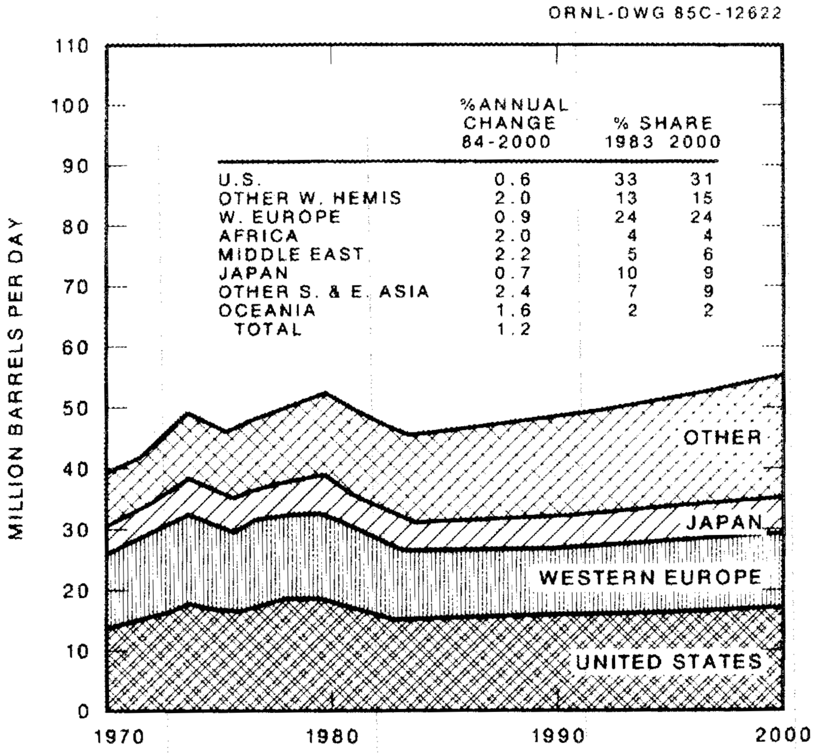

Fig. 2.9. Oil Consumption—non-Communist world (million barrels per day). *Source: World Energy Outlook, Forecast Through the Year 2000,* Chevron Corporation, July 1984.

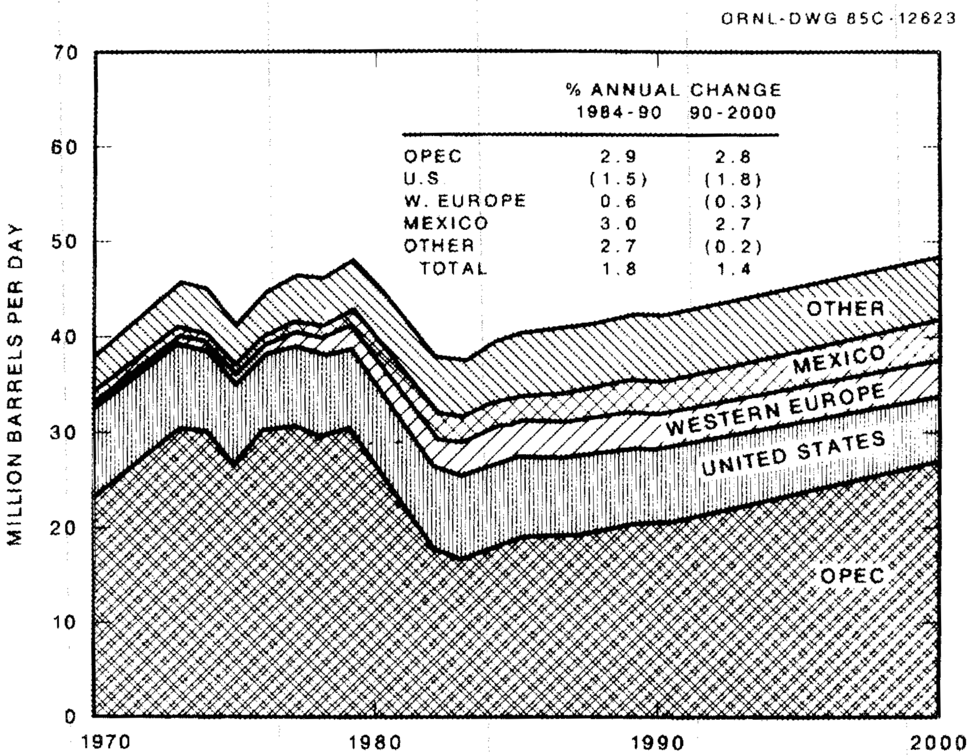

Fig. 2.10. Crude oil production—non-Communist world (millions barrels per day). *Source: World Energy Outlook, Forecast Through the Year 2000,* Chevron Corporation, July 1984.

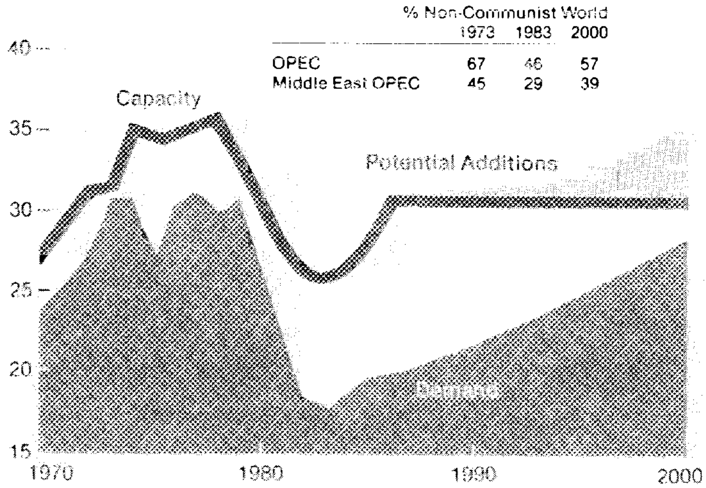

Fig. 2.11. OPEC crude oil production capacity (million barrels per day). *Source: World Energy Outlook, Forecast Through the Year 2000,* Chevron Corporation, July 1984.

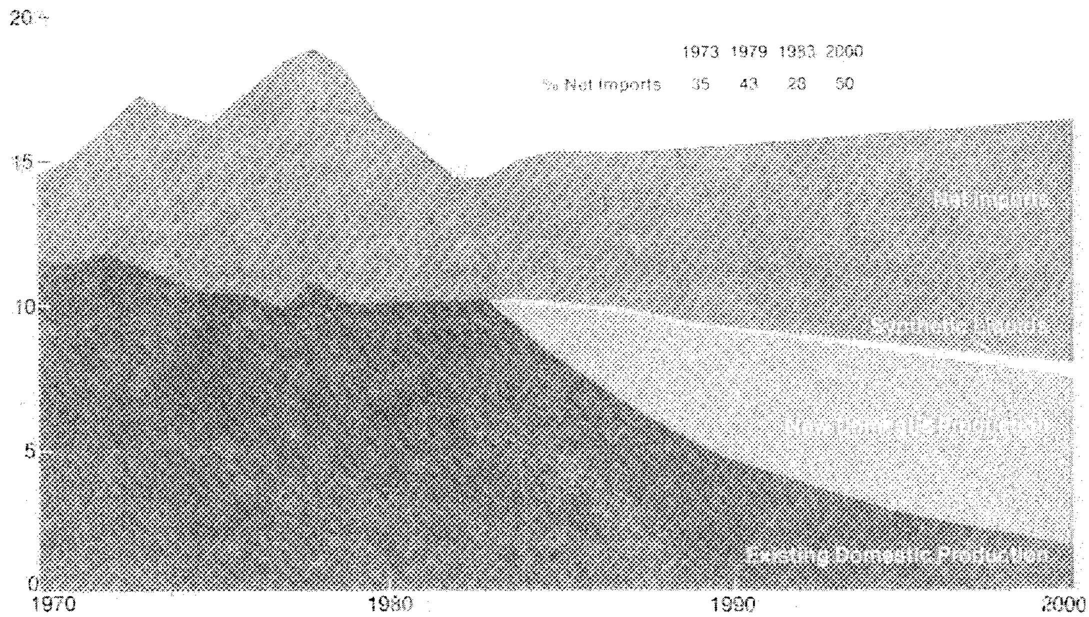

Fig. 2.12. U.S. oil supply (million barrels per day). *Source: World Energy Outlook, Forecast Through the Year 2000,* Chevron Corporation, July 1984.

Middle East (see Fig. 2.13), and rates of discovery have generally declined during the past 20 years even though exploration activities have increased. The Geological Survey's estimates of reserves and production by country and the average API gravity by world region are presented in Appendix C of this report.

2.5. UNCERTAINTIES ASSOCIATED WITH PROJECTIONS

A significant amount of uncertainty is present in these projections. Past projections have been in error, and such might be the case for any of the projections cited in this report. The supply and kind of oil available are subject to variations imposed by political decisions, technical developments, swings of the U.S. business cycle or of the world economy, natural or man-made disasters, and any number of other influences. Many of these influences are impossible to predict, even in the short term, such as the rise to power of an anti-Western charismatic leader in an oil-rich country. For these reasons, such projections must be continually updated with the most recent data available.

2.6. DATA TO SUPPORT THE PROJECTIONS

It is virtually impossible for such projections to predict the production and qualities of crude oil from tens of thousands of oil fields around the world. However, the bulk of world petroleum resources occur in a relatively small number of very large fields. With more than 30,000 known

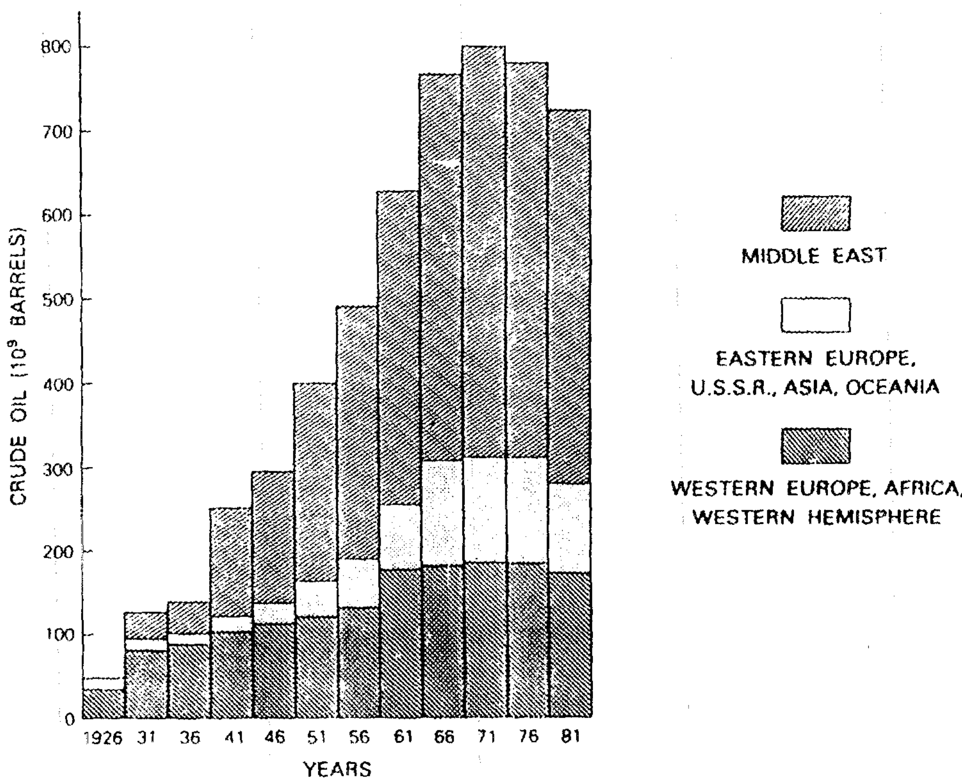

Fig. 2.13. Demonstrated reserves of crude oil in 5-year intervals. *Source:* C. D. Masters, D. H. Root, and W. D. Dietzman, "Distribution and Quantitative Assessment of World Crude Oil Reserves and Resources," *U.S. Geological Survey Open-File Report,* USGS-OFR-83-728, 1983.

fields globally, more than half of the known recoverable oil is in the 33 fields classified as super-giants (>5 billion barrels), and more than three-quarters is in the few hundred giant fields (>500 million barrels).[16] This makes it feasible to roughly describe the quality of petroleum and possible future production patterns by using data from a small number of fields and countries to characterize regional patterns.

It should be noted that while data on reserves and crude quality are extant for each field, these data are not always available in the open literature. The DOE/EIA Dallas Field Office maintains files on world reserves by field, and the DOE/EIA Washington Marketing Office tabulates U.S. imports by crude stream. These data sets are not published, but both are accessible.[6]

Assay data on the most important crude streams in world trade are published occasionally, for example by the *Oil and Gas J.*[17,18] A typical published assay is shown for Arabian Heavy crude in Table 2.2. These assays include both field assays (for the crude) and laboratory assays of the distillation components. Full assays represent a laboratory cost in excess of $10,000 and are not always readily available. The National Institute of Petroleum and Energy Research, Bartlesville, Oklahoma, and Petroconsultants, Inc., Houston, Texas, maintain files of laboratory assays on crude oils.

Some estimation may be required to transform published or publicly available assay data into a form suitable for use in a particular refinery model or to estimate the future quality characteristics of selected products.

For the sake of anticipating the quality of feedstocks to U.S. refineries over the next decade or two, it is possible to provide reasonable bounds closely tied to historic trends. There are, as previously described, a number of detailed projections of crude production. The DOE/EIA projections of crude quantities are particularly well documented and could serve as a basis for projecting crude qualities.

2.7. SUMMARY

Currently available data overwhelmingly support the notion that both domestic and imported crude supplies have deteriorated in quality and will continue to do so despite brief reverses caused by economic slowdowns and alternative supply sources. Furthermore, refinery capabilities are continually changing in response to this outlook.

This trend is coupled with statistical trends toward lower U.S. consumption, lower imports of foreign crude oil, and lower worldwide production of oil. Some data indicate reversals of these trends. If the recent increase in consumption continues, it will exacerbate the problems caused by the progressive degradation of refinery feedstocks.

Current oil production and reserves are so dominated by a small number of fields within a small number of countries that future production and quality of all the world's petroleum can be estimated by focusing on this small number of sources (125 fields in 16 countries and states).

This review identified sources of data that could be used as inputs in computer models of the production of mobility fuels. These sources include the DOE/EIA data that are already used in the models selected for this study as well as several other published and unpublished compilations of data.

Table 2.2. Arabian Heavy, Saudi Arabia

Field Assay

- Crude
  - Gravity, °API: 27.9
  - Sulfur, wt %: 2.85
  - Pour pt, °F.: −20
  - RVP, psi: 7.5
  - Kin. vis., cSt @ 70°F.: 37.0
    - @ 100°F.: 19.0
- Light Gas Oil
  - Range, °FVT: 455–650
  - Yield, vol %: 16.5
  - Gravity, °API: 35.2
  - Sulfur, wt %: 1.30
  - Pour pt, °F.: 5
  - Aniline pt, °F.: 154
  - Kin. vis., cSt @ 100°F.: 3.45
    - @ 210°F.: 1.30

Laboratory Assays

- Light Naphtha
  - Range, °FVT: 68–212
  - Yield, vol %: 7.9
  - Gravity, °API: 79.9
  - Sulfur, wt %: 0.0059
  - RVP, psi: 8.5
  - Paraffins, vol %: 88.6
  - Naphthenes, vol %: 10.2
  - Aromatics, vol %: 1.2
  - RON, clear: 58.0
- Heavy Gas Oil
  - Range, FVT: 650–1,049
  - Yield, vol %: 30.6
  - Gravity, °API: 20.9
  - Sulfur, wt %: 2.92
  - Pour pt, °F.: 95
  - Aniline pt, °F.: 173
  - Kin. vis., cSt @ 100° F.: 77.0
    - @ 210° F.: 8.46
- Heavy Naphtha
  - Range, °FVT: 212–302
  - Yield, vol %: 6.8
  - Gravity, °API: 60.5
  - Sulfur, wt %: 0.016
  - P/N/A, vol %: 70.8/19.5/9.7
- Residual Oil
  - Range, °FVT: 650+
  - Yield, vol %: 53.8
  - Gravity, °API: 12.6
  - Sulfur, wt %: 4.34
  - Pour pt, °F.: 60
  - Con. carbon, wt %: 13.3
  - Kin. vis., cSt @ 100° F.: 4,103
    - @ 210° F.: 94.2
- Kerosene
  - Range, °FVT: 302–455
  - Yield, vol %: 12.4
  - Gravity, °API: 48.4
  - Sulfur, wt %: 0.16
  - Aromatics, vol %: 18.9
  - Freeze pt °F.: −67
  - Smoke pt, mm: 26
  - Luminometer no.: 57
  - Aniline pt. °F.: 141
  - Kin. vis., cSt @ −30° F.: 5.14
    - @ 100° F.: 1.14
- Residual Oil
  - Range, °FVT: 1,049+
  - Yield, vol %: 23.2
  - Gravity, °API: 3.0
  - Sulfur, wt %: 6.0
  - Pour pt, °F.: 120+
  - Con. carbon, wt %: 27.7
  - Kin. vis., cSt @ 210° F.: 55,292
    - Furol, sec @ 275° F.: 1,309
  - V/Ni/Fe, ppm: 205/64/30

Source: McNelis, F. P., "Exxon Organizations: Modern Crude Oil Assay Practices," *Oil and Gas J.*, 94 (March 21, 1983).

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3. PRELIMINARY REVIEW OF PETROLEUM-REFINING TRENDS

3.1. TASK OBJECTIVES

The objective of this section is to review current refinery trends and their potential impact on the future availability of Navy mobility fuels during the period from 1990 to 2000. While numerous scenarios can be developed to examine fuel availability under stressed political and/or economic conditions, such as regional conflicts in the Middle East, this section is restricted to examining fuel availability under BAU conditions. The changes occurring in the U.S. refining industry today, as well as those expected in the future, can be used in the models for forecasting future U.S. production of mobility fuels.

3.2. PETROLEUM REFINING OPERATIONS

Petroleum refineries are manufacturing plants that convert crude oil into products that meet market demands, such as gasoline, jet fuel, and diesel oil. A brief overview of refining operations is presented as follows:

1. Distillation physically separates a mixture of components (such as crude oil) into its constituent products (such as naphtha, kerosene, distillate, and residual oil). Atmospheric distillation is generally one of the first operations performed on a crude oil in a petroleum refinery. The amount of constituent products produced from a crude oil depends upon the characteristics of the crude.

2. Conversion processes chemically transform certain low-value refinery streams (such as resids and gas oils) into higher-value product streams (such as gasoline and distillate fuels). Conversion operations include catalytic cracking, reforming, alkylation, isomerization, and hydrocracking.

3. Treating processes remove objectionable components (such as sulfur, nitrogen, salt, and trace metals) and other impurities from the raw refinery streams. Treating operations include desalting, hydrodesulfurization, hydrotreating, and Merox sweetening.

4. Blending involves mixing the various refinery product streams, mixing in additives (as required), and producing the desired finished marketable products (such as gasoline, jet fuels, kerosene, and distillates).

5. Utilities are the ancilliary processes that enable the petroleum refinery to operate. These include facilities for steam and power generation, waste treatment, and product storage and transfer.

Additional information is presented in the glossary in Appendix A.

Petroleum refineries range in complexity from simple to complex. Simple refineries generally have a crude oil distillation unit and some limited downstream processing capabilities, and they produce a limited slate of products. These refineries are also referred to as topping or hydroskimming refineries. Figure 3.1 is a sketch of a "typical" hydroskimming refinery.[1] Complex refineries have additional and often extensive downstream processing units that upgrade the residue from the crude distillation towers to make more of the lighter and more marketable products, such as gasoline and distillate fuels. Figure 3.2 is a simplified flow diagram of a "typical," modern, complex petroleum refinery.[2] Large, modern petroleum refineries generally fall into the latter

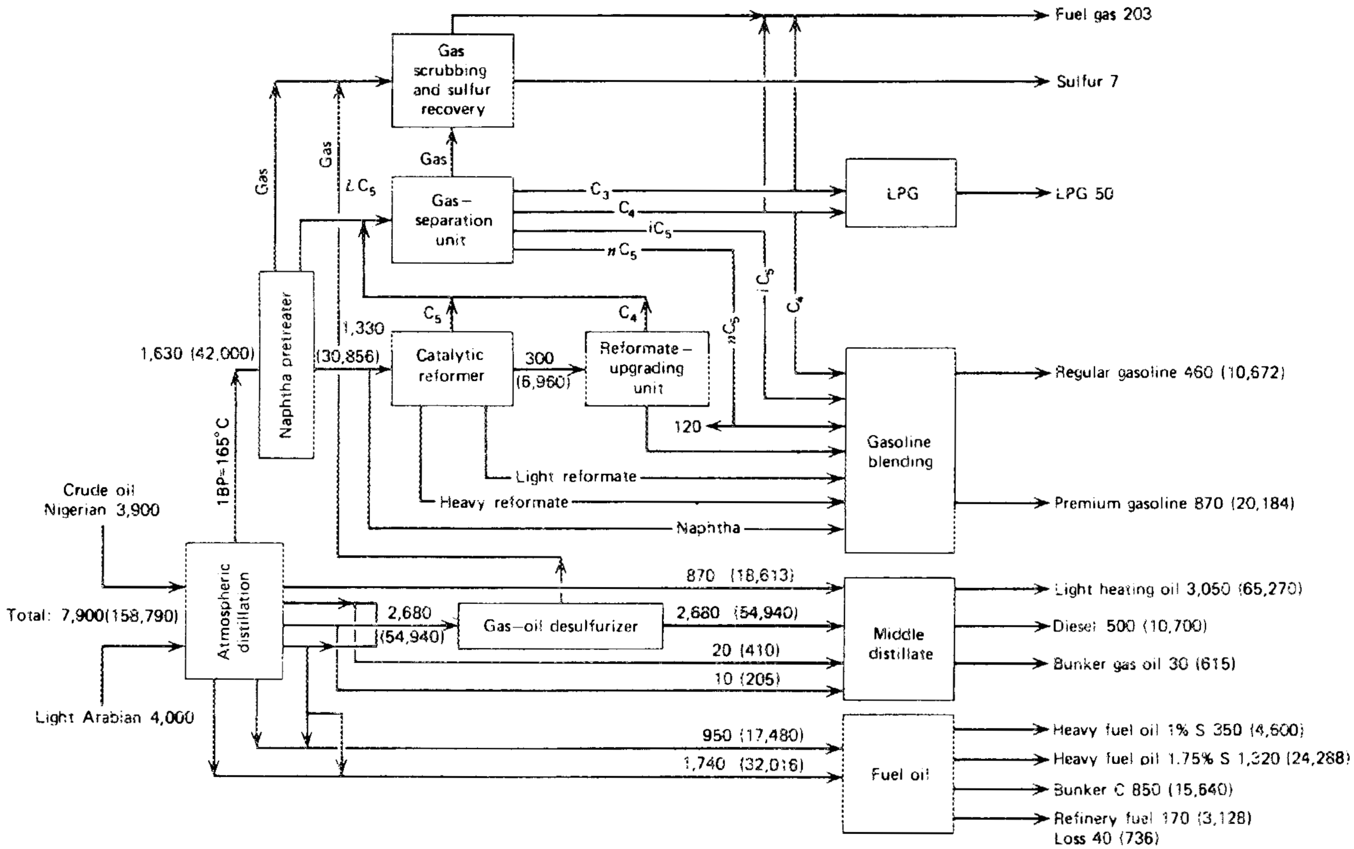

Fig. 3.1. Hydroskimming refinery: input and product slate (2). Inputs and outputs are in 10^3 metric tons per year. Approximate conversions to barrels per day are in parentheses. IBP equals initial boiling point. *Source*: R. E. Kirk and D. F. Othmer, *Encyclopedia of Chemical Technology*, vol. 17, Third Ed., John Wiley & Sons, New York, 1982.

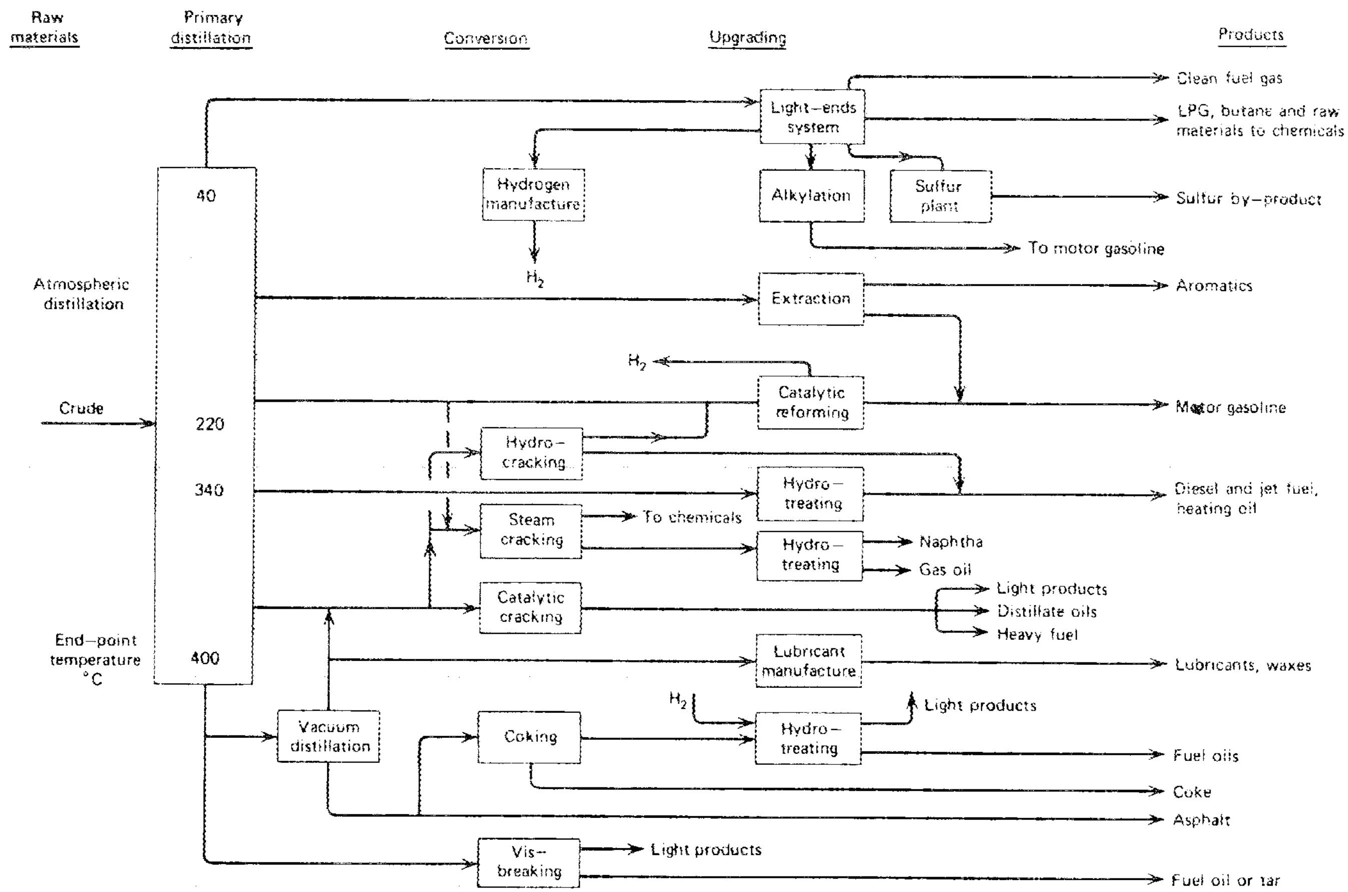

Fig. 3.2. Simplified flow diagram of a typical U.S. refinery. *Source:* American Petroleum Institute, Standard Definitions for Petroleum Statistics, Technical Report No. 1, 3rd ed.

category and are often referred to as refining complexes. In the recent past, refineries in the United States have generally been designed to maximize gasoline production, whereas foreign refineries tend to favor distillate production, primarily because of market demands.

Petroleum refineries are also classified by size. Refinery size or throughput is a measure of the crude distillation capacity of the atmospheric distillation unit(s) at the refinery and is usually measured in thousands of barrels per calendar day (B/CD) or stream day. Refineries range in size from less than 10,000 to more than 400,000 B/CD. Generally speaking, the smaller-size refineries tend to be topping refineries, and the larger refineries tend to be refining complexes.

3.3. CURRENT U.S. PLANTS AND THEIR PRODUCTS

As of January 1, 1984, the United States had 247 operable refineries, having a combined operable distillation capacity of 17.1 million barrels per stream day.[3] Table 3.1 gives a breakdown of the operable refineries by crude distillation and selected categories of downstream processing capacity.

As a general rule, refinery flexibility is a function of the downstream capabilities of a refinery. While refiners have some flexibility in the types of crude that can be fed to the atmospheric still and in the operating conditions, this flexibility is limited. Greater processing flexibility is obtained as more downstream processing operations are added. From Table 3.1 it can be seen that approximately 20% of the U.S. refineries are in the 100,000+ B/CD class and that these refineries have 62% of the crude distillation capacity. These refineries also have the largest capacity of downstream processing, thereby indicating that the present U.S. refining industry has considerable flexibility in its operation both in terms of the crudes processed and the products produced.

3.4. HISTORIC TRENDS IN PETROLEUM REFINING

Because of changing market demands, the current trend in the petroleum refining industry is to shut down uneconomic refining capacity and to increase downstream processing capabilities. The United States (and the world, especially Europe) has had excess refining capacity since 1979. Worldwide refining capacity utilization rates from 1979 to 1983 are shown in Table 3.2 and have varied from 69% in 1980 and 1981 to 74% in 1983.[4] U.S. refinery capacity utilization rates have also varied over the years and were approximately 76% in 1983.

Table 3.3 lists the number of operable refineries in the United States by refinery size for the past five years. The following trends are evident from that table:

1. the total number of operable refineries has decreased from 324 in 1980 to 247 in 1983; and

2. the largest decrease in the number of operable refineries has been in simple refineries with a crude oil distillation capacity of 30,000 B/CD or less.

Table 3.4 gives a breakdown of the aggregate U.S. refinery and selected categories of downstream processing capacities for the past four years.[4] From Table 3.4, it can be seen that downstream processing capacity of U.S. refineries generally increased during the past four years, whereas crude distillation capacity decreased.

During the past five years, the refining industry has gone through a period of considerable change. While changes continue to be made as the industry tries to stay competitive, the rate of

Table 3.1. Crude distillation and downstream processing capacity of U.S. petroleum refineries as of January 1, 1984

Refinery size (MB/CD[b])	Number of operable refineries	Cumulative operable unit capacities in MB/SD[a]						
		Crude distillation	Vacuum distillation	Thermal operations	Catalytic cracking[c]	Catalytic reforming	Catalytic hydrocracking	Catalytic hydrotreating
<10	63	351	122	20	51	30	6	74
10+ to 30	55	1,226	358	75	228	148	6	185
30+ to 100	82	4,968	1,944	465	1,867	1,100	149	2,363
100+	47	10,514	4,742	1,292	3,656	2,629	791	6,387
TOTAL	247	17,059	7,166	1,852	5,802	3,907	952	9,009

[a]Thousands of barrels per stream day.

[b]Thousands of barrels per calendar day.

[c]Includes fresh and recycle catalytic cracking capacity.

Source: Energy Information Administration, *Petroleum Supply Annual 1983,* vol. 1, DOE/EIA-0340 (83)/1, June 1984.

Table 3.2. World refining capacity utilization rates, 1979–1983

	Percent of operable capacity				
	1979	1980	1981	1982	1983
North America	81	76	68	74	76
United States	(81)	(75)	(67)	(73)	(76)
Western Europe	66	61	56	64	69
Belgium	(61)	(60)	(53)	(77)	(57)
France	(74)	(68)	(60)	(60)	(64)
Germany	(69)	(66)	(58)	(62)	(63)
Italy	(50)	(47)	(47)	(52)	(52)
Netherlands	(71)	(56)	(52)	(53)	(58)
United Kingdom	(73)	(66)	(55)	(72)	(77)
Japan	82	73	65	61	67
Oceania	83	74	75	83	76
Middle East	67	60	68	70	70
Latin America	70	77	73	76	78
South Asia	82	81	89	85	95
East/Southeast Asia	72	68	70	67	66
Africa	60	72	74	80	75
China	100	99	99	99	99
Communist Europe	80	77	82	82	77
World	74	69	69	73	74

Source: F. Fesharaki and D. Isaak, "The Changing Structure of World Refining Industry: Implications for U.S. Energy Security," Notes on presentation made to the U.S. Department of Energy at Washington, D.C. by the OPEC Downstream Project Resource Systems Institute East-West Center, Honolula, Hawaii, January 23, 1985.

Table 3.3. Number of operable refineries in the United States by size from January 1, 1980 to 1984

Crude distillation capacity (B/CD)	Years				
	1984	1983	1982	1981	1980
Less than 10,000	63	67	82	91	102
10,001–30,000	55	59	80	93	83
30,001–50,000	41	40	44	42	39
50,001–100,000	41	44	43	44	44
100,001–175,000	26	26	30	27	25
Over 175,000	21	22	22	27	26
Total	247	258	301	324	319

Source: Energy Information Administration, *Petroleum Supply Annual 1983,* vol. I, DOE/EIA-0340 (83)/1, June 1984.

Table 3.4. Operable U.S. crude distillation and downstream processing capacities from 1981 to 1984

Year	Number of operable refineries	Operable unit capacities in MB/SD[a]						
		Crude distillation	Vacuum distillation	Thermal operations	Catalytic cracking[b]	Catalytic reforming	Catalytic hydrocracking	Catalytic hydrotreating
1981[c]	301	19,018	7,197	1,782	6,036	3,966	892	8,539
1982[c]	258	17,871	7,180	1,715	5,890	3,918	883	8,354
1983[b]	247	17,059	7,165	1,852	5,802	3,907	952	9,009
1984[d]	247[e]	17,191	7,244	1,896	5,870	3,890	1,020	9,063

[a]Thousands of barrels per stream day.

[b]Calculated from information in Energy Information Administration, *Petroleum Supply Annual 1983,* vol. 1, DOE/EIA-0340 (83)/1, June 1984.

[c]Source: E. E. Campbell, "Trends in Refinery Capacity and Utilization (Results of 1983 EIA Refinery Survey)," *Proceedings of the Energy Information Administration Symposium on Petroleum Supply Information,* Arlington, Virginia, August 26, 1983, DOE/EIA-0425, September 1983.

[d]Projected.

[e]Estimated.

change has begun to level, and the industry seems to be entering a period of relatively stable operation. Several factors responsible for these upheavals were

1. the worldwide recession of 1980 to 1981 and increased energy conservation resulted in a significant drop in product demand;

2. the demand for lighter gasoline-type products increased, whereas the demand for heavier residual fuel type products decreased;

3. decontrol of domestic crude oil prices and the termination of the Crude Oil Entitlements Program in 1981 resulted in a large number of small refineries being shut down because they became uneconomical; and

4. the input crude oil quality shifted to "heavier" (i.e., lower API gravity) and higher-sulfur content crudes that contain fewer of the desired hydrocarbons needed to produce lighter products, such as gasoline. The changes in the crudes' quality resulted in refiners' increasing downstream processing capacity to convert the resid to lighter, more desirable products and, as a corollary, shutting down those refineries that did not have adequate downstream processing capabilities.

3.5. FORECASTS

3.5.1. Expected Developments

The near-term trend in the industry is to further match refining capacity to product demand. One scenario for the petroleum products demand for the remainder of the eighties is shown in Fig. 3.3. According to this EIA scenario, petroleum products demand is likely to increase to 17 or 18 million barrels per day (MMB/D) by the late eighties; however, there will be sufficient domestic refinery capacity to meet the demand.[6] The EIA's report states that "only evolutionary changes in refinery configurations are expected for the next few years as refiners continue to increase their flexibility in responding to changing demand patterns and in processing a wide range of crude oil types."

Discussions with petroleum industry and engineering/construction personnel and supplemental reviewing of pertinent literature produced the following forecasts of petroleum consumption trends for the 1990 to 2000 timeframe. The forecasts are for a BAU scenario and should be recognized as educated guesses rather than as blueprints of the future.

1. Energy consumption worldwide is expected to grow about two-thirds as fast as the world economy.[7]

2. World crude supplies are likely to be tight by the year 2000. The crudes supplied to U.S. refineries are likely to be heavier and contain more sulfur. The gravity of the U.S. crude slate is likely to drop from an average of 32 degrees API to a level of 30 degrees API, and the average crude sulfur level will likely increase to more than 1.1%.[8]

3. Synthetic fuels are not likely to make a major contribution to the world's energy supply until the 21st century.[7]

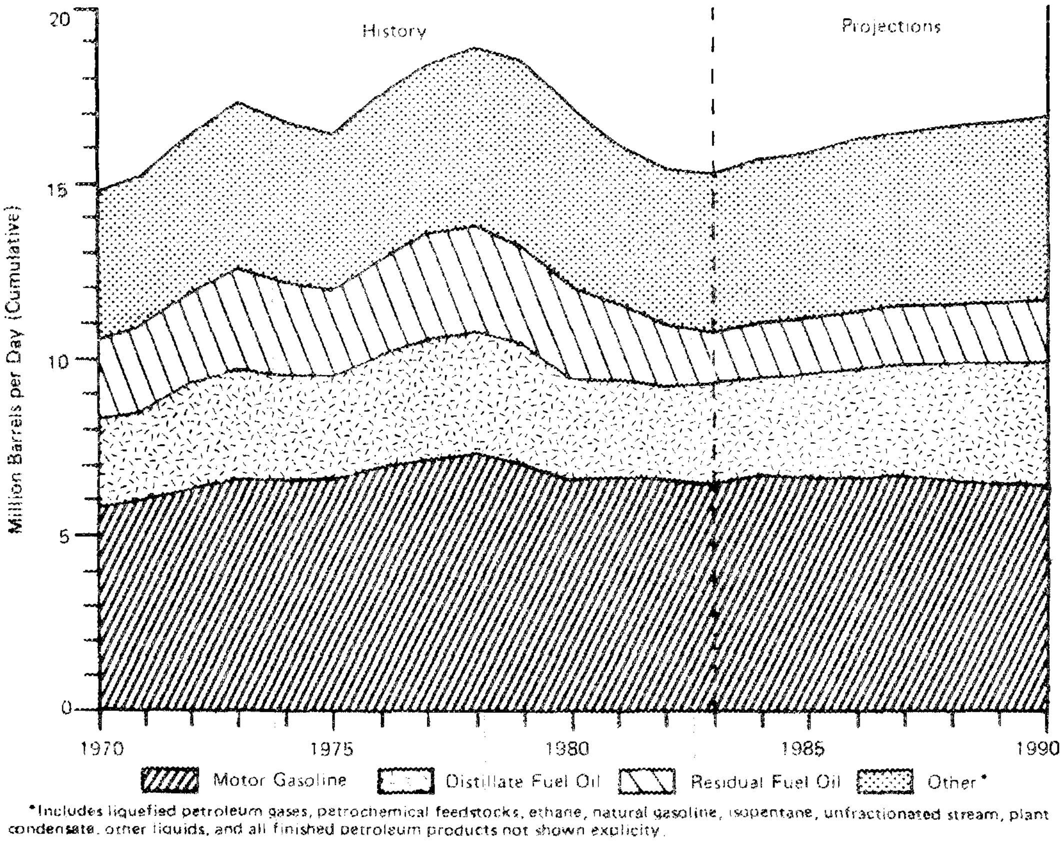

Fig. 3.3. Demand for petroleum products, midprice scenario, 1970 to 1990. *Source:* Energy Information Administration, "Refinery Capacity Trends and Outlook," *Petroleum Supply Monthly*, April 1984.

4. Demand for distillate fuels in the United States is likely to increase, while the demand for gasoline is likely to decrease because of anticipated growth in airline and freight traffic and improved automobile efficiencies. Consequently, as much as 40% of the future refinery output is likely to be middle-of-the-barrel products such as kerosene, jet, and diesel fuels.[8]

3.5.2. Expected Responses of the Refining Industry

A comprehensive review of world and U.S. refinery trends by the National Petroleum Council is currently under way. The results of this survey will be available later this year. However, discussions with industry experts and literature reviews indicate that the following responses from the refining industry are probable:

1. Two to three million barrels per day of some type of cracking capacity will probably be added to petroleum refineries to convert residuum to needed lighter products.[8] The cracking capacity added could be either as catalytic cracking, hydrocracking, coking, or visbreaking, depending upon the individual refiner's needs and economics. Planned U.S. refinery construction in 1984 (with expected completion in 1987) is shown in Table 3.5. From Table 3.5, it can be seen that U.S. refiners are planning to add significant catalytic hydrocracking (and related hydrogen production), thermal cracking, and isomerization capacity.[9]

Table 3.5. Planned U.S. refinery construction, 1984 (Completion 1984–1987)

	New capacity (barrels per day)	Percent of 1984 capacity
Crude distillation	259,000	1.55
Vacuum distillation	162,200	2.31
Thermal cracking	134,610	7.75
Catalytic cracking	59,500	1.01
Catalytic reforming	33,000	0.85
Catalytic hydrocracking	122,900	13.36
Catalytic hydrorefining	67,500	2.95
Catalytic hydrotreating	65,200	0.98
Alkylation	16,600	1.78
Aromatics/isomerization	32,500	6.87
Hydrogen (MMcfd)	285.5	12.99
Coke (t/d)	3,489	5.26

Source: B. K. Bailey, N. R. Sefer, and B. R. Bright, *Naval Fuel Property Projections, Phase I, General Trends,* Report No. AFLRL No. 179, Aug. 1984.

2. Petroleum refiners are likely to augment distillate volumes by broadening boiling ranges and by greater use of additives.[8]

3. Refinery capacity worldwide is expected to be more than sufficient to meet petroleum product demand. Figure 3.4 suggests a refinery utilization rate of about 70% from now to the end of this century.

4. Recent government pronouncements to stop the use of leaded additives in gasoline will require hydroconversion and reforming of more gas oils and distillates to produce gasoline blending stocks with sufficient octane rating. These regulations will lead to a decrease in feedstocks for distillate production. In addition, Hoffman[10] indicates that several refiners not having sufficient downstream capabilities may shut down because they will not be able to compete under a no-lead situation. These shutdowns will result in a further reduction of petroleum refining capacity in the United States. At present, such a reduction may be beneficial; however, the long-term consequences may be to force the Navy to buy more of its fuel from overseas refineries, increasing its vulnerability to fuel supply interruptions.

5. Increased imports of finished and semifinished petroleum products from overseas refineries will further drive down U.S. refining capacity. According to the American Independent Refiners Association (AIRA), from the first half of 1983 to the first half of 1984, finished gasoline imports rose by 40%, residual fuel oil by 30%, liquefied petroleum gas by 65%, and distillate fuels from virtually zero to more than 200,000 barrels per day.[11] For many overseas refineries,

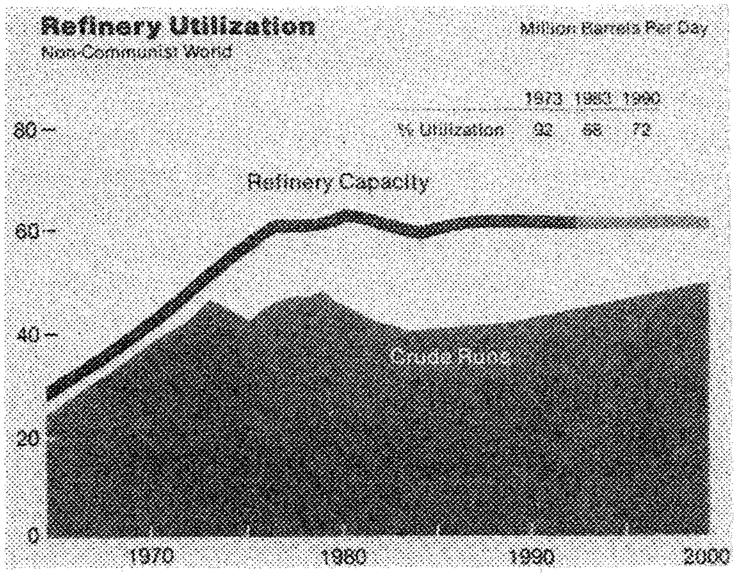

Fig. 3.4. Refinery capacity and crude runs forecast to the year 2000. *Source:* Chevron Corporation Economics Department, *World Energy Outlook-Forecast Through the Year 2000*, July 1984.

gasoline is not the main product but a by-product of the refining process, and with more refining capacity coming onstream overseas, the trend toward increased imports of petroleum products is likely to gain strength. This trend has several U.S. refiners concerned about the permanent loss of U.S. petroleum refining capacity because most U.S. refiners will be unable to compete with the price of the imported products.

3.5.3. Potential Impacts on Navy Mobility Fuels

The changes in the petroleum refining industry during the next 10 to 15 years can produce significant impacts on the availability and quality of Navy mobility fuels.

Because the crudes processed are likely to be heavier, to be of poorer quality, and to contain less of the hydrocarbon components desirable for JP-5 and F-76 stock, the volume of virgin stock available is likely to be less. However, additional downstream processing of the residuum and gas oils from these crudes will yield more distillate stock that will be used to augment the distillate pool. Therefore, the total volume of the distillate pool available nationally should be sufficient to meet the Navy's projected mobility fuel requirements.

Because of additional downstream processing by refiners to augment distillate volumes, it is very likely that the fuel quality could be worse in some respects than the quality of mobility fuels available today. For instance, because of blending of hydrocrackates with virgin JP-5 stock, the lubricity of the blended stream is likely to be less than that of the virgin stock.[12] Likewise, the cetane number, water-shedding capabilities, and other properties of F-76 could be worse than those of today's fuel. Of course, some of these fuel property deficiencies could be corrected by using appropriate additives.[8]

Because both JP-5 and F-76 are specialty cuts from the distillate pool and because the overall demand for distillate fuels is projected to increase with time, the Navy mobility fuel requirements may have to compete with concurrent civilian demands for the distillate pool, and hence the price of the mobility fuels could increase because of increased demand for a diminishing resource. If the projected decrease in gasoline demand in the U.S. materializes, however, residual feedstocks and the hydrocracking and catalytic cracking facilities used in the production of gasoline could be used to produce mid-distillates and JP-5.[12]

Significant volumes of JP-5 and F-76 are not likely to be produced from shale or coal-derived synthetic crudes at least until the 21st century.[7] Any marketable synthetic crudes produced in the intervening time period will most likely be small in volume and will be blended and processed with naturally occurring crude oils with little or no impact on mobility fuel quality or quantity.

Although in the United States the distillate pool may be sufficient to supply the Navy's mobility fuel requirements, regional shortages could occur in the United States. For example, there could be a shortage of JP-5 in PADD 5 between 1995 and 2000.[13] The refineries supplying JP-5 to the Navy in FY 1978 are given in Table 3.6, which shows that the U.S. refineries supplying JP-5 to the Navy at that time were located in PADDs 3 and 5. In the future, average crude quality is expected to deteriorate, especially for refineries located in PADD 5, about half of which are relatively small and have no middle distillate hydroprocessing capabilities. Moreover, an increased demand for civilian jet fuel is expected in that region. As a result, these PADD-5 refineries may have problems supplying JP-5.[13] Refineries located in the Caribbean, Europe, and the Far East that currently provide some of the Navy's JP-5 stock offer the potential for increased production of JP-5. However, attempts to increase gasoline production by these refineries may reduce their ability to provide Navy mobility fuels.

3.6. SUMMARY

The number of refineries in the United States is declining, and the remaining refineries are broadening their capabilities to accommodate the heavier crudes that are becoming more prevalent on the world petroleum market. This broadening of capability (and flexibility) is taking the form of increased capacities for thermal and catalytic cracking, catalytic hydrocracking and hydrorefining, alkylation, isomerization, hydrogen production, and other processes involved in downstream refining. In general terms, under BAU conditions, these developments indicate (1) an overall sufficient supply of Navy mobility fuels, (2) the occurrence of some regional shortages, (3) the encroachment on the supply of military fuels by other market demands and (4) the decline of the quality of those mobility fuels produced. As work progresses, these developments can be used to cross-check and enhance the inputs to the models that make up the Navy Mobility Fuels Forecasting System to provide more reliable and useful information from that system.

Table 3.6. Refineries supplying JP-5 to the U.S. Navy in FY-1978

Refinery location	Crude distillation capacity (MB/CD)	Middle distillate hydrotreating capacity (MB/CD)	Middle distillate hydrocracking capacity (MB/CD)	JP-5 produced in FY-78 (MM gal)
United States				
PADD 5				
California				
Douglas Oil Co., Paramount	46.5	6.3	None	36
Mobil Oil Co., Torrance	123.5	23.9	17.6	96
Fletcher Oil Co., Carson	20.1	None	None	24
Powerine Co., Santa Fe Springs	44.1	None	None	58
Beacon Co., Hanford	12.3	None	None	6
Newhall Co., Newhall	11.5	None	None	6
Exxon Corp., Benecia	93.0	20.7	21.9	67
Lion Oil Co., Avon	126.0	30.0	22.0	
Total	477.0	80.9	61.5	293
Washington				
Arco, Ferndale	106.0	10.8	37	38
Mobil, Ferndale	71.5	18.9	None	
U.S. Oil Co., Tacoma	21.4	None	None	20
Total	198.9	29.7	37	58
Hawaii				
Hawaiin Independent Oil Co.	62.5	None	None	75
Total for PADD 5	738.4	80.6		426
PADD 3				
Texas				
Shell Oil, Deerpark	285.0	77.0	23.5	72
Mobil Oil Co., Beaumont	325.0	100	27.6	105
Gulf Oil Co., Port Arthur	334.5	59.0	14.3	80
Total	944.5	236.0	65.4	257
Louisiana				
Exxon, Baton Rouge	510.0	24.0	63.0	103
Total for PADD 3	1454.5	260.0	128.4	360
Total for United States	2192.9	370.6	226.9	786

Table 3.6 (continued)

Refinery location	Crude distillation capacity (MB/CD)	Middle distillate hydrotreating capacity (MB/CD)	Middle distillate hydrocracking capacity (MB/CD)	JP-5 produced in FY-78 (MM gal)
Foreign				
Latin America				
Lago Oil, Aruba	480.0	100.0	None	16
Shell Oil, Curacao	362.0	120.0	None	56
Total	842.0	220.0	None	72
Europe				
Exxon, Augusta, Sicily	205.0	29.3	None	67
Shell, France,				
Berre	270.0	63.0	None	11
Pauillac	85.0	24.0	None	
Petil Couronne	375.0	71.0	None	
Motor Oil, Hellis, Greece	140.0	25.8	None	4
Total	1075.0	213.1	None	82
Middle East				
Kuwait National Petroleum, Mena Adullah Shuaiba Mina-Al-Ahm	200.0	104.0	44.0	53
Total	200.0	104.0	44.0	53
Far East				
Chinese National Petroleum, Taiwan	425.0	30.0	18.0	18
Guam Oil & Refining Co., Guam	29.5	None	None	11
Total	454.5	30.0	18.0	29
Total for Foreign	2571.5	546.1	62.0	236
Total for Foreign & Domestic	4764.4	907.7	289.0	1022

Source: M. Lieberman and W. F. Taylor, *Effects of Refining Variables on the Properties and Composition of JP-5,* Report No. RL.2PE.80, Exxon Research and Engineering Company, November 1980.

3.7. REFERENCES

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4. ASSEMBLING AND TESTING THE NAVY MOBILITY FUELS FORECASTING SYSTEM

4.1. BACKGROUND

The investigations of crude oil and refinery trends, discussed in the preceding sections, provide the essential foundation of information for the assembly of the Navy Mobility Fuels Forecasting System. This computerized system for evaluating the availability, costs, and characteristics of Navy mobility fuels has been activated and tested by ORNL. The system is based on three publicly available models: the OMS model, the PAL model, and the domestic refinery yield model of the REMS. These models have been specially enhanced to use an expanded, validated input data set and to produce data for special fuels of particular interest to the Navy (i.e., aviation turbine fuel JP-5 and Naval distillate fuel F-76). Test runs of the models have provided data for the full product slate of the modeled refineries, but only the JP-5 results are reported here.

The OMS model produces forecasts of world petroleum prices, related data on aggregated foreign oil supply, and regional demand for oil by an econometric approach that balances supply and demand. An abridged example of output from OMS is the array of point estimates of world crude oil prices for 1979 to 1995 shown in Table 4.1. The OMS model outputs are combined with crude oil characterization data derived from a variety of data sets and are input to the PAL model.

The PAL model predicts refining destination for crude oils. It considers production and refining on a region-by-region basis. Decisions are made by matching (1) supply with demand and (2) crude

Table 4.1. Oil Market Simulation model estimates of world crude oil price

Year	Price[a] (in 1982 dollars per barrel)
1979	27.48
1980	39.32
1981	39.27
1982	33.59
1983	29.54
1984	25.82
1985	25.47
1986	28.24
1987	31.53
1988	34.11
1989	35.68
1990	36.71
1991	39.53
1992	43.81
1993	48.57
1994	52.35
1995	54.97

[a]The world oil price developed by the OMS model is the average delivered price of all crude oil (both spot and contract) imported into the United States.

characteristics with refineries' capabilities (among other variables). In Phase I of the project, the Navy Mobility Fuels Forecasting System was exercised in evaluations of hypothesized scenarios for Bureau of Mines District 13 (BOM 13, the U.S. West Coast). BOM 13 is of particular interest because it is a relatively independent refining region, because it is a substantial JP-5 producer, and because some studies have suggested that in the future it may not produce sufficient kerosene jet fuel. Table 4.2 illustrates PAL forecasts for 1990 and the 1983 actual crude and raw material runs to refineries of BOM 13.

The OMS crude oil price estimates and the PAL forecasts of crude runs are input into the detailed domestic refinery yield model of REMS. The REMS refinery yield model can be used to assess the response of the production of military mobility fuel to changes in numerous variables including processing capacity, feedstock assay and quantity, product specifications and demand, raw material costs and product prices, and environmental considerations.

ORNL's analyses with these models in Phase I of the project have focused on strategies for increasing the production of JP-5 by substituting alternate crude oils, by altering fuel specifications, or by offering a higher price for the finished product.

The OMS model was developed by EIA as a tool for simulating the impact of market forces on world oil prices.[1] In the model, the world oil market is divided into three groups of participants who have different objectives: oil consumers, non-OPEC oil producers, and OPEC oil producers. The behavior of this market is determined by the interactive behavior of these three groups of participants. To simulate the world oil market, the model specifies a set of behavioral rules for each market sector. These rules, which are expressed as mathematical relationships, reflect the price elasticity of demand and other factors that affect supply/demand relationships. With the aid of these rules, the model calculates the price structure that would produce a world balance of supply and demand.

The PAL model simulates the world trade of crude oil and refined products during BAU and disrupted market conditions and can quantify the movement of crude oil and refined products to and from all regions of the world.[2] Flows to the United States and to other International Energy

Table 4.2. Petroleum Allocation model forecasts of crude and other inputs to all refineries of BOM District 13 for 1990

Origin of raw material	Input (MB/CD)	
	1990 PAL forecast	1983 actual
Crude		
BOM District 13	950.0	1889.6
Alaska N. Slope	1514.5	
S. Arabia Light	82.3	
Indonesia	64.4	183.8
Venezuela	1.6	5.0
Algeria	9.3	1.1
W. So. America	36.8	2.9
Butanes	38.0	12.4
Natural Gasoline	10.1	8.6
Others		57.1
Total	2707.0	2160.5

Agency (IEA) countries from the Organization of Arab Petroleum Exporting Countries (OAPEC) and OPEC are particularly emphasized. In addition, the model simulates how the flows of crude and products may shift in the event of a supply disruption and expresses quantitatively the changes in movement of crude and products from each supply source.

These simulations can be examined under two basic scenarios. In one, the shifts occur under the assumption that the market mechanism is allowed to function; that is, crude and product flows will shift to minimize the cost of satisfying the specified demand. In the model, these shifts are restricted to a range determined by historical trends. If desired, the simulation may also be performed with the assumption that petroleum allocation is not constrained by historical patterns. In the other basic scenario, PAL simulates how crude and product flows may shift under the assumption that available supplies will be allocated according to the emergency sharing agreements between the United States and other members of the IEA. PAL also has a limited ability to take into consideration the capabilities and flexibilities of refineries around the world.

The REMS petroleum refinery yield model[3] is a linear program that maximizes the predepreciation, pretax margin of an average petroleum refinery, subject to linearized constraints describing refinery operations. The precise number of descriptive elements differs with each refining scenario, but approximately 350 constraints are described in terms of 1100 activities.

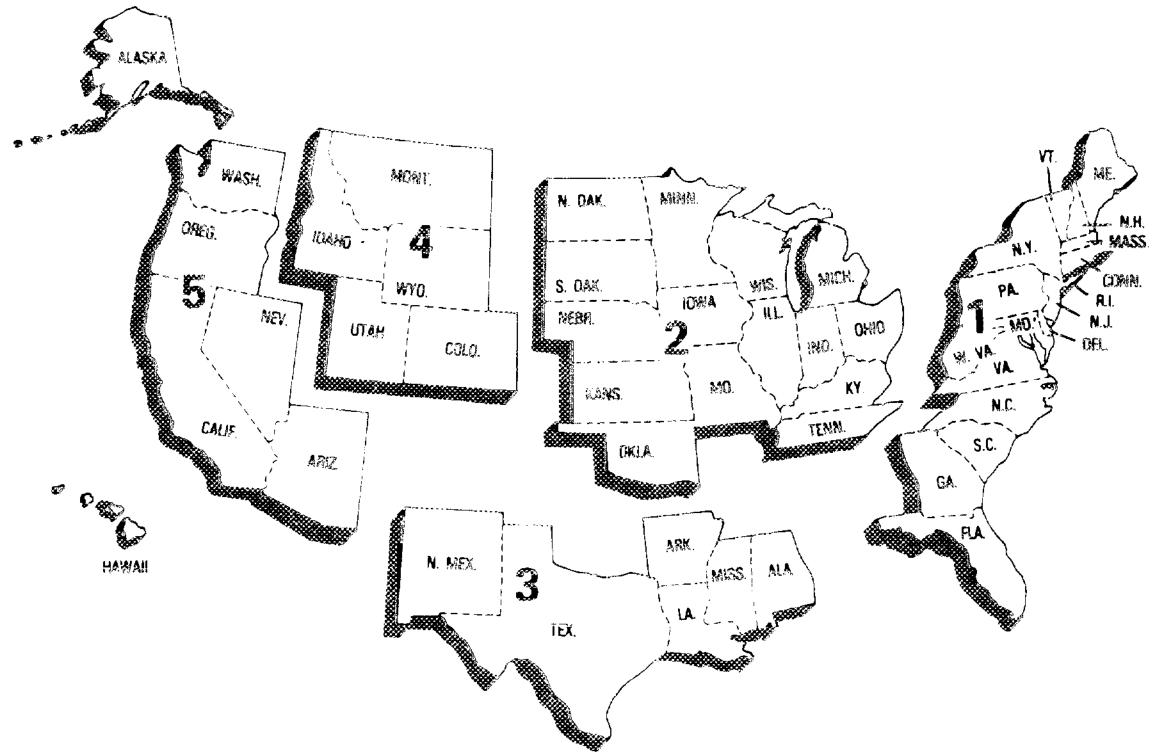
Regional differences in average refinery characteristics are represented by ten different model data sets. One model data set represents an average refinery at the national level, and the remaining data sets describe an average refinery for BOM refining districts. Figure 4.1 illustrates the 13 BOM regions and compares them with the Petroleum Administration for Defense Districts (PADD), which are used by other researchers to describe regional refinery operations. For reasons of convenience related to model data specification, BOM Districts 1 and 2 are described within the same data set; the same is true for Districts 3 and 4, Districts 7 and 11, and Districts 9 and 10. The average refinery for each model data set is represented by processing capacity values equal to the total processing capacity of the modeled geographic area scaled by one-tenth.

As shown in Table 4.3, an average refinery is described in terms of 21 types of processing units. Power generation, steam production, and plant fuel mixing are also represented. New processes can easily be added to the model if the product yield structure, utility requirements, and variable operating costs for those processes are known.

The average refinery can process any number of crudes. Detailed assays for the 41 principal crudes shown in Table 4.4 are represented within an assay data set. New crudes can be added directly to the assay data set or, alternatively, can be expressed as linear combinations of any of the principal crudes.

The operating strategy for the average refinery is the linear programming optimal solution that describes the use of the raw material slate and the utilization of processing units to produce a refined product slate. As shown in Table 4.5, the production of more than 30 refined products can be represented. The expected refiner's revenue, or gate price, for each unit of each product is specified by the user in the model data set. The price of refined products may influence the quantity of that product demanded by consumers. Because the consuming sector will demand a specific level of commodity offered at a particular price, the production of products may be demand-constrained within the model data set. Demand constraints presume and enforce an equilibrium between refiners (suppliers) and consumers. Demand constraints would not be applied if the analyst were interested in the refinery's "level of choice" of production of a given product. For example, in the absence of demand constraints, the refinery would be free to produce volumes of a product in excess of the marketable level if refinery economics were favorable.

Petroleum Administration for Defense Districts



Bureau of Mines Refining Districts

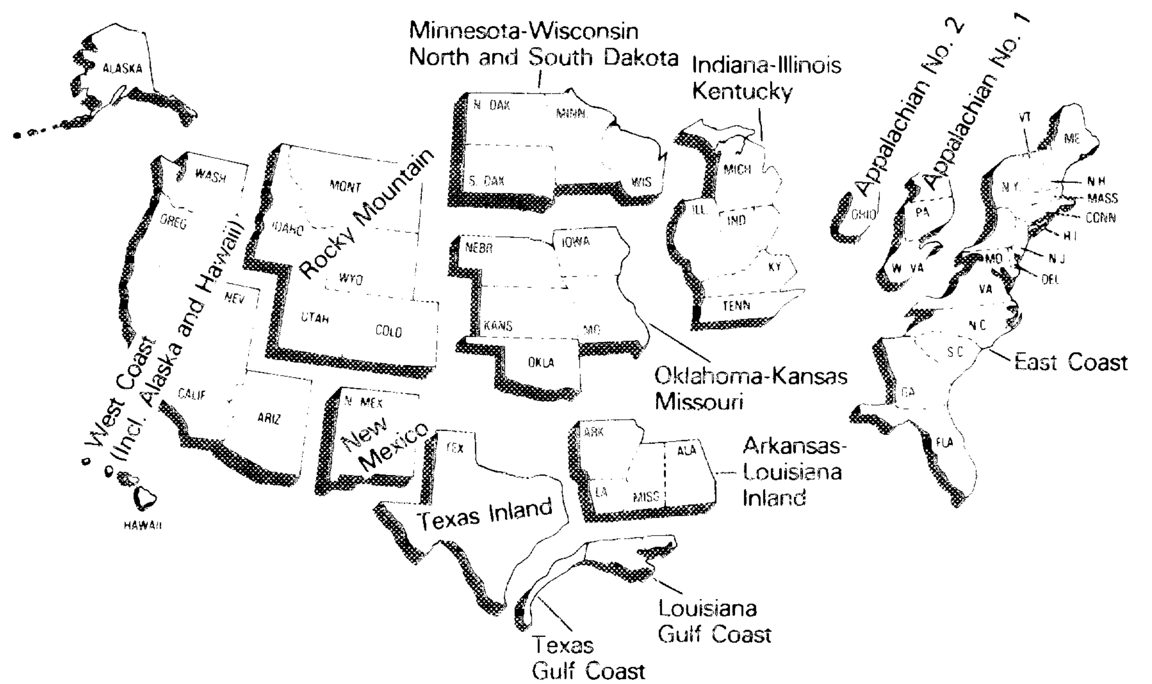


Fig. 4.1. Domestic regions for refinery analyses.

Table 4.3. Processing units of the REMS refinery yield model and scaled refinery capacities for 1990 BAU in BOM District 13

Processing unit	Capacity (MB/CD)
Crude distillation	333.4
Delayed coker	38.3
Fluid coker	9.2
Visbreaker	6.1
Naphtha hydrotreater	62.1
Distillate hydrodesulfurization	37.0
Fluid catalytic cracker feed hydrofiner	26.6
Resid desulfurizer	9.6
Catalytic reformer 450 psi	8.0
Catalytic reformer 200 psi	58.6
Fluid catalytic cracker	75.4
Fluid catalytic cracker gasoline splitter	56.5
Hydrocracker—two-stage	39.7
Alkylation	13.3
Catalytic polymerization	0.7
Hydrogen plant (fuel oil equivalents)	5.3
Sulfur plant, t/d	54.4
Aromatics recovery plant	0.6
Pentane/hexane isomerization	1.3
Butane isomerization	1.0
Lube and wax plants	1.7

The refined product slate is produced in compliance with the specification requirements of the product-user. Standard specification limits should be modified in the modeling process to reflect margins for blending errors, testing variability, and chemical or physical changes that might occur within the product between manufacture and use.

The model selects motor gasoline blends subject to specifications for research octane, motor octane, control octane, lead limitations, Reid vapor pressure, and several distillation points. Because lead is being phased out, the model provides for octane enhancement by the addition of limited amounts of MTBE (methyl t-butyl ether) and Oxinol (a 50/50 mixture of methanol and t-butyl alcohol). A valid representation of motor gasoline production is essential because it is the major refined product, and its production affects the production of all other refinery products, including military mobility fuels.

Distillate and fuel oil products are blended by the model to meet specification subsets of the following properties: gravity, aromatics content, sulfur content, freeze point, luminometer number, pour point, cetane index, flash point, viscosity, Reid vapor pressure, and several distillation points. Smoke point for jet fuels can be specified by a correlation with luminometer number. The model provides for cetane number enhancement by the addition of diesel ignition improver.

Because of the large number of variables described in the REMS refinery yield model, the number of types of problems that can be addressed by the model is large. The model can be used to evaluate the implications of changes in process unit capabilities, process unit utilization, refined product prices, demand for products, crude oil supply, crude oil assay, costs of utilities and plant

Table 4.4. Principal domestic and foreign crudes incorporated in the refinery yield model data set

Crude oil	API gravity	Sulfur (wt %)
Algeria Hassi-Messaoud	44.0	0.2
Canada Federated	40.4	0.2
Canada Rgld		
Canada Conds		
Indonesia Minas	34.7	0.1
Iran Heavy	30.9	1.6
Libya Brega	40.2	0.2
Nigeria Bonny	34.8	0.1
Saudi Arabia Light	34.8	1.6
Saudi Arabia Heavy	28.2	2.8
Venezuela Tiajuana		
Mexican Maya	34.0	1.7
North Sea	35.8	0.2
Gabon		
Alaska Cook Inlet	36.7	0.2
Alaska Prudhoe Bay	27.8	0.9
California Outer Continental		
California Wilmington	20.9	1.4
California Sjv Heavy	13.7	1.3
California Ventura	29.7	1.2
California San Ardo	12.5	2.0
Florida Jay	51.0	0.4
Illinois Weeks	38.6	0.2
Kansas Common	35.6	0.5
Louisiana North	40.3	0.3
Louisiana Ostrica	32.9	0.4
Mississippi Hey Light	37.9	1.2
Mississippi Baxterville	21.0	2.0
Montana/Wyoming Rebeki	36.9	0.3
Oklahoma Garber	41.7	0.1
Oklahoma Cement	34.3	0.2
Oklahoma Condensate	47.6	
Texas West Sour	32.4	1.8
Texas West Scurry		
Texas Gulf Refugio	34.3	0.1
Texas East	38.5	0.3
Texas East Hawkins	26.6	2.1
Texas West Light	42.3	0.2
Texas West Intermediate	40.1	0.4
Utah Altamount	41.6	0.2
Wyoming Sour	23.6	2.7

fuels, costs of additives, product specifications, process unit yields, plant product losses or gains, and other situations. Section 4.4 discusses specific applications of the REMS refinery yield model in the analysis of future petroleum refining operations on the West Coast under such varying conditions.

As described in the preceding sections, the flow of information within the Navy Mobility Fuels Forecasting System consists of (1) price, oil supply, and oil demand data produced by OMS for input to PAL; (2) price data produced by OMS for input to REMS; and (3) forecasts of crude runs to stills produced by PAL for input to REMS.

Table 4.5. Refined products of the REMS refinery yield model and production quantities from all refineries for 1990 BAU in BOM District 13

Product	Quantity (MB/CD)
Regular motor gasoline	488.0
Premium unleaded motor gasoline	125.1
Unleaded motor gasoline	455.9
Aviation gasoline	6.1
Naphtha to petrochemicals	4.3
Special naphtha	3.0
Aromatics	5.4
Jet fuel B	108.8
Jet fuel A	450.8
Jet fuel JP-5	45.2
Kerosene	13.0
Distillate fuel	284.0
Navy distillate	10.1
Residual fuel, 0.3% sulfur	0.0
Residual fuel, 0.5% sulfur	1.5
Residual fuel, 1.0% sulfur	0.0
Residual fuel, 2.0% syulfur	309.6
Residual fuel, >2.0% sulfur	0.0
Lubes and waxes	13.5
Gas oil to petrochemicals	17.8
Road oil and asphalt	54.6
Coke, low sulfur,t/d	11.7
Coke, high sulfur, t/d	5.4
Sulfur, t/d	2.3
Process gas	0.0
Still gas to petrochemicals	1.8
Ethane	0.0
Propylene to petrochemicals	44.5
Propane fuel	22.6
Propane to petrochemicals	4.6
Butylene to petrochemicals	54.8
Normal butane	10.8
Plant fuel burned	230.2
Total (excluding coke and sulfur)	2765.9

Operational relationships of the forecasting system are shown in Fig. 4.2. Given exogeneous inputs describing world and domestic energy and economic factors, the OMS model balances oil supply and demand at a world oil price. Relevant OMS data are converted automatically by data preprocessing programs into PAL-compatible data files.

The PAL model of world production, refining, and transportation relationships automatically accesses, on an as-needed basis, the preprocessed OMS data to forecast disaggregate regional petroleum supply/demand balances.

Relevant PAL data on crude runs to stills are manually preprocessed for input to the detailed REMS model representation of domestic refinery operations. OMS world oil price data are also

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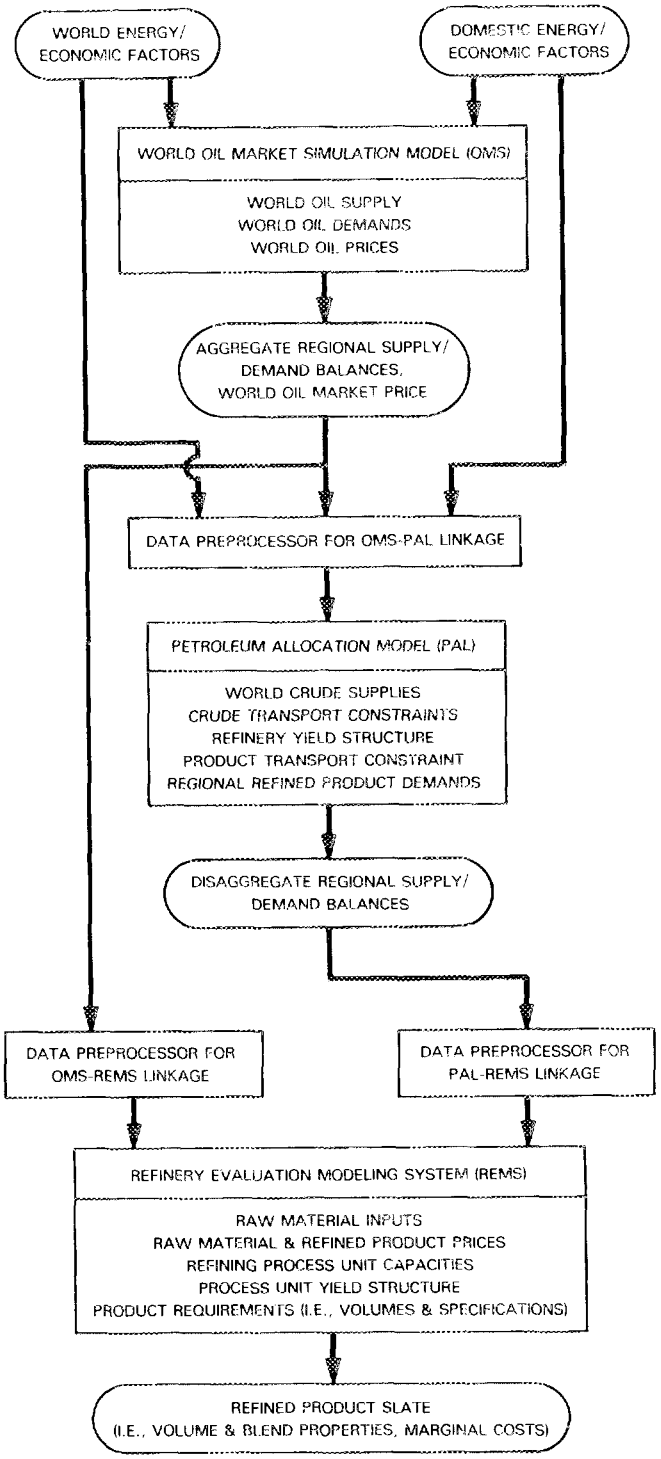

Fig. 4.2. Operational linkage of models.

manually converted to specific crude oil prices for input to REMS. Among other outputs, REMS computes the refined product slate which maximizes the refiner's gross margin. REMS produces hard copy output and/or stores the problem solution for automatic retrieval. The manual OMS-REMS and PAL-REMS data linkages are to be automated in Phase II of the project.

4.2. SENSITIVITY TESTING OF THE REFINERY YIELD MODEL STRUCTURE

Prior to integration of the refinery yield model into the total mobility fuels forecasting system, ORNL conducted an examination of the model's sensitivity to the three key variable categories of crude type, product specification, and refinery complexity. Because REMS was not available at the start of the analysis, the sensitivity examination was performed on the refinery yield model of Turner, Mason & Associates of Dallas, Texas (the TMA model). The structure of the TMA model is virtually identical to the structure of the REMS refinery yield model. In fact, the REMS model is an updated version of a 1978-vintage TMA model in which (1) a more efficient matrix-operations module is used and (2) raw material and product yield vectors are automatically transmitted to a downstream product distribution model. ORNL made the necessary alterations and updates to the TMA model to represent JP-5, F-76, and total refinery operations for 1983, the year of most recently available operating data.

ORNL selected a set of values for each variable category and exercised the TMA model under the conditions defined in Appendix A. As defined in Appendix A, the model's representation of military mobility fuels is sufficiently sensitive to crude inputs; product specifications of flash point, freeze point, and cetane index; and refinery complexity. All these categories of variables are of importance to the availability and cost of military mobility fuels.

4.3. COMPARISON OF REMS AND EXXON MODELS

Exxon has used its refinery yield model to evaluate the producibility of kerosene jet fuels in the United States, Canada, and Europe. Exxon's model is a proprietary linear program, and an explicit comparison to the REMS structure cannot be performed. However, a comparison of the solutions of the two models, given identical input assumptions, is instructive.

Exxon has defined "producibility" as that amount of a fuel that a particular refinery configuration can make when simultaneously satisfying the market demand for all other refined petroleum products. Within economic constraints, the refinery configuration of this definition is permitted to purchase additional crudes and to invest in process units to meet overall product demands.

Exxon and REMS have been compared through analysis of the producibility of kerosene jet fuels in BOM District 13 for the year 1990. Results are presented in Table 4.6 for the production of two study fuels by various combinations of refinery configurations and crude runs. The three refinery configurations were

1. *Hydroskimming* in which a crude is distilled to produce a distribution of products appropriate to that crude. This refining configuration included atmospheric distillation, catalytic reforming, and hydrorefining process units.

2. *Low Conversion* for which vacuum distillation, catalytic cracking, and alkylation process units were added to the hydroskimming configuration.

Table 4.6. Kerosene jet fuel yields for the REMS-Exxon comparison

Refinery-crude model	1990 West Coast (% of crude run)			
	Baseline yield of kerosene Jet (TF-1)		Property relaxation yield kerosene Jet (TF-4)	
	REMS	Exxon	REMS	Exxon
Hydroskimming, low sulfur	7.49	7.30	7.49	7.30
Low Conversion, low sulfur	14.55	9.90	14.98	10.40
High Conversion, low sulfur	8.93	9.70	10.19	10.19
High Conversion, medium sulfur, Heavy	13.47	8.70	13.47	12.18
High Conversion, high sulfur, Heavy	9.76	9.80	11.27	12.25

Source of Exxon data: AGARD Propulsion and Energetics Panel, *Producibility and Cost Studies of Aviation Kerosene*, Draft report received January 25, 1985.

3. *High Conversion* for which coker and hydrocracking process units were added to the low conversion configuration.

Crude inputs to the modeled refinery were categorized by sulfur content and density. A high-sulfur crude contained more than 1.0 wt % sulfur. Medium-sulfur crude contained 0.5 to 1.0 wt % sulfur. Low-sulfur crudes contained less than 0.5 wt % sulfur. A crude was designated as "Heavy" if at least 15% boiled above 1050°F at atmospheric pressure.

Table 4.7 shows key specifications for the test fuels TF-1 and TF-4. TF-1 is an average quality kerosene jet fuel based on 1978 Jet A inspection reports. TF-4 is a fuel for which the TF-1 baselihe inspections have been relaxed for aromatics, smoke point, and freezing point. Process stocks, including hydrocracked stocks, were not permitted in either study fuel.

Table 4.7. Test fuel specifications for the REMS-Exxon comparison

Property	Test fuel designation	
	TF-1	TF-4
Aromatics, max., vol %	18	33
Smoke point, min., mm	21.5	14
Flash point, min., °F	109.4	109.4
Freezing point, max., °F	−45.4	−20.2
Process stocks allowed	No	No

As shown in Table 4.6, yield results for the Exxon and REMS models agree quite closely in all cases, with the greatest variations occurring in the analyses for low-conversion/low-sulfur and high-conversion/medium-sulfur/heavy refinery-crude combinations. Exxon has an enviable reputation in refinery modeling, and the credibility of REMS is enhanced when REMS generates solutions similar to the Exxon model.

4.4. ANALYSIS OF WEST COAST PETROLEUM OPERATIONS FOR 1990

The REMS refinery yield model has been used to evaluate petroleum operations on the West Coast under BAU and supply disruption scenarios for the year 1990. BOM District 13 was selected for analysis because it is an important source of Navy JP-5. In 1978, the region produced 42% of total Navy JP-5 supplies. The domestic share of BOM 13 production of JP-5 was 54% in 1978. Also, the region is relatively independent of other refining regions, and other investigators[4,5] have suggested potential difficulties in meeting specifications for kerosene aviation turbine fuels in the region.

4.4.1. The Business-as-Usual Scenario

For the BAU study, inputs to the REMS model were based on the PAL vector of 1990 refinery runs of raw materials shown previously in Table 4.2. For crudes with inconsistent definitions between the PAL and REMS models, historical apportionment was applied. For example, the PAL estimate of 64.4 thousand barrels per calendar day (MB/CD) of Indonesia crude was translated for REMS into 23.5 MB/CD of Indonesia Minas and 40.9 MB/CD of Indonesia Light. This apportionment honors the 1982 ratio of 73:27 for the two crudes.

As shown previously in Table 4.1, the OMS model estimates a 1990 world oil price of $36.71 per barrel. This amount was assumed to be the BAU price of Saudi Arabia Light crude. The prices of all other hydrocarbon streams (crudes, products, and additives) were adjusted by the ratio of the price of Saudi Arabia Light in the year 1990 compared to its observed price in the year 1982 (i.e., $36.71 per barrel: $30.36 per barrel equals 1.209). For all other variable costs, no real increases were assumed to occur between 1982 and 1990. Although model cost data are expressed to the nearest absolute cent per barrel, it is important to note that model inputs and results are often best interpreted in terms of relative rather than absolute magnitudes.

Based upon the analysis of Sect. 3, it was assumed that the BOM 13 refinery configuration would be relatively stable between 1982 and 1990. Process unit capacities for the BAU scenario are listed in Table 4.3. Stream-day factors are specified in the data set to reflect turnaround and other downtime for the process units.

In the 1990 product specifications, it was assumed that no lead will be permitted in motor gasolines. Other 1990 product specifications were assumed to be equal to 1982 specifications.

Demands were fixed at 1990 PAL projection levels for all products except Jet A, JP-5, kerosene, distillate fuel, and F-76, which were to be produced at the level of choice of the REMS refinery. The Jet A, JP-5, kerosene, distillate fuel, and F-76 share many of the same blending components. By producing the products at the refiner's level of choice, production of JP-5 can be augmented by transferring blending components from the pools of Jet A, kerosene, distillate fuel, and F-76. This approach assumes that the market will absorb whatever is produced, and inventories of these nonfixed products are sufficient to assure that demands will be satisfied at the specified gate price.

Table 4.5 displays the 1990 product slate that maximizes the gross refining margin for BOM 13 in the BAU scenario. In the BAU scenario, JP-5 output for BOM 13 is 45.2 MB/CD, and its production is limited by specifications for flash point and smoke point. "Smoke point," "flash point," and other refining terms are defined in a glossary in Appendix A.

4.4.2. The Crude Oil Supply Disruption Scenario

All the projected foreign crudes for 1990 refinery runs in BOM 13 are from nations that are currently members of OPEC. The refinery yield model was used to evaluate the effects of a total loss of OPEC crudes in 1990 in BOM 13. This loss is 7.3% of BAU total crude runs, and will be designated the "basic disruption." It was assumed that, relative to BAU operations, no change would occur in real operating costs, raw material cost and product gate prices. In reality, rapid price and commodity demand adjustments might occur. These important adjustments are extraordinarily difficult to predict and beyond the scope of this investigation.

The loss of OPEC imports results in a 7.5% loss of JP-5 production relative to 1990 BAU operations. As in the BAU case, JP-5 production during the disruption is limited by specifications for flash point and smoke point.

4.4.3. Strategies for Recovery

Three strategies for recovery of JP-5 production were considered: (1) crude replacement, (2) JP-5 specification relaxation, and (3) JP-5 price inducements. One additional constraint was placed upon the model in the assessment of these recovery strategies. Jet A production was fixed at the basic disruption level, and the demand ratio relating Jet A to JP-5 production was removed. This modeling tactic was incorporated to free JP-5 from possible limitations in Jet A production.

Figure 4.3 presents a comparison of JP-5 production for BAU, basic disruption, and three crude oil replacement scenarios. With the disruption, production declined 3400 B/CD. A 76% recovery of JP-5 production is realized with scenario IIIA, in which lost crude is replaced by proportionally increasing all domestic crudes. A 41% recovery of JP-5 production results in scenarios IIIB and IIIC in which lost crude is replaced by California Heavy, the poorest-quality crude from the BAU slate. Scenarios IIIB and IIIC specify different prices for California Heavy. The BAU price is used in IIIB, and the higher weighted average price of lost imports is applied to California Heavy in IIIC. Although the same volume of JP-5 is produced in scenarios IIIB and IIIC, the refining revenue is lower for the case in which the California Heavy price is higher. In summary, REMS suggests that full recovery of BAU JP-5 production is not possible with the crude replacement options considered here.

Relaxations of flash and smoke points were evaluated for recovery of JP-5 production. Figure 4.4 shows that, as the flash point is reduced to 132°F, JP-5 production can be increased. Below 132°F, no additional recovery is realized because other constraints begin to bind JP-5 production. It is important to remember that, for the recovery studies, the model permits production at the level of choice for JP-5, kerosene, distillate fuel, and F-76. Therefore, gains in JP-5 production result from declines in the production of other middle distillates. In reality, consumers would be expected to compete for reduced supplies of distillate fuel by bidding higher prices for the commodity in shortage. The refiner might well respond to higher bid prices by modifying his operating plan to produce more distillate at the expense of jet fuel. Obviously, a more rigorous analysis would require consideration of the dynamic interactions among price, supply, and demand.

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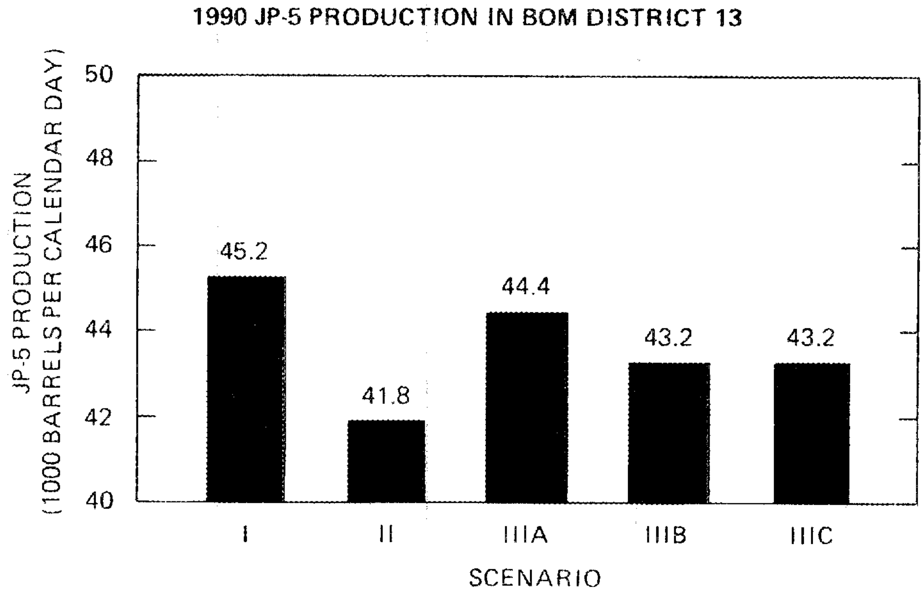

SCENARIO I: BUSINESS AS USUAL
SCENARIO II: TOTAL LOSS OF OPEC IMPORTS/NO REPLACEMENT
SCENARIO IIIA: SCENARIO II WITH PROPORTIONAL REPLACEMENT
SCENARIO IIIB: SCENARIO II WITH REPLACEMENT BY CAL HEAVY @ $24.55
SCENARIO IIIC: SCENARIO II WITH REPLACEMENT BY CAL HEAVY @ $36.34

Fig. 4.3. JP-5 production response to crude slates.

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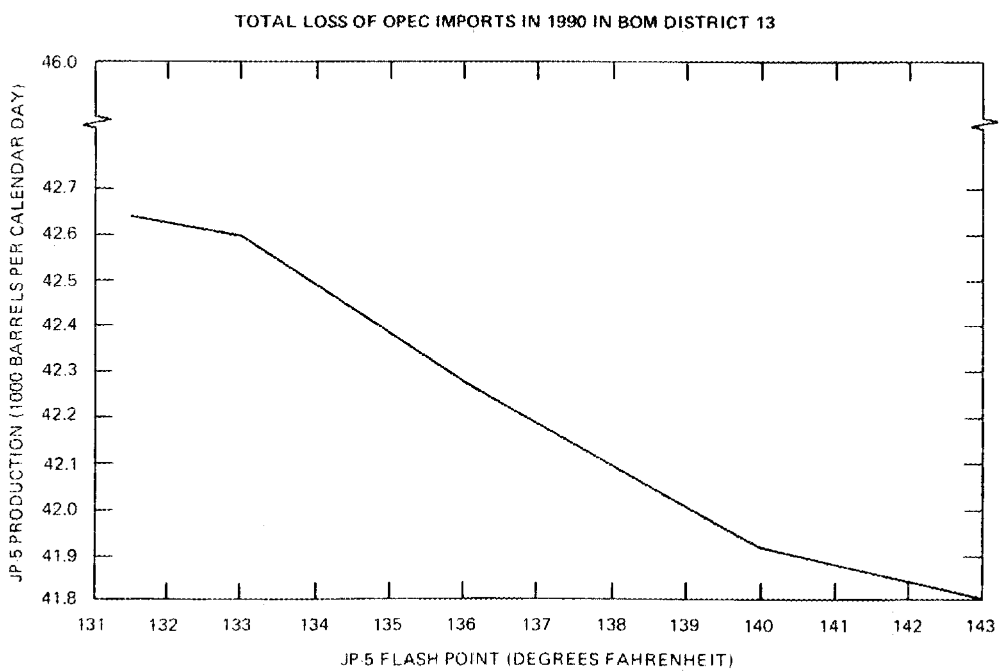

Fig. 4.4. JP-5 production response to flash point specification.

Figure 4.5 plots JP-5 production against smoke point. It indicates that full recovery of BAU production of JP-5 is possible if the smoke point is reduced to 17.2 mm or lower.

The JP-5 price-response curve of BOM 13 refineries is given in Fig. 4.6. Discontinuities, which reflect changes in the linear program solution basis, result when the modeled refinery discards one activity in favor of a new activity. Full recovery of BAU production of JP-5 is possible if the refiners are offered $45.32 per barrel of JP-5, an increase of $1.95 per barrel above the BAU price. In fact, at $45.32 per barrel and with no constraints on JP-5 production, BOM 13 refineries would increase production of JP-5 to 47.6 MB/CD, exceeding the BAU production level of 45.2 MB/CD.

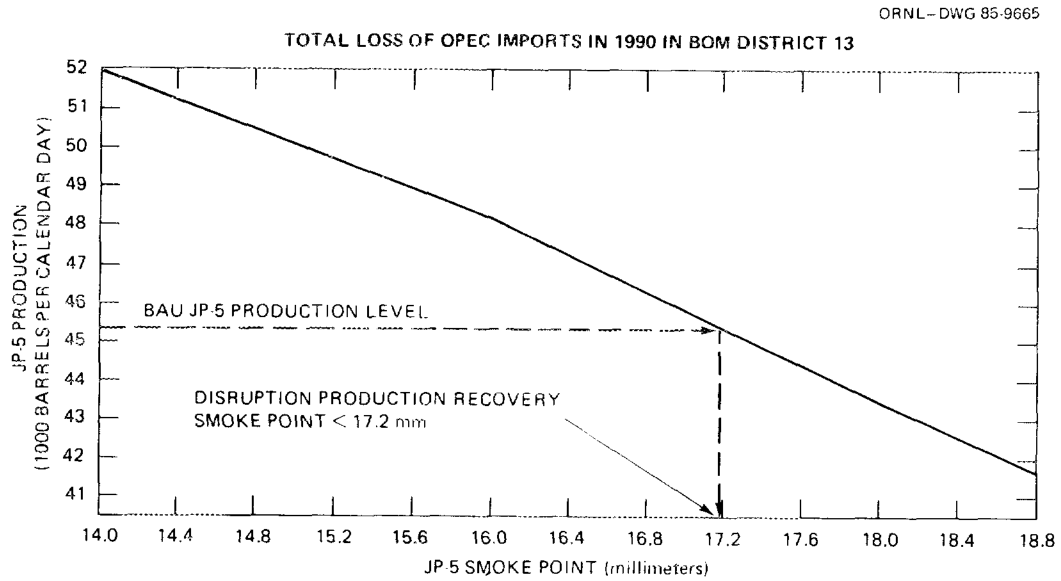

Fig. 4.5. JP-5 production response to smoke point specification.

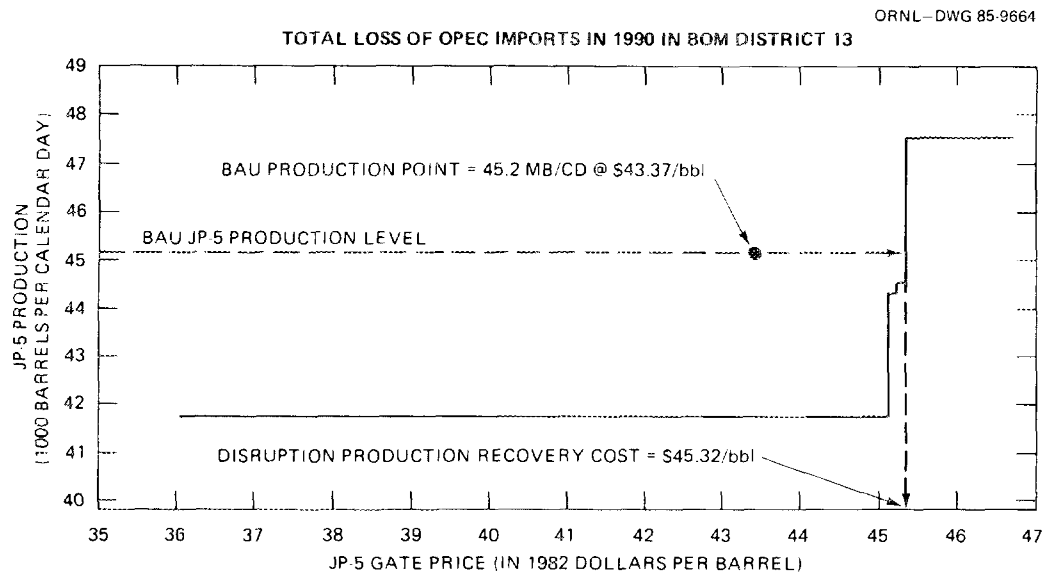

Fig. 4.6. JP-5 production response to gate price.

4.5. SUMMARY

The available models for predicting future movements in the petroleum industry were surveyed and studied. Three models (OMS, PAL, and REMS) were selected for use because in concert they appeared to be able to reliably provide predictive data of interest to Naval planners and researchers. These models were adapted to operate in a coordinated fashion, to provide information of specific interest to the Navy Mobility Fuels Forecasting System, and to use enhanced sources of information to improve their accuracy.

The sensitivity of the REMS refinery yield model to differences in values of critical variables was tested, and the model was found to be sufficiently sensitive. REMS was also found to replicate well the results of Exxon's refinery yield model in an analysis of jet fuel producibility on the West Coast.

The predictive capabilities of the linked models were then tested for a 1990 scenario in which all OPEC crude imports to the West Coast are terminated. The system allowed evaluation of various strategies for recovery of JP-5 production to the predisruption refining level. Refinery production of middle distillates was unconstrained, and the price responsiveness of consumers was not considered in the analyses.

The forecasting system indicated that partial recovery of JP-5 production was possible by replacement of the lost imports by reapportionment of the predisruption domestic crude slate for the West Coast or by relaxing the flash point specification. It indicated that full recovery of production would result from a decrease of the smoke point specification or by offering refiners a $1.95 per barrel increase in the JP-5 gate price.

The modeling system could be applied to consider the shortage mitigation possibilities of other strategies (such as joint adjustments of smoke point and price) or market overrides (such as rationing). Furthermore, it could be used to predict responses to disruptions for any or all of the BOMs.

Because JP-5 and other Navy mobility fuels are produced globally, future work will address worldwide refinery representation by models with structural detail similar to that of the domestic REMS refinery yield model. ORNL is presently considering the construction of model data sets which will account for capacity contributions of freeworld refineries in 10 regions which are geographically compatible with the PAL model: North Europe, South Europe, Canada, Caribbean, Latin America, Africa, Mid-East, Japan, Pacific, and Asia.

The importance of supply-and-demand responsiveness to price in the forecasting system has been noted several times. Although it is extremely difficult to portray these phenomena over the mid- to long-range horizon, it is advisable to support the refinery yield model with some systematic method for estimating price elasticities of demand. This enhancement is planned for the second phase of work.

Lastly, ORNL is constantly monitoring the quality of data which support the forecasting system. In mid-summer, 1985, the National Petroleum Council (NPC), a federal advisory committee to the Secretary of Energy, will complete the acquisition of detailed survey data describing current and projected domestic and foreign refining operations. ORNL will evaluate the applicability of NPC data and make appropriate updates to the REMS data sets.

4.5. REFERENCES

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Appendix A

GLOSSARY

A. GLOSSARY

Alkylation—A conversion process for improving the antiknock properties of gasoline. Specifically, alkylation converts isobutane and olefins, such as butenes, to iso-octane and other similar hydrocarbons in the presence of a strong acid catalyst, such as sulfuric or hydrofluoric acid.

API Gravity—An arbitrary scale expressing the density of liquid petroleum. The measuring scale is calibrated in terms of degrees API, which may be calculated by the following formula:

$$\text{Deg API} = \left\{141.5/\text{sp gr}\right\} - 131.5,$$

where the specific gravity is measured at 60°F.

Aromatics—Unsaturated cyclic hydrocarbons characterized by the benzene ring which may be present either singly or multiply and with or without side chains.

Asphalt—A blackish, bituminous, thermoplastic mixture of hydrocarbons, including high molecular weight asphaltenes, oily constituents, and intermediate molecular weight resins.

Atmospheric Distillation—A process that performs the initial separation of crude oil into gas, naphtha, distillates, and residuum.

Aviation Gasoline—All special grades of gasoline for use in aviation reciprocating engines.

Barrel—A volumetric measure equivalent to 42 U.S. gallons.

Blending—The combination in various proportions of refinery streams into commercially saleable products that meet given specifications.

Bunker Fuel Oil—A high viscosity fuel oil (grade 6) used mostly in commercial and industrial heating.

Butane—A normally gaseous paraffinic hydrocarbon ($C_4 H_{10}$) which is extracted from natural gas or refinery gas streams.

Butylene—An olefinic hydrocarbon ($C_4 H_8$) recovered from refinery processes.

Catalyst—A substance that contributes to chemical reactions without itself undergoing any change. Catalysts usually lower the activation energy required to initiate a chemical reaction, permitting the reaction to proceed at milder conditions.

Catalytic Cracking—A conversion process that uses silicon oxide and aluminum oxide catalysts (which may contain other metal oxides and metals) and temperatures substantially lower than thermal cracking to convert a raw oil charge into branched-chain hydrocarbons of excellent octane number. Fluid catalytic cracking (FCC) converts virgin atmospheric, vacuum gas oils, and heavy stocks derived from other refinery operations into high octane "cat" gasoline and light fuel oils called "cycle stocks." Olefin-rich gases, which can be directed to polymerization or alkylation operations to produce gasoline, are co-products. Typically, yields of liquid products will exceed 75 to 80 vol % of the FCC feed. The term "fluid catalytic cracking" is derived from the use of a catalyst consisting of small particles that, when aerated with a vapor, behave as a fluid. This fluidized catalyst will flow and is circulated within the system.

Catalytic Hydrocracking—A fixed-bed conversion process that catalytically cracks and hydrogenates hydrocarbon feeds. Hydrocracking is the most severe form of hydroprocessing, and practically any stock can be hydrocracked, including refractory feeds that resist conversion by other processes. Yields of jet fuel approximating 85 to 90 vol % of feed can be achieved, with the concurrent production of liquified petroleum gas and light gasoline.

Catalytic Hydroprocessing—A category of operations in which a variety of petroleum fractions may be treated at elevated temperature and pressure with hydrogen in the presence of a catalyst to reduce sulfur; to improve stability, odor, combustion characteristics, and appearance; and to convert heavy fractions to lighter and more valuable products. See hydrotreating, hydrorefining, and hydrocracking.

Catalytic Hydrorefining—A hydroprocessing operation that usually involves only minor molecular changes of the feed, with hydrogen consumption in the range of about 100 to 1000 cubic feet per barrel. Applications include desulfurization of a wide range of feeds (naphtha, light and heavy distillates, and certain residue) and occasional pretreatment of catalytic cracker feeds.

Catalytic Hydrotreating—A hydroprocessing operation that essentially involves no reduction in molecular size, with hydrogen consumption less than 100 cubic feet per barrel. A primary application is to remove small amounts of impurities, with typical uses including the odor improvement of naphtha and kerosene.

Catalytic Reforming—A conversion process in which a series of reactions occurs in the presence of a platinum catalyst. The most important of these reactions is aromatization. The desired product has approximately the same boiling range as the feed, but the molecules have been reformed into higher octane compounds. Reforming is also the major source of hydrogen for many refinery operations.

Cetane Index—An approximation of a cetane number based on API gravity and a mid-boiling point of a fuel.

Cetane Number—A measure of the ignition quality of a diesel fuel. Higher cetane numbers indicate a shorter ignition lag and are associated with better all-around performance in most diesel engines, especially in sensitive engines of the high-speed type.

Conversion Process—The chemical transformation of a refinery stream into products of higher value.

Crude Oil—A complex mixture of hydrocarbons containing mainly paraffin hydrocarbons plus some naphthenes and aromatics. Molecular weights may range from the lightest to more than 6,000. In addition to hydrocarbons, compounds containing oxygen, sulfur, and nitrogen as well as traces of metal salts are also present.

Delayed Coking—A conversion operation to produce low-carbon-residue gas oil for catalytic cracking feedstock and for gasoline.

Distillate Fuel Oil—A general classification for a petroleum fraction used primarily for space heating, on-and-off highway diesel engine fuel, and electric power generation.

Entitlements Program—A program that essentially required large refiners to subsidize small refiners if the latter's crude oil acquisition cost was higher than the national average. The Entitlements Program was a result of provisions of the Emergency Petroleum Allocation Act of 1973 and the Energy Policy and Conservation Act of 1975.

Ethane—A normally gaseous paraffinic compound (C_2H_6) extracted from natural gas and refinery gas streams.

Flash Point—The lowest temperature at which an air-vapor mixture will ignite in the presence of an ignition source.

Fluid Coking—A thermal process that uses the fluidized-solids technique for continuous conversion of heavy, low-grade oils into lighter products.

Freeze Point—The temperature at which crystals of hydrocarbon formed on cooling disappear when the temperature of the fuel is allowed to rise.

Gasoline—A light hydrocarbon distillate of relatively high antiknock value suitable to serve as a fuel for gasoline engines. First-quality gasoline requires a number of special features: (1) volatility high enough for easy starting and rapid warm-up, but not so high as to induce vapor lock; (2) inhibition of carburetor icing tendencies; (3) cleanliness characteristics to prevent the buildup of carburetor deposits and to reduce the possibility of spark plug fouling; and (4) antiknock properties that meet the requirements of the engine in which the gasoline is used.

Hexane—A volatile paraffinic hydrocarbon ($C_6 H_{14}$).

Ignition Lag—The delay between time when conditions are suitable for ignition and time when ignition actually occurs in an internal combustion engine. The longer the ignition lag, the greater the tendency of the engine to knock.

International Energy Agency Petroleum Sharing Agreement—A petroleum disruption mitigation agreement that commits participating countries to share available supplies based on historical consumption, production, and import levels. All countries are required to maintain an emergency reserve commitment equal to a 90-day supply of imports and must have demand-restraint measures in place. The agreement can be triggered by a 7% shortfall experienced by a single country or by the entire group. At the 7% shortfall level, the country invoking the agreement must absorb the first 7% through demand-restraint measures. If the shortfall is 12% or more, at least 10% of the shortfall must be absorbed. After 50% of emergency reserve commitments have been reached, the petroleum-sharing procedures go into effect. Under these procedures, each country receives a supply right (normal consumption minus 10% minus storage commitments). A country whose supply right exceeds the sum of its normal domestic production and actual net imports receives an allocation right equal to the difference. A country whose supply right is less than the sum of these two quantities would be required to redirect the excess to countries in the first category.

Isomerization—A conversion process used to convert normal butane into isobutane (an alkylation-process feedstock) and normal pentane and hexane into isopentane and isohexane (high-octane gasoline components).

Kerosene—A petroleum distillate that boils at temperatures between 300 and 550°F.

Kerosene-Type Jet Fuel—A relatively low freezing point distillate of the kerosene type, used primarily for turbojet and turboprop aircraft engines.

Knock—Detonation occuring in the cylinder of an internal-combustion engine and caused by sudden excessive pressures developed during combustion. Knock reduces efficiency and can be destructive to engine parts.

Lead Alkyl—One of the several lead compounds used to improve octane number in a gasoline. The maximum allowable lead content of domestic leaded gasoline will drop from the current 1.1 grams per gallon to 0.1 grams per gallon by January 1, 1986, with an interim standard of 0.5 grams per gallon effective July 1, 1985.

Lubricating Oil—A substance produced from either distillates or residues that is used to reduce friction between bearing surfaces.

Lubricity—A moderate load-carrying ability of an oil over and above that indicated by the oil's viscosity.

Luminometer Number—A measure of an aviation turbine fuel's radiation characteristics. The higher the luminometer number, the greater the flame radiation and combustion characteristics.

Naphtha—A generic term covering a range of light petroleum distillates. Naphthas are not necessarily naphthenic, but may be paraffinic, naphthenic, aromatic, or any combination thereof.

The term "light crude naphtha" usually refers to the first liquid overhead fraction, with a boiling range of 100 to 375°F. "Heavy crude naphtha" is usually the second overhead fraction, with a boiling range of 350 to 450°F.

Naphthenic Hydrocarbon—A saturated cyclic hydrocarbon.

Natural Gas—Gas occurring naturally in the earth, consisting mainly of methane but also ethane, propane, butane, and minor quantities of heavier materials.

Octane Number—A measure of the antiknock properties of a gasoline. The Motor Method of measure is considered to give better correlation with high engine speed or part-throttle conditions. The Research Method correlates better with low engine speed.

Olefins—A class of double-bonded chain hydrocarbons.

Paraffinic Hydrocarbon—A saturated straight or branched-chain hydrocarbon.

Pentane—A volatile paraffinic hydrocarbon (C_5H_{12}).

Petroleum—A term applicable to crude oils and the hydrocarbon products and materials that are derived from them.

Petroleum Coke—A residue that is the final product of the condensation process in cracking. Marketable coke is produced in delayed or fluid cokers and may be sold or further purified. Catalyst coke is deposited on and deactivates catalysts of many refining processes.

Polymerization—An operation in which two or more unsaturated molecules combine to form a polymer, a different molecule of higher molecular weight.

Pour Point—The lowest temperature at which an oil will flow, a factor of significance in cold-weather start-up.

Propane—A normally gaseous paraffinic compound (C_3H_8).

Propylene—An olefinic hydrocarbon (C_3H_6) recovered from refinery or petrochemical processes.

Reid Vapor Pressure—The absolute vapor pressure exerted by a liquid at 100°F.

Residual Fuel Oil—The topped crude of refinery operations, which includes grade 5, grade 6, and Navy special fuel oil. Residual fuel oil is used for the production of electric power, space heating, vessel bunkering, and various industrial purposes.

Road Oil—Any heavy petroleum oil, including residual asphaltic oil used as a dust palliative and surface treatment on roads and highways.

Smoke Point—The maximum flame height obtainable in a test lamp without smoking. Cleaner-burning aviation turbine fuels have higher smoke points.

Special Naphthas—All finished products within the gasoline range that are used as paint thinners, cleaners, or solvents.

Still Gas—Any form or mixture of gas produced in refineries by distillation, cracking, reforming, or other processes. The principal constituents are methane, ethane, ethylene, butane, butylene, propane, propylene, etc.

Strategic Petroleum Reserve—Petroleum stocks maintained by the Federal Government for use during periods of major supply disruption.

Sour Crude Oil—Crude oil that contains as much as 0.05 cubic feet of dissolved hydrogen sulfide per 100 gallons.

Sulfur Content—The amount of naturally occurring sulfur in petroleum products.

Thermal Cracking—A conversion process in which heat and pressure are used to break down, rearrange, or combine hydrocarbon molecules.

Vacuum Distillation—Distillation under reduced pressure, which lowers the boiling temperature of the liquid being distilled. This technique, with its relatively low temperatures, prevents cracking or decomposition of the charge stock.

Visbreaking—A thermal cracking process in which vacuum distillation bottoms are cracked to increase production of distillate products.

Viscosity—A measure of a fluid's resistance to flow, ordinarily expressed in terms of the time required for a standard quantity of the fluid at a certain temperature to flow through a standard orifice.

Wax—Petroleum components of plastic consistency derived from distillates or residues by such treatments as chilling, precipitating with a solvent, or de-oiling.

Appendix B

NAVY MOBILITY AND THEIR SPECIFICATIONS

B. NAVY MOBILITY FUELS AND THEIR SPECIFICATIONS

The Navy mobility fuels are aviation gasoline; motor vehicle gasoline; aviation turbine fuel, grade JP-4; aviation turbine fuel, grade JP-5; diesel fuel marine; Naval distillate fuel, grade F-76; and Naval special fuel oil residual.

JP-5 is a kerosene jet fuel. Kerosene jet fuels are specialty cuts of the kerosene fraction of the crude. Generally, they are cut directly from the crude oil in the atmospheric fractionator. The amount of jet fuel so produced (referred to as virgin jet fuel) depends upon the crude characteristics and can range from 7 to 19 vol % of the crude. While many of the properties of JP-5 are similar to those of other kerosene jet fuels (such as the commercial Jet A/A-1 and the USAF JP-8), it has a unique requirement in that it must have a minimun flash point of 60°C (140°F). The specifications for JP-5 are summarized in Table B.1. The specifications for commercial jet fuels and JP-8 are also given in that table for comparison.

F-76 is a distillate fuel that is similar to No. 2 fuel oil. The fuel characteristics, covered by military specification MIL-F-16884H, are summarized in Table B.2.

Table B.1 Jet fuel specifications

U.S. military specifications —
Operational fuels

	Issuing agency:		USAF		USAF	
	Specification:		MIL-T5624 K, Ammend. 1		MIL-T-83133	Test method
	Latest revision date		Nov. 12, 1976		May 3, 1976	ASTM FTMS 791
	Grade designation:		JP-4	JP-5	JP-6	
	Fuel types:		wide-cut	kerosene	kerosene	
Composition	Acidity, total (mg KOH/g)	Max.	0.015	0.015	0.015	D3242
	Aromatics (vol %)	Max.	25.0	25.0	25.0	D1319
	Olefins (vol %)	Max.	5.0	5.0	5.0	D1319
	Sulfur, mercaptan (vol %)	Max.	0.001	0.001	0.001	D1323
	or doctor test N = neg.		N	N	N	D484
	Sulfur, total (wt %)	Max.	0.4	0.4	0.4	D1266/1552/2622
	Color, Saybolt		Report	Report	Report	D156
Volatility	Distillation Init. BP°C		Report	Report	Report	
	Temp. 10% rec (°C)	Max.	Report	205 (186)	205 (186)	D66/D2887 (1)
	20% rec (°C)	Max.	145 (130)	Report	Report	
	50% rec (°C)	Max.	190 (185)	Report	Report	
	90% rec (°C)	Max.	245 (250)	Report	Report	
	Final BP (°C)	Max.	270 (320)	290 (320)	300 (320)	
	Residue (vol %)	Max.	1.5		1.5	
	Loss (vol %)	Max.	1.5		1.5	
	Explosiveness percent	Max.		50		1151
	Flash point (°C)	Min.		60	38	D93
	Gravity, API (60°F)				37–51	D287
	Density (15°C) kg/m^3		751–802	788–848	775–840	D1298
	Vapor pressure 38°C (kPa)	Max.	14–21			D323/D2851
Fluidity	Freezing point (°C)	Max.	−58	−46	−50	D2386
	Viscosity at −20°C (cSt)	Max.		8.5	8.0	D445
Combustion	Aniline-gravity product	Min.	5250	4500		D1405
	or net heat of comb. (MJ/kg)	Min.	42.8	42.6	42.8	D2382/D3338 (2)
	Smoke point (mm)	Min.	20.0	19.0	25	D1322
	or naphthelenes (vol %)	Max.			3.0 (3)	D1840
	or hydrogen content (wt %)	Min.	13.6	13.5	13.6	D1018/D3343 (4)
Corrosion	Copper strip (2 h at 100°C)	Max.	1b	1b	1b	D130
Stability	Coker ΔP (mm Hg)	Max.	25	25	25	D3241 (5)
	Coker tube color code	Max.	<3	<3	<3	
Contaminants	Existent gum (mg/100 ml)	Max.	7	7	7	D381
	Particulates (mg/l)	Max.	1	1	1	D2276 (6)
	Water reaction interface	Max.	1b		1b	D1094
	Water reaction separation	Max.	1		2	D1094
	WSIM	Min.	70	86	70	D2550
	Filtration time, min	Max.	15			(6)
Additives	Anti-icing, vol %		0.10–0.15	0.10–0.15	0.10–0.15	5327
	Antioxidant		Required (7)	Req. (7)	Option	
	Corrosion inhibiter		Required	Option	Required	
	Metal deactivator		Option	Option	Option	
	Antistatic		Option		Option	
Other	Conductivity (pS/m)		50–300 (8)		50–300 (8)	D2624/D3114
	Service		All	Navy	USAF	
	NATO code No.		F-40	F-44	F-34	

Notes:

(1) Test limits for G.C. distillation by D2887 appear in parentheses.
(2) D3338 allowed for JP-4 and JP-6.
(3) Plus Smoke Point of 20 mm, minimum.
(4) D3343 allowed for JP-4 and JP-6.
(5) Test at 260°C and 3.45 M Pa pressure. No peacock or abnormal deposits by visual rating. Report span TDR ratings.
(6) Minimum one-gallon sample. Filtration time by Appendix A of MIL-T-5624K also used for D2278 particulates.
(7) If hydrogen treated blend stocks used, concentration equals 17.2 to 24 mg/l. Optional if no hydrotreating used.
(8) If anti-series additive used, one wppm maximum to meet limits.

Source: M. Lieberman and W. F. Taylor, *Effect of Refining Variables on the Properties and Composition of JP-5,* Final Report September 1978–February 1980, Exxon Research and Engineering Company, Linden, N.J.

Table B.1. (continued)

	Commercial specifications Airlines				
	Issuing agency: Specification: Latest revision date:		United Airlines FUE 4500-7 Nov. 8, 1976		Test method ASTM
	Grade designation: Fuel type:		Jet A/A-1 kerosene	Jet B wide-cut	
Composition	Acidity, total (mg KOH/g)	Max.	0.1		D974/D3242
	Aromatics (vol %)	Max.	25 (1)	25	D1319
	Olefins (vol %)	Max.			D1319
	Sulfur, mercaptan (wt %)	Max.	0.003	0.003	D1323
	or doctor test N = neg.		N	N	D484
	Sulfur, total (wt %)	Max.	0.3	0.3	D1266
Volatility	Distillation init. BP°C				
	Temp. 10% rec (°C)	Max.	204		D86
	20% rec (°C)	Max.		143	
	50% rec (°C)	Max.	Report	188	
	90% rec (°C)	Max.	Report	243	
	Final BP (°C)	Max.	300		
	Residue (vol %)	Max.	1.5	1.5	
	Loss (vol %)	Max.	1.5	1.5	
	Flash Point (°C)	Min.	37.8		D56/D3243
	Gravity, API (60°F)		37–51	45–57	D287
	Density (15°C) kg/m^3		775–840	751–802	D1298
	Vapor pressure 38°C (kPa)	Max.		20.6	D323
Fluidity	Freezing point (°C)	Max.	−40 (2)	−50	D2386
	Viscosity at −20°C (cSt)	Max.	8		D445
Combustion	Aniline-gravity product	Min.			D1405
	or net heat of comb. (MJ/kg)	Min.	42.8	42.8	D2382
	Luminometer No.	Min.	45	45	D1740
	or smoke point (mm)	Min.	25	25	D1322
	or naphthalenes (vol %)	Max.	3 (1) (3)	3 (1) (3)	D1840
Corrosion	Copper strip (2 h at 100°C)	Max.	1	1	D130
Stability	Coker ΔP (mm hg)	Max.	25	25	D3241 (5)
	Coker tube color code	Max.	<3	<3	
Contaminants	Existent gum (mg/100 ml)	Max.	7	7	D381
	Particulates (mg/l)	Max.			D2276
	Water reaction interface	Max.	1b	1b	D1094
	Water reaction separation	Max.	2	2	D1094
	WSIM	Min.			D2550
Additives	Anti-icing		Agreement	Agreement	
	Antioxidant		Option	Option	
	Corrosion inhibiter		Agreement	Agreement	
	Metal deactivator		Option	Option	
	Antistatic		Option	Option	
Other	Conductivity (pS/m)		50–300 (4)	50–300 (4)	D2624

Notes:

(1) If actual aromatics content over 20 vol % and/or Smoke Point below 20 mm, a report must be submitted to United Airlines.

(2) If Jet A-1 specified, Freezing Point is −50°C, maximum.

(3) Plus Smoke Point of 18 mm, minimum.

(4) Applies only when anti-static additive is used and under the conditions at point of use.

(5) Test at 260°C tube temperature. Repeat test at 245°C that meets stated limits considered to pass. D1660 is alternative at 149°C preheat 204°C filter temperature with maximum test limits of 76.2-mm Hg filter ΔP and code 3 tube rating.

Table B.2. Military specifications MIL-F-16884H for Naval distillate fuel (F-76)

Characteristics	Requirements	FED-STD-791 test method	ASTM test method
Ignition quality, cetane number (min)	45		D613
Appearance at 21°C (70°F) or ambient temperature whichever is higher	Clear, bright, and free from visible particulate matter[a]		
Distillation:			
50% point, °C (°F)	Record		
90% point, °C (°F) (max)	357°C (675°F)		D86
End point, °C (°F) (max)[b]	385°C (725°F)		
Residue plus loss, percent (max)	3.0		
Flash point, °C (°F) (min)	60°C (140°F)		D93
Pour point, °C (°F) (max)	−6°C (20°F)[c]		D97
Cloud point, °C (°F) (max)	−1°C (30°F)[c]		D2500
Viscosity at 40°C (104°F) Kinematic, centistokes	1.7–4.3		D445
Carbon residue, on 10% bottoms, percent (max)	0.20		D524
Sulfur, percent (max)	1.00		D129[d]
Corrosion (max) at 100°C (212°F)	No. 1 ASTM		D130
Color (max)	3		D1500
Ash, percent (max)	0.005		D482
Gravity (hydrometer)	Record		D1298[e]
Demulsification at 25°C (77°F), minutes (max)	10		D1401
Acid number (max)	0.30		D974
Neutrality	Neutral	5101	
Aniline point, °C (°F)	Record		D611
Accelerated stability, total insolubles mg/100 ml (max)	1.3[f]		D2274

[a]A slight haze is acceptable providing a maximum (max) water and sediment of 0.01% is obtained using procedure ASTM D2709.

[b]As the end point of the distillation is approached, if either a thermometer reading 385°C (725°F) or a decomposition point is observed, discontinue the heating and resume the procedure as directed in ASTM D86.

[c]The ASTM methods for pour and cloud points permit optional use of either Celsius or Fahrenheit procedures; therefore, requirements are specified for either option.

[d]ASTM D1552 and ASTM D2622 may be used as alternative methods.

[e]ASTM D287 may be used as an alternative method.

[f]Average of three determinations is acceptable.

Source: Ref. 2, *Military Specification, Fuel, Naval Distillate,* MIL-F-16884H, U.S. Government Printing Office, May 3, 1983.

Appendix C

THE MAJOR PRODUCING FIELDS

C. THE MAJOR PRODUCING FIELDS

The U.S. Geological Survey estimated the recoverable resources of the major known oil fields of the world and of likely undiscovered fields. The production to date, the estimated reserves, and the probable undiscovered resources are presented in Table C.1. The data are arranged by geographic area. The distribution of the average API gravity of each region's production is also given, when known.

Table C.1 World estimate of original recoverable resources of conventional crude oil

(in billions of barrels)

	Cumulative production (as of 1/1/81)	Reserves (as of 1/1/81)		Probability range of undiscovered recoverable resources (as of 3/83)			Ultimate recoverable sources (mode)
		Demonstrated	Original	95%	Mode	5%	
North America	142.2	62.7	205.6	104	163	322	369
U.S.A.	124.0	29.8	153.8	64	80	105	
Canada	10.1	6.4	16.5	19	26	48	
Mexico	8.1	26.5	34.6	26	50	170	
Other			0.7	1	2	8	
Cuba							
Guatemala							
Greenland				1	2	8	
Percent original reserves	10–20	20–25 25–35	>35				
by avg API gravity	11	16 37	36				
South America	47.2	34.2	81.5	20	33	69	115
Venezuela	36.1	25.5	61.6	12	17	38	
Other	11.2	8.7	19.9	10	14	28	
Argentina	3.5	2.5	5.9				
Bolivia	0.2	<0.1	0.3				
Brazil	1.2	1.6	2.8				
Chile	0.3	0.1	0.4	8	12	26	
Columbia	2.2	0.8	2.9				
Ecuador	0.7	2.3	3.0				
Peru	1.2	0.9	2.1				
Trinidad	2.0	0.5	2.5	1	2	4	
Percent original reserves	10–20	20–25 25–35	>35				
by avg API gravity	8	15 63	14				
Europe (less USSR)	11.2	26.5	37.7	13	20	49	58
Western	5.7	24.9	30.6	12	17	40	
U.K.	1.9	14.0	15.9	9	15	34	
Norway	0.8	8.8	9.6				
Other (inc. Med)	3.0	2.1	5.2				
Austria	0.6	0.1	0.8				
Denmark	<0.1	0.3	0.3				
Ireland		0.1	0.1				
France	0.4	<0.1	0.5				
W. Germany	1.3	0.4	1.7				
Greece		0.2	0.2				
Italy	0.23	0.4	0.6				
Netherlands	0.4	0.3	0.7				
Spain	0.1	0.1	0.2				

Table C.1 (continued)

	Cumulative production (as of 1/1/81)	Reserves (as of 3/83)		Probability range of undiscovered recoverable resources (as of 3/83)			Ultimate recoverable sources (mode)
		Demonstrated	Original	95%	Mode	5%	
Eastern	5.5	1.6	7.1	1	2		
Romania	3.9	0.9	4.8				
Other	1.6	0.7	2.3				
Albania	0.2	0.2	0.4				
Bulgaria	<0.1	<0.1	0.1				
Czechslov.	<0.1	<0.1	0.1				
E. Germany	<0.1	<0.1	0.1				
Hungary	0.4	0.2	0.6				
Poland	0.4	<0.1	0.4				
Yugaslavia	0.5	0.3	0.7				
Percent original reserves by avg API gravity	10-20 2	20-25 25-35 7 18	<35 73				
U.S.S.R	67.8	69.8	137.6	59	107	343	245
Percent original reserves by avg API gravity	10-20	20-25 25-35	>35				
Africa	32.1	52.9	85.0	28	46	105	131
Libya } North Africa	12.8	24.3	37.1	4	7	25	
Algeria } North Africa	6.4	11.7	18.0	3	5	17	
Egypt } North Africa	2.4	4.0	6.3	1	2	12	
Tunisia } North Africa	0.4	0.7	1.1	1	2	9	
Nigeria	8.4	7.9	16.3	2	6	23	
Other	1.7	4.3	6.1	10	21	45	
Angola	0.6	0.7	1.3				
Cameroon	<0.1	0.4	0.4				
Gabon	0.9	0.6	1.5	1	3	11	
Ghana		<0.1	<0.1				
Ivory Coast		0.8	0.9				
Congo	0.1	0.4	0.5				
West Sahara				0	0		
Morocco	0.04	0.02	0.1	0.1	0.2	2	
Benin		<0.1	<0.1				
Chad		1.0	1.0	0.8	2	8	
Sudan		2.0	0.4	1.6	3	15	
Zaire	<0.1	0.1	0.1				
Niger				0	1	2	
Mali				0.0	tr	0.1	
Mauritania				0.0	tr	0.5	
Ethiopia				0.1	0.2	2	
Somalia				0.1	0.2	6	
Percent original reserves by avg API gravity	10–20 2	20–25 25–35 3 29	>35 66				

Table C.1 (continued)

	Cumulative production (as of 1/1/81)	Reserves (as of 3/83)		Probability range of undiscovered recoverable resources (as of 3/83)			Ultimate recoverable sources (mode)
		Demonstrated	Original	95%	Mode	5%	
Middle East	123.6	441.7	565.3	72	125	337	690
Saudi Arabia	40.8	170.5	211.3	23	40	109	
Kuwait	20.3	88.6	108.9	1	2	7	
Neutral Zone	3.3	12.6	15.9	1	2	4	
Iran	30.0	63.8	93.8	11	19	51	
Iraq	15.8	50.8	66.6	32	56	150	
Abu Dhabi } Dubai	7.1	46.5	53.6	3	5	13	
Other	6.3	8.9	15.2	<1	1	4	
Bahrain	0.7	0.3	1.0	0	0		
Oman	1.5	3.5	5.0	<1	1	4	
Qatar	3.2	3.6	6.8	0	0		
Syria	0.6	1.2	1.8				
Israel	<0.1	<0.1	<0.1				
Turkey	0.4	0.2	0.6				
Percent original reserves	10–20	20–25 25–35	>35				
by avg API gravity	5	3 68	24				
Asia/Oceania	21.0	34.6	55.6	33	58	176	114
China	6.1	16.3	22.4	14	34	90	
Indonesia	9.4	10.5	19.9	5	9	35	
Other	5.6	7.7	13.3	12	21	34	
Australia }	1.6	2.1	3.7	4	6	11	
N. Zealand }				0.05	0.15	0.5	
Malaysia }	2.2	2.4	4.6				
Brunei }							
Thailand		<0.1	<0.1	tr	1		
Vietnam				1	3	8	
Philippines		0.2	0.2				
Papua N.G.							
Afghanistan							
Pakistan	0.1	0.5	0.6				
India	1.0	2.4	3.4				
Bangladesh				3	5	9	
Burma	0.4	0.1	0.6				
Japan	0.2	<0.1	0.3				
Percent original reserves	10–20	20–25 25–35	>35				
by avg API gravity	2	12 45	41				
Antarctica	0	0	0	0	0	19	0
World	445.1	723	1168	321	550	1417	1718
Percent original reserves	10–20	20–25 25–35	>35				
by avg API gravity	5	6 57	32				

Source: C. D. Masters, D. H. Root, and W. D. Dietzman, "Distribution and Quantitative Assessment of World Crude Oil Reserves and Resources," *U.S. Geological Survey Open-File Report,* USGS-OFR-83-728, 1983.

Appendix D

SOURCES OF INFORMATION

D. SOURCES OF INFORMATION

Forecasting conditions in the world oil market require a wide range of up-to-date information. One major source of this information has been the Department of Energy, Energy Information Administration (EIA). This agency is Congressionally mandated to monitor and document current energy supply and demand information for the United States and the world on an annual basis. The EIA maintains current information on crude oil reserve and production characteristics and on refinery capacities and capabilities, both domestic and international. In addition, the EIA makes annual forecasts of energy supply and demand and prices using a variety of models and assumptions. The three models referred to in Sect. 1 and described in detail in Sect. 4 are used by the EIA and others to make annual forecasts of energy supply and demand and prices to the year 1990 and 1995. In addition to the data and models of the EIA, information from a variety of research programs at federal and private laboratories has been collected and studied. Examples of these sources of information are cited in Fig. D.1. As part of its role of integrating contractor for this project, ORNL is continuing to maintain contact with these facilities to ensure awareness of any information from these sites that will be useful to the current Navy Mobility Fuels Forecasting System.

ORNL WS-38977

ORNL'S ROLE AS INTEGRATING CONTRACTOR FOR NAVY MOBILITY FUELS REQUIRES THAT WE DRAW UPON THE EXPERIENCE IN SEVERAL PUBLIC AND PRIVATE AGENCIES

DOD

NAPC
DTNRDC
NRL
DFSC
SwR
FT. BELVOIR
WRIGHT PAT.
WARREN
PORT HUENEME/ CHINA LAKE

NASA

LEWIS

DOE

EIA
NIPER
MORGANTOWN/PITTSBURGH
OAK RIDGE

DOI/USGS

RESTON
DALLAS
DENVER

PRIVATE

EXXON
CHEVRON
PHILLIPS
BECHTEL
BATTELLE
SRI
CONSULTANT

Fig. D.1. Federal and private agencies conducting research programs or providing information useful in developing the Navy Mobility Fuels Forecasting System.

Appendix E

SENSITIVITY ANALYSIS OF THE REFINERY YIELD MODEL

E. SENSITIVITY ANALYSIS OF THE REFINERY YIELD MODEL

E.1 INTRODUCTION

The purpose of the Navy Mobility Fuels Forecasting System is to provide forecasts and relevant information for analyses of trends in the worldwide availability, quality, and dependability of petroleum-based and synthetic liquid fuels that will be useful to the Navy in planning research and development activities for Navy mobility fuels. The proposed analytical system consists of a three-model linkage: the Oil Market Simulation (OMS) model, the Petroleum Allocation (PAL) model, and a domestic refinery modeling system. The domestic refinery model will be a version of the Refinery Yield Model of Turner, Mason & Associates [the most recent Department of Energy version of which is known as the Refinery Evaluation Modeling System (REMS)].

This appendix summarizes an evaluation of the ability of the Refinery Yield Model of Turner, Mason & Associates (the TMA model) to represent the sensitivity of fuel production to three key refining variable categories: crude type, product specification, and refinery complexity. A set of values was selected for each variable category, and the TMA model was exercised under the conditions described here. These preliminary results indicated that the TMA modeling framework is sensitive to the key variables examined. Because the Department of Energy is modifying the data tables that support the TMA model, the impact of these modifications on the model's performance will be continually reviewed.

The reader is advised to keep in mind that the sensitivity analyses presented in this appendix are in no way comparable to Exxon's "producibility" approach discussed in Sect. 4.3. Section 4.3 presents a strong case for the ability of REMS to replicate product yield and sensitivity results of the Exxon Refinery model. However, "producibility" implies that additional crude can be purchased rather easily to meet fixed product demands. In this appendix, sensitivity is evaluated under a condition of fixed crude availability and relatively unconstrained limitations on the product slate.

E.2 FUEL PRODUCTION SENSITIVITY TO CRUDE

The ability of the TMA model to portray fuel production sensitivity to crude type was evaluated in terms of the product yields and the marginal costs of products manufactured by a refinery configuration representing Petroleum Administration for Defense District 5 (PADD 5), which consists of seven western states. The PADD 5 model was selected for this analysis because other investigations have indicated potential difficulties in meeting specifications for kerosene turbine fuels on the West Coast.[1] The 1983 configuration of the average refinery in PADD 5 is presented in Table E.1. For a given execution of the model, the PADD 5 refinery was constrained such that only one of eight different crudes could be processed. The crudes were selected[2] to represent all combinations of high and low levels of gravity, sulfur content, and gross chemical structure (i.e., paraffinic and naphthenic). Given a crude input level equal to the observed 1983 level of 39,818 barrels per day (B/D), the average refinery was required to produce the product volumes listed in Table E.2. The refinery was allowed to select the optimal levels of production of motor gasolines, Jet A, JP-5, kerosene, No. 2 fuel oil, Navy distillate (NATO symbol F-76), highway diesel, and No. 6 fuel oils.

Table E.1. Configuration of PADD 5 average refinery (1983)

Process Unit	Capacity[a] (MB/D)
Atmospheric distillation	52.6
Atmospheric distillation (hydroskimming)	3.4
Coker (delayed)	6.4
Coker (fluid)	2.1
Visbreaker	1.0
FCC feed desulfurizer	5.0
Naphtha hydrotreater	11.4
Distillate desulfurizer	6.6
Residual desulfurizer	0.7
Catalytic reformer (450 psi)	6.6
Catalytic reformer (200 psi)	6.0
Fluid catalytic cracker (FCC)	14.2
FCC gasoline splitter	3.9
Hydrocracker (two-stage)	7.5
Alkylation plant	2.5
Aromatics plant	0.1
Butane isomerization	0.2
Pentane/hexane isomerization	0.2
Lube and wax plants	0.3
Hydrogen plant (fuel oil equivalent)	1.2
Sulfur plant (M short t/d)	0.07

[a]Capacity is a true arithmetic average. Table 4.3 reflects total region capacity scaled by an arbitrary factor.

Table E.2. Required product volumes for average PADD 5 refinery

Product	Volume (B/D)
Aviation gasoline	115
Special naphtha	57
Jet fuel JP-4	902
Lubes	218
Waxes	36
Road oil	515
Asphalt	515
Naphtha to petrochemical feedstocks	82
Gas Oil to petrochemical feedstocks	335
Still gas to petrochemical feedstocks	34
Propane (fuel/other)	427
Propane to petrochemical feedstocks	87
n-Butane (fuel/other)	165
n-Butane to petrochemical feedstocks	38

Note: Model is allowed to select the optimal levels of production of three grades of motor gasoline, Jet A, JP-5, kerosene, No. 2 fuel oil, Navy distillate (NATO symbol F-76), highway diesel, and No. 6 fuel oils.

Yields of turbine fuel JP-5 and Navy distillate F-76 are presented in Table E.3. Also shown in Table E.3 is the yield of motor gasoline, the product category that has the greatest influence on refiner decisions. Model sensitivity to crude type is illustrated in Table E.3 by the following:

1. Five crudes cannot satisfy all the constraints of the model.
2. Saudi Arabian Heavy crude cannot meet requirements related to disposition of heavy gas oils, special naphthas, and naphtha for petrochemical feedstocks.
3. California Wilmington crude cannot meet requirements related to disposition of heavy gas oils.
4. Saudi Arabian Light crude cannot meet requirements related to heavy gas oils, JP-4, special naphthas, and naphtha for petrochemical feedstocks.
5. Both Texas West Sour and Nigeria Bonny crudes cannot meet requirements related to heavy gas oils.

The three crudes that satisfy model constraints have a 12.3% difference between their maximum and minimum JP-5 yields, a 69.3% difference between their maximum and minimum yields of F-76, and a 7.8% difference between their maximum and minimum yields of motor gasoline. With the 53 refineries of PADD 5 receiving a total crude input of 2,110,330 (B/D), an absolute difference between the maximum and minimum productions of 13,323 B/D of JP-5, 2,910 B/D for F-76, and 109,226 B/D for motor gasoline would result.

Table E.3 Fuel production sensitivity to crude input

Crude	Barrels of product per barrel of crude		
	JP-5	F-76	Motor gasoline
Saudi Arabian Heavy (H,H,P)[a]		Infeasible	
California Wilmington (H,H,N)		Infeasible	
Oklahoma Garber (H,L,P)	0.020256	0.002063	0.513422
Louisiana Ostrica (H,L,N)	0.017756	0.002230	0.565180
Saudi Arabian Light (L,H,P)		Infeasible	
Texas West Sour (L,H,N)		Infeasible	
Hassi-Messaoud (L,L,P)	0.024069	0.000684	0.521063
Nigeria Bonny (L,L,N)		Infeasible	

[a]H indicates high level; L indicates low level; P indicates paraffinic. N indicates naphthenic. Given (I,J,K): I refers to specific gravity level; J refers to sulfur level; K refers to chemical structure (P or N).

The marginal cost of a product is the cost that would be incurred by the refiner in the manufacture of an additional barrel of that product. The refiner would not be expected to produce the incremental barrel unless the product price equalled or exceeded the marginal cost. A reflection of the economic and technical environment in which a product is manufactured, the marginal cost is another indicator of the ability of the TMA model to represent fuel production sensitivity to model variables. Model sensitivity to crude type is illustrated in Table E.4 by the following:

1. Among the three crudes that satisfy model constraints, the difference between maximum and minimum marginal costs per barrel are $6.90 for JP-5, $18.96 per barrel for F-76, $2.21 per barrel for regular motor gasoline, $3.98 per barrel for premium motor gasoline, and $1.10 per barrel for unleaded motor gasoline.

2. With a $0.03 per barrel cost difference, Oklahoma Garber ($28.80 per barrel) and Louisiana Ostrica ($28.83 per barrel) are the most similarly priced crudes. Among the three feasible crude scenarios, a comparison of the Garber and Ostrica cases would most effectively remove the impact of crude cost. In fact, the differences between maximum and minimum marginal costs for JP-5, F-78, and all motor gasolines occur in the comparison of Garber and Ostrica crudes. Marginal costs are higher for each product for the Garber case compared with the Ostrica case.

Table E.4. Fuel cost sensitivity to crude input

Crude	Marginal cost of product[a] (dollars per barrel)				
			Motor gasoline		
	JP-5	F-76	Regular	Premium	Unleaded
Saudi Arabian heavy (H,H,P)[b]			Infeasible		
California Wilmington (H,H,N)			Infeasible		
Oklahoma Garber (H,L,P)	43.82	58.39	37.30	46.93	38.65
Louisiana Ostrica (H,L,N)	36.92	39.43	35.09	42.95	37.55
Saudi Arabian Light (L,H,P)			Infeasible		
Texas West Sour (L,H,N)			Infeasible		
Hassi-Messaoud (L,L,P)	39.25	40.85	37.01	46.40	38.50
Nigeria Bonny (L,L,N)			Infeasible		

[a]All costs expressed in 1983 dollars.

[b]H indicates high level; L indicates low level; P indicates paraffinic; N indicates naphthenic. Given (I,J,K): I refers to specific gravity level; J refers to sulfur level; K refers to chemical structure (P or N).

E.3. FUEL PRODUCTION SENSITIVITY TO PRODUCT SPECIFICATION

The TMA model's ability to represent fuel production sensitivity to adjustment in the product specification was assessed for perturbations in flash point and freeze point specifications for JP-5 manufactured in PADD 5 refineries processing the 1983 crude slate. In addition, the sensitivity of F-76 production to middle distillate cetane number specification was investigated.

Table E.5 indicates that a reduction in JP-5 flash point from 144 to 102°F results in a 5.9% yield increase in JP-5, a 20% yield increase in F-76, and a 3.5% yield decrease in motor gasoline. As shown in Table E.6, a substantial $6.70 per barrel reduction in marginal cost of JP-5 is associated with the flash point decrease. The marginal cost of F-76 increases $5.80 per barrel, and the marginal costs of motor gasolines decrease negligibly.

Table E.7 shows that an increase in JP-5 freeze point from −51 to −12°F has a very small impact on the yields of JP-5 and motor gasolines. The JP-5 freeze point increase causes a 3.5% increase in the yield of F-76. The marginal costs of Table E.8 suggest that the refiner is making processing adjustments to accommodate revisions in the JP-5 freeze point. When compared with the −51°F freeze point case, the −12°F freeze point case results in a marginal cost per barrel

Table E.5. Fuel production sensitivity to JP-5 flash point specification

Flash point of JP-5 blend	Barrels of product per barrel of crude		
	JP-5	F-76	Motor gasoline
102	0.013870	0.000817	0.552032
144	0.013095	0.000681	0.57214

Table E.6. Fuel cost sensitivity to JP-5 flash point specificiation

Flash point of JP-5 blend (°F)	Marginal cost of product[a] (dollars per barrel)				
			Motor gasoline		
	JP-5	F-76	Regular	Premium	Unleaded
102	37.55	40.05	35.55	43.79	37.78
144	44.25	34.25	35.60	43.88	37.80

[a]All costs expressed in 1983 dollars.

Table E.7. Fuel cost sensitivity to JP-5 freeze point specification

Freeze point of JP-5 blend (°F)	Barrels of product per barrel of crude		
	JP-5	F-76	Motor gasoline
−51	0.013095	0.000681	0.572164
−12	0.012970	0.000705	0.572149

Table E.8. Fuel cost sensitivity to JP-5 freeze point specification

Freeze point of JP-5 blend (°F)	Marginal cost of product[a] (dollars per barrel)				
			Motor gasoline		
	JP-5	F-76	Regular	Premium	Unleaded
−51	44.25	34.25	35.60	43.88	37.80
−12	43.22	36.41	35.40	43.51	37.70

[a]All costs expressed in 1983 dollars.

decrease of $1.03 for JP-5; an increase of $2.16 for F-76; and a decrease of $0.10 to $0.37 for motor gasolines.

The influence of the blend values of predominantly civilian fuels on the availability of military fuels is illustrated in Table E.9. When the cetane number of highway diesel is increased from 40 to 45, there is a 6.0% yield decrease for F-76. This result is a consequence of two similar fuels competing for the same pool of cetane-number barrels. The impact on JP-5 and motor gasoline yield is small. As shown in Table E.10, the marginal costs per barrel of F-76 increases by $3.60, JP-5 falls $3.04, and motor gasolines decrease $0.25 to $0.91.

Table E.9. Fuel production sensitivity to highway diesel cetane number specification

Highway diesel cetane number	Barrels of product per barrel of crude		
	JP-5	F-76	Motor gasoline
40	0.013095	0.000681	0.572164
45	0.013159	0.000640	0.573691

Table E.10. Fuel cost sensitivity to highway diesel cetane number specification

Highway diesel cetane number	Marginal cost of product[a] (dollars per barrel)				
			Motor gasoline		
	JP-5	F-76	Regular	Premium	Unleaded
40	44.25	34.25	35.60	43.88	37.80
45	41.21	37.85	35.10	42.97	37.55

[a]All costs expressed in 1983 dollars.

E.4. FUEL PRODUCTION SENSITIVITY TO REFINERY COMPLEXITY

The TMA model's ability to represent fuel production sensitivity to refinery complexity was assessed in terms of two refinery configurations.[3] The capacities of key processing units for the "large" and "small" refineries are shown in Table E.11. Given the product constraints of PADD 5, these refineries were allowed to purchase that quantity of any combination of crudes in the 1983 slate that would result in an 80% crude unit operating rate. The raw material of choice was California Wilmington crude for both refinery configurations.

Table E.12 indicates a strong fuel production sensitivity to refinery complexity. The yield of JP-5 is virtually lost in small refinery operations relative to large refinery operations. The large refinery yield of F-76 is 18.9% lower than the small refinery yield. The large refinery uses its advantage in treating and conversion capacity to produce a motor gasoline yield that is 104% greater than the small refinery yield. The marginal costs of products (shown in Table E.13) are similar for JP-5, $13.34 per barrel higher for F-76 produced in the large refinery, and $2.97 to $10.71 per barrel lower for motor gasolines.

Table E.11. Key processing units of large and small refineries

Process	Capacity (MB/D)		
	Large	Small	
		Actual	Adjusted[a]
Atmospheric distillation	141.32	31.39	141.32
Catalytic cracking	47.30	7.33	33.00
Catalytic reforming	34.14	6.30	28.35
Hydrocracking	8.95	0.94	4.24
Hydrofining/hydrotreating	48.37	4.31	19.42
Alkylation	8.31	1.45	6.55
Coking	13.44	1.34	6.02

[a]Adjusted equals actual × 141.32/31 to remove economies of scale.

Table E.12. Fuel production sensitivity to refinery size

Refinery category	Barrels of product per barrel of crude		
	JP-5	F-76	Motor gasoline
Small	0.000023	0.002282	0.217998
Large	0.006152	0.001851	0.445519

Table E.13. Fuel cost sensitivity to refinery size

Refinery category	Marginal cost of product[a] (dollars per barrel)				
			Motor gasoline		
	JP-5	F-76	Regular	Premium	Unleaded
Small	37.05	38.30	40.98	53.56	40.49
Large	37.09	51.64	35.03	42.85	37.52

[a]All costs expressed in 1983 dollars.

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Appendix F

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Appendix G

TABLES OF USEFUL INFORMATION

G. TABLES OF USEFUL INFORMATION

Miscellaneous Measurement Conversions

Multiply this	By this	To obtain this
ton (long)	1016.047	kg
	1.12	ton (short)
tonne (metric)	1000	kg
	2204.62	lb

The "Système International (SI)" of Metric Units

Conversion Tables

Note: "E" (exponent) implies 10 raised to a power:
2.0E + 03 = 2.0×10^3 = 2000

Customary Unit × Conversion Factor = Preferred Metric Unit

SI unit	Customary unit	Preferred metric unit	Conversion factor
Volume, capacity m^3	bbl (42 gal)	m^3	1.590E−01
	gal	m^3	3.785E−03
Temperature (customary) K	°F	°C	5/9(°F−32)
	°F	K	5/9(°F+459.6)
Pressure Pa	atm	kPa	1.013E+02
	lb/in^2	kPa	6.895E+00
Viscosity (dynamic) Pa·s	cP	Pa·s	1.000E−03
Viscosity (kinematic) m^2/s	cSt	m^2/s	1.000E−06

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